Transport Layer solution for bulk data transfers over Heterogeneous Long Fat Networks in Next Generation Networks

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DOCTORAL THESIS

Title	Transport Layer solution for bulk data transfers over Heterogeneous Long Fat Networks in Next Generation Networks
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Declaration of authorship

I, Alan Briones Delgado, declare that this thesis entitled, "Transport Layer solution for bulk data transfers over Heterogeneous Long Fat Networks" and the work presented in it are my own. I confirm that:

• This work was done wholly or mainly while in candidature for a research degree at this University.

• Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

• Where I have consulted the published work of others, this is always clearly attributed.

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• Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

“Life has three rules: Paradox, Humor, and Change.

- Paradox: Life is a mystery; don't waste your time trying to figure it out.

- Humor: Keep a sense of humor, especially about yourself. It is a strength beyond all measure.

- Change: Know that nothing ever stays the same.”

Dan Millman – The Peaceful Warrior

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Prologue

This thesis represents my search for knowledge, how everything is constantly evolving, how we can influence the evolution of society. During this trip I have worked and investigated in different application fields of the New Generation Networks with the mere objective of learning and, whenever possible, contributing and innovating. That is why an important part of this thesis is about showing all the knowledge acquired over the last 8 years through projects and research, always together with the different people with whom I have been fortunate to share this path.

Abstract

This compendium thesis focuses its contributions on the learning and innovation of the New Generation Networks. That is why different contributions are proposed in different areas (Smart Cities, Smart Grids, Smart Campus, Smart Learning, Media, eHealth, Industry 4.0, among others) through the application and combination of different disciplines (Internet of Things, Building Information Modeling, Cloud Storage, Cybersecurity, Big Data, Future Internet, Digital Transformation).

Specifically, the sustainable comfort monitoring in the Smart Campus is detailed, which can be considered my most representative contribution within the conceptualization of New Generation Networks. Within this innovative monitoring concept, different disciplines are integrated, such as the Internet of Things and Building Information Modeling, in order to offer information on people's comfort levels. This concept goes beyond technology, since it considers the influence of different users and their profiles within this digital transformation of university environments, added to its possible applicability in other more massive and less controlled environments. This also implies a change in mentality within Higher Education Institutions due to the different implications of the introduction of disruptive technology in their management and the new services to offer. This research demonstrates the long journey that exists in the digital transformation of traditional sectors and New Generation Networks.

During this long learning about the NGNs through the different investigations, it was possible to observe a problematic that affected the different application fields of the NGNs in a transversal way and that, depending on the service and its requirements, it could have a critical impact on any of these sectors. This issue consists of a low performance operation during the exchange of large volumes of data on networks with high bandwidth capacity and remotely geographically separated, also known as Elephant networks, or Long Fat Networks (LFNs). Specifically, this critically affects the Cloud Data Sharing use case. That is why this use case and the different alternatives at the transport protocol level were studied, since they are responsible for the speed of sending the data (throughput). For this reason, the performance and operation problems suffered by layer 4 protocols are studied and it is observed why these traditional protocols are not capable of achieving optimal performance. This is mainly due to its conception for networks of lower capacity separated by small distances, and to the assumption that the networks are a fully wired environments, without considering the heterogeneity of the network and its implications.

Due to this situation, it is hypothesized that the introduction of mechanisms that analyze network metrics and efficiently exploit network’s capacity meliorates the performance of Transport Layer protocols over Heterogeneous Long Fat Networks during bulk data transfers.

First, the Adaptive and Aggressive Transport Protocol (AATP) is designed. An adaptive and efficient transport protocol with the aim of maximizing its performance over this type of elephant network, without considering, for the moment, a heterogeneous environment. The protocol introduces a mechanism to measure the maximum bandwidth, as well as a rapid recovery system in case of a congestion episode. In addition, due to the need of the use case, this protocol is designed aggressive towards other flows to be able to take advantage of most of the bandwidth, leaving the residual bandwidth to the rest of the flows that share the connection. The AATP protocol is implemented and tested in a network simulator and a testbed under different situations and conditions for its validation.

Once the AATP protocol was designed, implemented and tested successfully, it was decided to improve the protocol itself, Enhanced-AATP, to improve its performance over heterogeneous elephant networks, by being able to discern between losses due to congestion and those caused by the nature of the wireless media. Therefore, a mechanism based on the Jitter Ratio is designed, allowing this differentiation to be made. In addition, in order to upgrade the behavior of the protocol, its fairness system is improved for the fair distribution of resources among other Enhanced-AATP flows. Finally, this evolution is implemented in the network simulator and a set of tests are carried out to validate its performance and operation.

At the end of this thesis, it is concluded that the New Generation Networks have a long way to go and many things to improve due to the digital transformation of society and the appearance of brand-new disruptive technology. Furthermore, it is confirmed that the introduction of specific mechanisms in the conception and operation of transport protocols improves their performance on Heterogeneous Long Fat Networks.

Resumen

Esta tesis por compendio centra sus contribuciones en el aprendizaje e innovación de las Redes de Nueva Generación. Es por ello que se proponen distintas contribuciones en diferentes ámbitos (Smart Cities, Smart Grids, Smart Campus, Smart Learning, Media, eHealth, Industria 4.0 entre otros) mediante la aplicación y combinación de diferentes disciplinas (Internet of Things, Building Information Modeling, Cloud Storage, Ciberseguridad, Big Data, Internet del Futuro, Transformación Digital).

Concretamente, se detalla la monitorización sostenible del confort en el Smart Campus, la que se podría considerar mi aportación más representativa dentro de la conceptualización de Redes de Nueva Generación. Dentro de este innovador concepto de monitorización se integran diferentes disciplinas, como son el Internet of Things y el Building Information Modeling, para poder ofrecer información sobre el nivel de confort de las personas. Este concepto va más allá de la tecnología, ya que considera la influencia de los diferentes usuarios y sus perfiles dentro de esta transformación digital de los entornos universitarios, sumado a su posible aplicabilidad en otros entornos más masivos y menos controlados. Esto además supone un cambio de mentalidad dentro de los centros de educación superior debido a las diferentes implicaciones que supone la introducción de tecnología disruptiva en su gestión y los nuevos servicios a ofrecer. Esta investigación demuestra el largo recorrido que existe en la transformación digital de los sectores tradicionales y las Redes de Nueva Generación.

Durante este largo aprendizaje sobre las NGN a través de las diferentes investigaciones, se pudo observar una problemática que afectaba de manera transversal a los diferentes campos de aplicación de las NGNs y que, dependiendo del servicio y sus requerimientos, ésta podía tener una afectación crítica en alguno de estos sectores. Esta problemática consiste en el bajo rendimiento durante el intercambio de grandes volúmenes de datos sobre redes con gran capacidad de ancho de banda y remotamente separadas geográficamente, también conocidas como redes elefante, o Long Fat Networks (LFNs). Concretamente, esto afecta de manera crítica al caso de uso de intercambio de datos entre regiones Cloud (Cloud Data Data use case). Es por ello que se estudió este caso de uso y las diferentes alternativas a nivel de protocolos de transporte, ya que se encargan de la velocidad de envío de los datos (throughput). Por ello, se estudian las diferentes problemáticas que sufren los protocolos de nivel 4 y se observa por qué estos protocolos tradicionales no son capaces de alcanzar rendimientos óptimos. Esto es debido, principalmente, a su concepción para redes de menor capacidad separadas por menor distancia, y a la suposición de que las redes son un entorno totalmente cableado, sin contemplar redes heterogéneas y sus posibles implicaciones.

Debida a esta situación, se hipotetiza que la introducción de mecanismos que analizan las métricas de la red y que explotan eficientemente la capacidad de la misma mejoran el rendimiento de los protocolos de transporte sobre redes elefante heterogéneas durante el envío masivo de datos.

Primeramente, se diseña el *Adaptative and Aggressive Transport Protocol* (AATP), un protocolo de transporte adaptativo y eficiente con el objetivo maximizar el rendimiento sobre este tipo de redes elefante, sin considerar, por el momento, la heterogeneidad de la red. El protocolo introduce un mecanismo para medir el ancho de banda máximo de la comunicación, así como de un sistema de rápida recuperación en caso de pérdidas por congestión. Además, debido a la necesidad del caso de uso, este protocolo se diseña agresivo para con otros flujos para poder aprovechar la mayor parte del ancho de banda de la conexión, dejando el ancho de banda residual al resto de flujos que comparten conexión. El protocolo AATP se implementa y

se prueba en un simulador de redes y un testbed bajo diferentes situaciones y condiciones para su validación.

Una vez diseñado, implementado y probado con éxito el protocolo AATP, se decide mejorar el propio protocolo, Enhanced-AATP, sobre redes elefante heterogéneas con el objetivo de que sea capaz de discernir entre pérdidas por congestión y aquellas causadas por la naturaleza del propio medio inalámbrico. Por ello, se diseña un mecanismo basado en el Jitter Ratio que permite hacer esta diferenciación. Además, con tal de mejorar el comportamiento del protocolo, se mejora su sistema de *fairness* para el reparto justo de los recursos con otros flujos Enhanced-AATP. Finalmente, esta evolución se implementa en el simulador de redes y se realizan una serie de pruebas para la validación de su rendimiento y operación.

Al finalizar esta tesis, se concluye que las Redes de Nueva Generación tienen mucho recorrido y muchas cosas a mejorar debido a la transformación digital de la sociedad y a la aparición de nueva tecnología disruptiva. Además, se confirma que la introducción de mecanismos específicos en la concepción y operación de los protocolos de transporte mejora el rendimiento de estos sobre redes elefante heterogéneas.

Resum

Aquesta tesi per compendi centra les seves contribucions en l'aprenentatge i innovació de les Xarxes de Nova Generació. És per això que es proposen diferents contribucions en diferents àmbits (Smart Cities, Smart Grids, Smart Campus, Smart Learning, Mitjana, eHealth, Indústria 4.0 entre d'altres) mitjançant l'aplicació i combinació de diferents disciplines (Internet of Things, Building Information Modeling, Cloud Storage, Ciberseguretat, Big Data, Internet de el Futur, Transformació Digital).

Concretament, es detalla el monitoratge sostenible del confort a l'Smart Campus, la que potser es la meva aportació més representativa dins de la conceptualització de Xarxes de Nova Generació. Dins d'aquest innovador concepte de monitorització s'integren diferents disciplines, com són l'Internet of Things i el Building Information Modeling, per poder oferir informació sobre el nivell de confort de les persones. Aquest concepte va més enllà de la tecnologia, ja que considera la influència dels diferents usuaris i els seus perfils dins d'aquesta transformació digital dels entorns universitaris, sumat a la seva possible aplicabilitat en altres entorns més massius i menys controlats. Això a més suposa un canvi de mentalitat dins dels centres d'educació superior a causa de les diferents implicacions que suposa la introducció de tecnologia disruptiva en la seva gestió i els nous serveis a oferir. Aquesta investigació demostra el llarg recorregut que hi ha en la transformació digital dels sectors tradicionals i les Xarxes de Nova Generació.

Durant aquest llarg aprenentatge sobre les NGN a través de les diferents investigacions, es va poder observar una problemàtica que afectava de manera transversal als diferents camps d'aplicació de les NGNs i que, depenent del servei i els seus requeriments, aquesta podia tenir una afectació crítica en algun d'aquests sectors. Aquesta problemàtica consisteix en el baix rendiment durant l'intercanvi de grans volums de dades sobre xarxes amb gran capacitat d'ample de banda i remotament separades geogràficament, també conegudes com a xarxes elefant. Concretament, això afecta de manera crítica al cas d'ús d'intercanvi massiu de dades entre regions Cloud (Cloud Data Sharing use case). És per això que es va estudiar aquest cas d'ús i les diferents alternatives a nivell de protocols de transport, ja que s'encarreguen de la velocitat d'enviament de les dades (throughput). Per això, s'estudien les diferents problemàtiques que pateixen els protocols de nivell 4 i s'observa per què aquests protocols tradicionals no són capaços d'arribar a rendiments òptims. Això és degut, principalment, a la seva concepció per a xarxes de menys capacitat separades per grans distàncies, i a la suposició que les xarxes són un entorn totalment cablejat, sense contemplar la heterogeneïtat de la xarxa i les seves implicacions.

Deguda a aquesta situació, s'hipotetiza que la introducció de mecanismes que analitzen les mètriques de la xarxa i que exploten eficientment la capacitat de la mateixa milloren el rendiment dels protocols de transport sobre xarxes elefant heterogènies durant l'enviament massiu de dades.

Primerament, es dissenya l'*Adaptative and Aggressive Transport Protocol* (AATP), un protocol de transport adaptatiu i eficient amb l'objectiu de millorar el rendiment sobre aquest tipus de xarxes elefant, sense considerar, de moment, la heterogeneïtat de la xarxa. El protocol introdueix un mecanisme per mesurar l'ample de banda màxim de la comunicació, així com d'un sistema de ràpida recuperació en cas de pèrdues per congestió. A més, a causa de la necessitat del cas d'ús, aquest protocol es dissenya agressiu envers altres fluxos per poder aprofitar la major part de l'ample de banda de la connexió, deixant l'ample de banda residual a la resta de fluxos que comparteixen connexió. El protocol AATP s'implementa i es prova en un simulador de xarxes i un testbed sota diferents situacions i condicions per la seva validació.

Un cop dissenyat, implementat i provat amb èxit el protocol AATP, es decideix millorar el propi protocol, Enhanced-AATP, sobre xarxes elefant heterogènies amb l'objectiu que sigui capaç de discernir entre pèrdues per congestió i aquelles causades per la naturalesa del propi medi sense fil. Per això, es dissenya un mecanisme basat en el Jitter Ràtio que permet fer aquesta diferenciació. A més, per tal de millorar el comportament del protocol, s’adapta el seu sistema de *fairness* per al repartiment just dels recursos amb altres fluxos Enhanced-AATP. Finalment, aquesta evolució s'implementa en el simulador de xarxes i es realitzen una sèrie de proves per a la validació del seu rendiment i operació.

A l'acabar aquesta tesi, es conclou que les Xarxes de Nova Generació tenen molt recorregut i moltes coses a millorar causa de la transformació digital de la societat i de l'aparició de nova tecnologia disruptiva. A més, es confirma que la introducció de mecanismes específics en la concepció i operació dels protocols de transport millora el rendiment d'aquests sobre xarxes elefant heterogènies.

Contents

Glossary

AATP - Adaptive and Aggressive Transport Protocol

AC - Acoustic Comfort

ACK - Acknowledgment packets

AEC - Architecture, Engineering and Construction

AIMD – Additive Increasing Multiplicative Decreasing

AMQP - Advanced Message Queuing Protocol

API - Application Programming Interface

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers

AWS - Amazon Web Services

BBR - Bottleneck Bandwidth and Round-trip propagation time protocol

BDP - Bandwidth-Delay Product

BIC-TCP - Binary Increase Control TCP

BIM - Building Information Modeling

BUS - Building Use Studies Ltd.

BW - Bandwidth

CA - Congestion Avoidance

CAD - Computer-Aided Design

CAS - Complex Adaptive Systems

CBE - Center for the Built Environment

CBR - Constant Bit Rate

CEN - European Committee for Standardization

CERL - Congestion Control Enhancement for Random Loss

CIE - International Commission on Illumination

CoAP - Constrained Application Protocol

CWND - Congestion Window

DoS - Deny of Service

D-TCP - Dynamic TCP

DUACK - Duplicate ACK

ECN - Explicit Congestion Notification

ERDF - European Regional Development Fund

GRITS – Research Group in Internet Technologies and Storage

HF - High Frequency

HLFN - Heterogeneous Long Fat Network

HpFP - High-Performance and Flexible Protocol

HTTP - Hypertext Transfer Protocol

HVAC - Heating, Ventilation, and Air Conditioning

HW - Hardware

IaaS - Infrastructure as a Service

IACK - Instant ACK

IAQ - Indoor Air Quality

ICT – Information and Communications Technology

IEQ - Indoor Environmental Quality

IES/ANSI - Illuminating Engineering Society of North America

IoT - Internet of Things

ISO - International Organization for Standardization

ITU – International Telecommunication Union

JFI - Jain Fairness Index

JSCTP - Jitter Stream Control Transmission Protocol

JSON - JavaScript Object Notation

JTCP - Jitter TCP

LED - Light-Emitting Diode

LEED - Leadership in Energy and Environmental Design

LER - Light Efficiency Rating

LFN - Long Fat Networks

LTD - Loss Threshold Decision maker

MAS - Multi-Agent System

MQTT - Message Queuing Telemetry Transport

NGN – Next Generation Network

NVIS - Near Vertical Incidence Skywave

OS - Operative System

OWD - One-Way Delay

PaaS - Platform as a Service

PHP - Hypertext Preprocessor

PLC – Power Line Communications

PLR - Packet Loss Ratio

PMV - Predicted Mean Vote

QoS – Quality of Service

RFC - Request for Comments

RTO - Retransmission Timeout

RTT - Round Trip Time

SACK - Selective Acknowledgment

SAN - Storage Area Network

SBS - Sick Building Syndrome

SC/SMCM - Smart Campus

SCTP - Stream Control Transmission Protocol

SIoT - Social Internet of Things

SMCT – Smart City

SMEs - Small and Medium Enterprises

SMGD – Smart Grid

SR - Sending Rate

SS - Slow Start

TACK - Tamed ACK

TC - Thermal Comfort

TCP – Transmission Control Protocol

TER - Temperature Efficiency Rating

UDP - User Datagram Protocol

UDT - UDP-Based Data Transfer Protocol

URL - University Ramon Llull

UWP - Universal Windows Platform

VBR - Variable Bit Rate

VC - Visual Comfort

VOC - Volatile Organic Compounds

WF - Weighted Fairness

WSN - Wireless Sensor Networks

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1. Introduction

1.1 Motivation

Following the definition of the International Telecommunication Union (ITU) in 2009 [1], a Next Generation Network (NGN) is "a packet-based network in which service-related functions are independent from underlying transport-related technologies. NGN enables unfettered access for users to networks and to competing service providers and services of their choice. It supports generalized mobility which will allow consistent and ubiquitous provision of services to users [2]". This term refers to the most important advances in the access and core networks for the following decades. Some of the fundamental characteristics are enumerated below [1]:

- Packet-based transfer.
- Separation of control functions among bearer capabilities, call/session, and application/service.
- Decoupling of service provision from transport, and provision of open interfaces.
- Support for a wide range of services, applications and mechanisms based on service building blocks (including real time/streaming/non-real time services and multi-media).
- Broadband capabilities with end-to-end QoS and transparency Interworking with legacy networks via open interfaces.
- Generalized mobility unfettered access by users to different service providers.
- Converged services between Fixed and Mobile networks.
- Independence of service-related functions from underlying transport technologies.
- Support of multiple last mile technologies.

The ITU highlights the data transfer performance improvement over the new infrastructures to be deployed, focusing on the application field and the services deployed. It talks also about how the coexistence of wired and wireless sections (emphasizing the last mile) requires new solutions to provide converged services due to the heterogeneity of the network (Figure 1).

Figure 1. Next Generation Networks[1]

Some preliminary questions arose in my mind from this very first insight. How these new technologies and network deployments can be exploited? Do we have high performance solutions for these? How these new needs and services can take advantage of these new infrastructures? Can we define new infrastructures? Why? How the services' performance and its operation could be independent from the underlying media technology used? Are the

[1] Monitis Blog: What will the future internet look like https://blog.monitis.com/blog/what-will-the-future-internet-look-like/

network protocols those who will close the gap between technology and service? Are these protocols the key to provide high performance services over networks?

In order to start learning about the NGNs, my very first goal when I joined the Research Group in Internet Technologies and Storage (GRITS) was about understanding what a real NGN is and which are the different types [3][4][5][6]. It was about learning about its context, its characteristics and its possibilities. Moreover, I was interested about different application fields and how the distinct services can be deployed over these new networks considering the desired performance and requirements.

My first experience with NGN was related to the digital transformation of the cities, also known as Smart Cities. Referring to the European Commission's definition [7], a Smart City is a "place where traditional networks and services are made more efficient with the use of digital and telecommunication technologies for the benefit of its inhabitants and business". The deployment of new infrastructures, as it can be the optical fiber or wireless access technologies to increase the network capacity [8][9][10], the management and automation of the network that interconnects the city [11][12] and, also, the impact of new services [13] as is the Smart Metering [14], the remote and automatic operation of meters and other devices to improve the efficiency of the electric system and quality of service [15], were some of the main enrichments. Thanks to be collaborating in Smart City Malaga project [SMCT Málaga], I started to understand the real needs and requirements from the Next Generation Networks in the Smart Cities field and its efficiency.

After that, I became involved in the research of solutions for modern services' deployment over brand-new communication technologies, focusing on the energy sector, the Smart Grid [16][17]. Also following the European Commission definition [18], Smart Grids are "energy networks that can automatically monitor energy flows and adjust to changes in energy supply and demand accordingly. When coupled with smart metering systems, Smart Grids reach consumers and suppliers by providing information on real-time consumption", as it can be seen in Figure 2. Given the complexity of the sector, I understood the challenge of providing solutions over NGNs deployments and the implications of its application in real cases as it happened in the INTelligent Electrical GRId Sensor Communications project [INTEGRIS], that envisioned a novel design and development of a flexible Information and Communications Technology (ICT) infrastructure in the Smart Grids field. The Power Line Communications (PLC) [19] and the creation of the INTEGRIS devices (IDEVs), which provided different services to the network (Cybersecurity, real time information management) [20], were the key technology enabler elements. We continued working on this application field and improving the IDEVs (FIDEVs) in the FINESCE project [FINESCE].

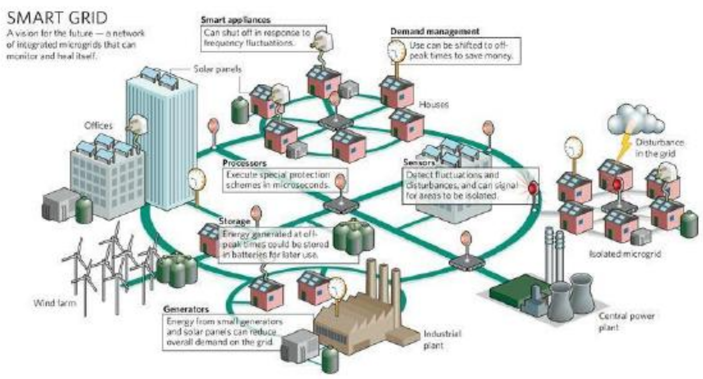

Figure 2. Smart City and Smart Grid[2]

At that point, the micro perspective focusing on the application field, as it can be a specific Smart City or Smart Grid, did not let me see the macro perspective. Open questions arose again. What are we going to do with all the information generated by the devices deployed in the different testbeds, sites, regions, grids or cities? How are we going to store it? Is it possible to use this information to get new outcomes, applications or information related to a specific service or site?

Widening my perspective, I continued to explore other domains through other initiatives as it were the VSNoverIPv6 project [VSNoIPv6], a project mainly focused on high performance data exchange over IPv6 NGN with different media service requirements and network circumstances, being networks with high capacity and big delays by applying different access technologies as satellite or optical fiber. Also, the Cloud centered project called Smart Hybrid Enterprise Cloud [SHECloud] raised other issues to consider. The exchange of the high amount of data generated and the necessity of storing it in the private infrastructure, in a scalable public one or a hybrid solution; or the possibility of processing the data gathered were ones of the important figures from the Cloud Storage and Big Data technologies to consider [21].

From these data requirements and the amount of information generated and shared, more specific questions were formulated. What was happening in the exchange of the data gathered between NGN regions? Are we getting the maximum performance? Are backbone networks ready to deal with the huge amount of data generated within these sites/regions? Following Statista [22], the volume of data/information created, captured, copied, and consumed worldwide doubles every two years, ten times more in 10 years, increasing from 12,5 zettabytes in 2014 to a prospected 149 zettabytes in 2024.

Thanks to these experiences, even if they were from a very technical role, I started to understand the magnitude and potential of the NGNs and the different requirements depending on the application field and the services deployed. The most outstanding key points were the network infrastructure and the communication protocols. I determined that NGNs' performance data transfer efficiency, in terms of networks, were not solved by only applying new available technology. It was also necessary to consider the emerging services and its requirements depending on the application field in order to get the maximum performance over the NGNs.

With all these insights from NGNs, I concluded that network characteristics and the application field services requirements are the main factors by which the communication protocols' performance will depend for the optimal data exchange over NGN.

1.2 Background

In order to know the performance achieved by transport layer protocols, those that control the data sending rate during the data transfer, I started to study and analyze the main common features of NGN and how its characteristics affect to current transport protocols' operation and performance.

The most widely used transport protocol because of its main characteristics of information integrity and reliability is the Transmission Control Protocol (TCP), designed in 1974 [23]. The receiver informs about the received packet to the sender using acknowledgment packets (ACK). TCP uses an Additive Increasing Multiplicative Decreasing (AIMD) mechanism to adjust the data

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[2] Smart City Hub: Smart grid: where social and digital innovation meet https://smartcityhub.com/technology-innnovation/smart-grid/

transfer speed. The main two mechanisms that control the communication are the Slow Start (SS), by considerably reducing TCP's throughput in case of a loss occurs during the data transmission, and the Congestion Avoidance (CA), in order to try to control protocol's throughput as it arrives to the maximum capacity of the link. This AIMD congestion control provokes a sawtooth effect in the transmitted flow that makes it not efficient over error prone links (Figure 3).

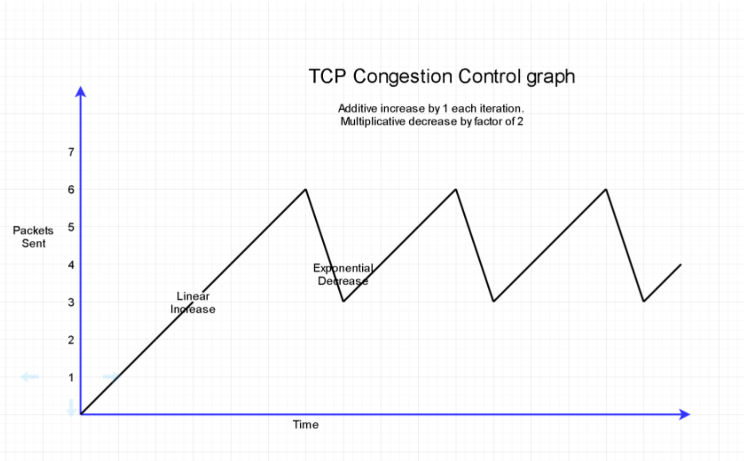

Figure 3. TCP sawtooth effect[3]. Source: Learnsteps.com

Two of the NGNs' aspects to consider are the long distance between regions and, also, the high bandwidth provided by new transmitting data technologies [2]. A network is denominated Long Fat Network (LFN), pronounced "elephan(t)", when the product of its Bandwidth (in bits per second) and its Round-Trip delay (in seconds), also known as Bandwidth-Delay Product (BDP), is greater than 12,500 bytes (10^5 bits). For example, a link of 1 Gbps and 1 ms of RTT, obtains a BDP of 10^6, being classified as LFN. The LFN concept and its effects over TCP's performance were firstly defined and detailed in the Request For Comments (RFC) 1072 (1988) [24], which was obsoleted by the RFC 1323 (1992) [25] to finally become the standard RFC 7323 (2014) [26].

These RFCs pointed out the problematics that TCP faces over these long-delay paths because of the high bandwidth and long round-trip delays, which implicate a considerable BDP. The BDP can be best seen as the number of bits it takes to fill the pipe (as it puts the example of the amount of unacknowledged data that TCP must handle in order to keep the pipeline full). The main TCP performance problems over LFNs arise due to the TCP design itself, such as the limitation of the congestion window, which only allows a maximum window of 65 KB because its field in the header is 16 bits long, limiting the maximum throughput reached. Another efficiency problem occurs due the activation of the TCP slow start mechanism after a packet loss event, which causes a drastic throughput reduction, draining the data pipeline. Moreover, given the high value of the Round-Trip Time (RTT), it is necessary to accurately measure the retransmission timeout (RTO) interval. In this type of high delay networks, TCP experience problems to calculate properly the RTO, considering the not acknowledged segments as a segment loss due to the delay, which also activates the slow start process and reduces its throughput due to unnecessarily retransmitting that segments.

Legacy TCP variants proposed different solutions to improve TCP performance. TCP Tahoe introduced the Fast Retransmit mechanism and, also, provided a new RTT calculation in order

[3] Learn Steps: https://www.learnsteps.com/do-you-know-about-the-aimd-method-in-tcp-congestion-control/

to improve its outcome, meanwhile TCP Reno included the Fast Recovery process [27]. TCP New Reno introduced a sending rate estimation at the beginning of the transmission [28]. By implementing the previous mechanism, TCP SACK introduced the Selective Acknowledgment (SACK) to indicate exceptional segment losses [29][30][31]. TCP Vegas focuses on the delay to determine the throughput [32]. Even including these mechanisms and increasing its performance over LFNs, the problem is not solved and different researches highlight the poor TCP's performance and from its different proposed modifications [33][34][35].

Related to its performance, TCP is conceived as a friendly protocol, which means that TCP flows let other flows to get part of the bandwidth and its efficiency can be reduced as other more aggressive protocols emerge [36][37]. This can be a problem in case a flow requires high efficiency due to the transfer requirements of a service, depending on the NGN application field.

Furthermore, added to the high BDPs and friendliness drawbacks, one more obstacle has to be evaluated. NGNs consider the heterogeneity of the network, which means that brand-new wired and wireless media access technologies coexist within them. The main inconveniences introduced by a wireless connection for communication protocols are bandwidth degradation, the interruption of the transmission caused by the nature of the media, and the network resource inefficiency caused by obstacles, interferences, or the mobility of the node [38]. The existence of wireless sections in the last mile of LFNs, denominated Heterogeneous Long Fat Networks (HLFNs), directly affects to the transport layer protocols' performance due to the aforementioned problems [39][40][41][42]. TCP conception [43] was meant for wired connections, meaning that in case a random loss occurs in the wireless section, TCP will consider it as a congestion loss and it will reduce its sending rate and, consequently, its efficiency is affected [44]. Different TCP enhancements have been proposed in order to solve these wireless issues [45][46].

When it comes to bulk data transfers over a separated high-speed Next Generation Network composed by wired-wireless sections, it can be concluded that, to the best of our knowledge, there is no specific transport protocol that provides optimal performance over Heterogeneous Long Fat Networks.

It is hypothesized that:

the introduction of mechanisms that analyze network metrics and efficiently exploit network's capacity meliorates the performance of Transport Layer protocols over Heterogeneous Long Fat Networks during bulk data transfers.

1.3 Research questions

First of all, related to the big picture, a broader perspective of Next Generation Networks is required. Considering all the disruptive technologies developed and the digitalized brand-new services, this digital transformation process of the society boosts new NGNs application fields and the integration of multidisciplinary technologies in traditional sectors [5]. It will be necessary to study the different types of NGNs in order to define where we can contribute, in terms of data transfers over HLFNs, from a practical point of view.

Our goal is to propose a Transport Layer solution for the bulk data transfer problematic over a specific real HLFN Use case and to learn about the different application fields that compose the NGNs' paradigm.

The transport layer is the OSI layer in charge of deciding the suitable data rate. The information considered by a transport protocol characterize its sending rate. Depending on the conception of a transport protocol, its operation can vary. Legacy transport layer protocols operation experiences some performance inefficiencies due to the network's evolution in terms of technology, deployment, architecture and service requirements. Concretely, focusing on Heterogenous Long Fat Networks, some particularities need to be discussed.

HLFNs are characterized by high capacities and far distances, which means a high Bandwidth-Delay Product. The transport protocol has to be able to achieve the maximum speed offered by the network and, at the same time, adapt its operation to optimally perform depending on the network circumstances, trying to avoid causing losses and instabilities in the system.

Moreover, due to the heterogeneity of the HLFNs, the network can be composed by wired and wireless sections that directly affect to the nature of the communication. As it was stated, the main cause of losses in wired sections is the congestion of the bottleneck, meanwhile, in wireless sections, these losses can also be caused due to a channel failure. The transport layer protocol has to be able to deal with the different types of losses occurred.

Given the situation where different factors have to be considered, it can be useful for the transport layer protocol to obtain information from the network with the objective of deciding consequently. Thanks to analyzing these network metrics, transport layer protocols can set up its distinct features to improve its performance without negatively affecting the network stats.

Research Question 1 (RQ1) Which Next Generation Network application fields are experiencing bulk data transfer problematics over Heterogeneous Long Fat Networks?

Research Question 2 (RQ2) Can transport layer protocols take advantage from the network metrics in order to achieve optimal performance over a Heterogeneous Long Fat Networks?

Research Question 3 (RQ3) Can transport layer protocols adapt its operation over wireless sections by distinguishing congestion and channel losses?

1.4 Thesis objectives

The objectives proposed for this thesis are meant to give a response to the research questions from Research questions section:

Objective 1 (O1). Identify the Next Generation Networks' problematics through the study of the NGNs' application fields and their characteristics

This holistic objective is aligned with my personal goal of learning about Next Generation Networks. It is proposed because we are going to study the NGN application fields and their problematics, mainly focusing on their network architecture and service requirements. This **O1** is meant to be present during my whole path and, concretely, it is going to help to answer to the **RQ1**.

Even if our main focus is on answering a technical issue, it is necessary to understand the background from the different sectors. If we are going to be contributing to the digital transformation of the society, it will be necessary to put in context the introduction of the new technology and define new NGNs paradigms [47].

Specifically, thanks to the know-how acquired during the achievement of this objective, this process will help us to find which application field could adopt HLFNs in their architecture. By this way, we will be able to identify which is of them consider the bulk data transfers over HLFNs and in which of them can be tentative to apply a Transport Layer solution to improve its data exchange performance.

Objective 2 (O2). Improve Transport Layer protocol performance over Long Fat Networks

First of all, it is necessary to analyze the State-of-the-Art of the last non-standardized transport layer protocols, specifically designed for long distance, and their performance over LFNs. The requirements and main issues of LFNs must be defined. As stated before, being the Bandwidth Delay Product the main inconvenience [26], it is necessary to consider both facts. On the one hand, we have the high bandwidth of the link (Fat) and, on the other hand, the high delay introduced (Long) due to the distance between endpoints. Furthermore, In order to comprehend the composition and features of a transport layer protocol, it is required to study the characteristics that define a transport layer protocol and, also, the different options to carry out these features.

It is essential to propose a protocol that gets information from the underlying network metrics and adapts its sending rate to the link situation during the data transfer, achieving the maximum throughput to optimize its efficiency. At the same time, with the same optimization purpose, it is fundamental that this protocol avoids the retransmission timeout limitations and the duplicity of the information in the network.

This objective aims at proposing the transport protocol design and proof-of-concept implementation that optimally performs over Long Fat Networks. By achieving the objective **O2**, we are going to be able to partially answer to **RQ2**.

Finally, it will be necessary to test and check its capabilities in a proof-of-concept deployment over LFNs, considering the physical implementation and, also, the simulation.

Objective 3 (O3). Propose the wireless adaptation of the base solution to improve its performance over Heterogeneous Long Fat Networks

After achieving the first objective (O1), it will be necessary to adapt the previously designed protocol to deal with the heterogeneity in Long Fat Networks. The aspiration of this second objective is adapting the transport protocol by introducing mechanisms to cope with wireless links and their main limitations. The accomplishment of the **O3** will mean that the **RQ3** is answered and, consequently, we will be able to provide a convincing answer to **RQ2**.

As is stated in the Background section, the incapacity of the aforementioned transport layer protocols to differentiate between congestion losses and channel losses seems to be one of the main operation problems. Due to this fact, the different network metrics have to be considered in order to establish a decision-making mechanism that aids the protocol to increase its performance over HLFNs.

The main inconveniences introduced by wireless sections and their impact on Heterogeneous Long Fat Networks must be analyzed. By this way, it will be necessary to define mechanisms, with the support of the extracted data, that allows the protocol to overcome the aforementioned wireless issues. In addition, the State-of-the-Art of the last wireless-oriented transport layer protocols must be studied.

With all the previous work done, new mechanisms based on network metrics will be defined and proposed to be introduced in the protocol operation in order to distinguish the type of losses occurred during the data transmission.

To conclude, the protocol will be adapted in the simulator by introducing the designed mechanisms. Performance tests will be run to validate the improved protocol's efficiency and proper operation under different network circumstances over HLFNs.

Objective 4 (O4). Progress towards protocol enhancement

This transversal fourth objective is related to the refinement of the protocol thanks to the performance analysis. This complementary objective reinforces the answers to **RQ2** and **RQ3** by improving the performance of the proposed solution. Given the distinct tests to verify the operation and performance of the proposed solution under different network circumstances, some inefficiencies can be identified and corrected.

This objective is meant to recognize the opportunities and flaws of the proposed solution and, if possible, propose solutions to the matters identified.

Overall approach

The main goal to be achieved, through the accomplishment of these 4 objectives (**O1**, **O2**, **O3** and **O4**), is the research of new technological solutions to be deployed over Heterogeneous Long Fat Networks in order to achieve a higher performance during the bulk data transfers in the context of Next Generation Networks.

It will be necessary that the concluded research is evaluated and validated by the scientific community. By this way, our intention is publishing it in indexed journals, which are subjected to the peer review process, in order to present thesis as a compendium of publications. Through the helpful comments from the reviewers, we will be able to improve and validate the work proposed and its novelty.

O1 provides us the perspective of the NGNs and their challenges. It is not only about proposing new technologies to new circumstances, it is about proposing solutions for the digital transformation of the society. It is necessary to put in context the different technological solutions that are developed and check how these affects to the NGN sectors. Through the accomplishment of this **O1**, the data transfers problematics over HLFNs can be identified in order to characterize the application field requirements.

O2 and **O3** are mostly focused on the design and test of a new transport layer protocol that solves the inefficiencies of contemporary protocols over New Generation Networks. The methodology to be followed in both objectives is studying the State-of-the-Art, identify the main weaknesses and specific points to work for the purpose of designing the new protocol's specification.

State-of-the-Art analysis of the current transport layer protocols suggested by the community to propose solutions over LFNs and wireless sections provides us the perspective of what is done under the different network composition and circumstances. Related to the objectives, the **O2** is more focused in the base design of the protocol that improves the performance over LFNs and the **O3** is more focused on the specific wireless feature. We have considered by this way because of the complexity of the two challenge that are proposed, as it is highlighted in the Background.

After this study, the protocol and its new mechanisms design will be conceived with the purpose of solving the identified drawbacks and improving the performance of previous work. The protocol will be implemented, deployed and tested. Very related to **O4**, through these testing activities, some possible misfunctions can be identified, as it might affect to the protocol performance, and, afterwards, solve them to validate the design. Also, improvement points will be recognized. With the overall result of the work done, the refinement of the protocol will be evaluated to increase its performance in the near future, depending on its scope, output and post-analysis.

1.5 Contributions

Thanks to be involved in R&D projects and work with other researchers, different contributions have been made so far.

My main goal during my PhD was learning about NGN, the different application fields and their problematics. I had the chance to contribute to different NGN application fields in different ways during my thesis hand in hand with my GRITS' colleagues and people from all of the project that I have been part of. The Next Generation Networks and the Digital Transformation process of the society have been very present during my career.

During this search of knowledge, I worked in a Cloud resource allocation proposal and its application to the Smart Grids [48]. Also, I have been part in the design process of an Internet of Things telemetry architecture for the natural disaster monitorization [49].

Thanks to coordinating the Technological Master in Digital Transformation and also be involved in Erasmus+ projects, I had the chance to contribute to the Smart Learning paradigm because of the transdisciplinary conceptualization of the Education through the integration of different disciplines (i.e, Big Data [50], IoT or Cybersecurity [51]) in the Digital Transformation of traditional sectors, as it can be the Industry 4.0 or the eHealth.

Going further in the integration concept, we contributed to the conceptualization of the Smart Cities by considering a cross-cultural and cross-organizational research, the Smart Campus [52]. Through the integration of distinct disciplines, as it is the Internet of Things and the Building Information Modeling, we have proposed an innovative solution for the comfort workspace monitorization.

Finally, thanks to this search of knowledge and experiences, we identified the problematic of bulk data transfers in the Cloud Data Sharing use case. It was when we decided to research on an optimal performance solution that meets the application field requirements and its service restrictions. We contributed to solve this issue by proposing our designed, implemented and tested Transport Layer protocol [53]. Moreover, we evolved this solution by enhancing its features to upgrade its performance over heterogeneous long fat networks [54].

Seven published articles in journals:

1. Resource Allocation on a Hybrid Cloud for Smart Grids [48].
2. Heterogeneous wireless IoT architecture for natural disaster monitorization [49].
3. Automatic tutoring system to support cross-disciplinary training in Big Data [50].
4. An Integral Pedagogical Strategy for Teaching and Learning IoT Cybersecurity [51].
5. A Smart Campus' Digital Twin for Sustainable Comfort Monitoring [52].
6. Adaptive and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks [53].
7. Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks [54].

One published congress paper:

8. Mecanismos de nivel de transporte para la optimización de envíos en base al ancho de banda estimado sobre Long Fat Networks [55].

One book chapter:

9. Security in Smart Grids [56].

A brief summary from each contribution is explained below:

1. ‘Resource Allocation on a Hybrid Cloud for Smart Grids’ [48] researches on the resource allocation methodology to be applied in a multi-cloud scenario based on the findings derived from the framework used for the FINESCE project. The purpose of this work is to define a methodology to assist on the hybrid cloud selection and configuration in the Smart Grid for both generic and highly-constrained scenarios in terms of latency and availability. Specifically, the presented method is aimed to determine which is the best cloud to allocate a resource by (1) improving the system with the information of the network and (2) minimizing the occurrence of collapsed or underused virtual machines.
2. ‘Heterogeneous wireless IoT architecture for natural disaster monitorization’ [49] proposes a monitorization architecture that addresses the communication with the public during emergencies using movable and deployable resource unit technologies for sensing, exchanging, and distributing information for humanitarian organizations. The challenge is to show how sensed data and information management contribute to a more effective and timely response to improve the quality of life of the affected populations.
3. ‘Automatic tutoring system to support cross-disciplinary training in Big Data’ [50] proposes a learning and teaching framework committed to train masters’ students in Big Data by conceiving an intelligent tutoring system aimed to (1) automatically tracking students’ progress, (2) effectively exploiting the diversity of their backgrounds, and (3) assisting the teaching staff on the course operation.
4. ‘An Integral Pedagogical Strategy for Teaching and Learning IoT Cybersecurity’ [51] proposes an integral pedagogical strategy for learning cybersecurity in IoT structured in three different stages, in a higher education institution. These stages focus not only on the content about IoT and cybersecurity but also on the competencies to acquire, the most suitable learning methodologies and the expected learning outcomes. The association of these concepts in each stage is detailed. Examples of courses are explained, the related competencies and learning outcomes are specified, and the contents and methodologies to achieve the expected results are described. An analysis of student results and stakeholder evaluations is provided to verify if the pedagogical strategy proposed is suitable. Furthermore, students’ feedback is included to corroborate the innovation, the suitability of the acquired skills, and the overall student satisfaction with the related courses and consequently with the proposed IoT cybersecurity pedagogical strategy.
5. ‘A Smart Campus’ Digital Twin for Sustainable Comfort Monitoring’ [52] is a cross-cultural and cross-organizational research. It offers great opportunities for innovative breakthroughs in the field of Smart Cities, mainly focused on the Smart Campus. Under the Smart Campus paradigm, this article proposes to investigate the integration of different disciplines and application fields, which includes building information modeling and Internet of Things. Moreover, it focuses on the environmental monitoring and emotion detection with comfort purposes. It is highlighted the preliminary result about the significance of monitoring workspaces.
6. ‘Adaptative and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks’ [53] presents the design and performance of the Adaptative and Aggressive Transport Protocol (AATP) for the optimization of the data transfers in a Long Fat Network use case, concretely, a Cloud Data Sharing use case. After analyzing distinct transport layer protocols meant for high capacity and high delay networks, the protocol is designed by introducing novel features as are the bandwidth estimation of the link and the adaptability of the protocol operation depending on the status of the

network, which includes its friendly aggressive behavior. Finally, different tests are proposed to demonstrate the AATP's performance.

7. 'Wireless Loss Detection over Fairly Shared Heterogenous Long Fat Networks' [54] proposes two new mechanisms to improve the AATP protocol. First, the Enhanced-AATP introduces the designed Loss Threshold Decision maker mechanism for the detection of different types of losses, being able to distinguish between congestion and channel losses. In addition, the Weighted Fairness index is included and it modifies the protocol's behavior for the fair use of the node's resources by prioritized bandwidth sharing between different Enhanced-AATP protocols. Different tests are deployed to demonstrate its proper operation and, to conclude, it is compared to other modern protocols.
8. 'Mecanismos de nivel de transporte para la optimización de envíos en base al ancho de banda estimado sobre Long Fat Networks' [55] presents a series of transport level mechanisms for the optimization of data transfers over LFN networks. These mechanisms offer high performance, while are reactive in case of losses to avoid network congestion.
9. 'Security in Smart Grids' [56] chapter talks about the great advance in technology, the need for greener and more sustainable power sources and energy laws promoted by the governments allowed the Smart Grid trend to become a reality. As networks become an integral part of corporations and everyone's lies, advanced network security technologies are being developed to protect data and preserve privacy.

The following table (Table 1) shows the information from the author's contributions.

Table 1. Contributions from the author

Title	Journal	Quartile (JCR)	Impact Factor	Reference
Resource Allocation on a Hybrid Cloud for Smart Grids	Network Protocols and Algorithms	-	-	[48]
Heterogeneous wireless IoT architecture for natural disaster monitorization	Journal on Wireless Communications and Networking	Q3	1,408	[49]
Automatic tutoring system to support cross-disciplinary training in Big Data	The Journal of Supercomputing	Q2	2,469	[50]
An Integral Pedagogical Strategy for Teaching and Learning IoT Cybersecurity	Sensors	Q1	3,275	[51]
A Smart Campus' Digital Twin for Sustainable Comfort Monitoring	Sustainability	Q2	2,576	[52]
Adaptative and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks	Future Generation Computer Systems	Q1	6,125	[53]
Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks	Electronics	Q2	2,412	[54]
Mecanismos de nivel de transporte para la optimización de envíos en base al ancho de banda estimado sobre Long Fat Networks	Proceedings JITEL'17	Congress	-	[55]
Security in Smart Grids	From Internet of Things to Smart Cities: Enabling Technologies	Book chapter (179 to 225)		[56]

1.5.1 Compendium

This thesis is meant to be a compendium of articles. Among all the articles, I have chosen the most relevant papers, those which have had the greatest impact on my path.

This compendium is composed by these three articles:

- A Smart Campus' Digital Twin for Sustainable Comfort Monitoring [52].
- Adaptive and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks [53].
- Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks [54].

The specific contributions from the author in each of the articles included in this compendium are presented below. The co-authors role is explained in each of the chapters related to the articles.

From those articles more related to the application field research, I have chosen one of the most representative publications, the Smart Campus [52], a cross innovative proposal for a NGN application field. Thanks to the background and experience achieved during this long path followed during my thesis, a cross innovation action for NGNs is contributed by presenting a sustainable comfort monitoring in the application field of the Smart Campus. The investigation, conceptualization and methodology have been carried out by Alan.

Moreover, after identifying the bulk data transfer problematic over HLFNs in the Cloud Data Sharing use case, my research also took a vertical path to propose a specific solution for this issue. Another main contribution of this thesis is the novel transport layer protocol designed, implemented and tested that accomplishes an optimal performance over Heterogeneous Long Fat Networks during bulk data transfers [53][54].

The novel protocol, Adaptative and Aggressive Transport Protocol (AATP) achieves high performance by adapting its operation relaying on the network stats. The bandwidth estimation process, its sending rate calculation based on packet-burst operation and lost packets gaps recovery system are the most remarkable features introduced. At the same time, its friendly aggressiveness focuses on overcoming the other coexisting flows in the link, leaving the residual bandwidth for them [53]. Alan directly contributed to the investigation, conceptualization and specification of the AATP protocol. As well as, he has collaborated in the tests deployment and formally analyzed the outcomes obtained. Also, he led the paper writing.

Moreover, due to the heterogeneity of the network, a novel mechanism is designed and included to enhance the protocol's operation (Enhanced-AATP). This mechanism allows the protocol to distinguish between the type of losses occurred in a heterogeneous network, which can be a congestion loss or a channel loss [54]. Alan led to the investigation, conceptualization and specifications of the new mechanisms included in the Enhanced-AATP protocol. In addition, he has been involved in the testing methodology and formal analysis of the results. Also, Alan led the paper writing.

Given the different tests deployed, the protocol has been evaluated during the different experiments and analysis. Thanks to that, apart from improving its operation and performance by introducing refinements, a new system of fairness towards other flows of the same kind is designed to introduce a weighted fairness model in the communication, also included in the Enhanced-AATP [54]. It was necessary due to the original aggressiveness conception of the AATP. By this way, this aggressive behavior can be adjusted through priorities.

The following table (Table 2) shows the articles that constitute this compendium.

Table 2. Publications of this compendium

Title	Journal	Quartile (JCR)	Impact Factor	Reference
A Smart Campus' Digital Twin for Sustainable Comfort Monitoring	Sustainability	Q2	2,576	[52]
Adaptative and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks	Future Generation Computer Systems	Q1	6,125	[53]
Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks	Electronics	Q2	2,412	[54]

1.6 Roadmap

Since I joined the Internet Technologies and Storage Research Group (GRITS) in 2013, I have been very related to research projects. My path in the research group, as is depicted below (Figure 4), can be divided in two main parts. During the first part (2013-2016), my role in the projects were very focused on learning and understanding, through projects from different application fields, about Next Generation Networks, its requirements and new technologies. In 2016 I started officially my PhD, being the starting point of the second phase (2016-2021). It was more focused on providing my own contribution to the NGN paradigm while I was increasing my knowledge of NGNs through distinct projects. All the information about the projects can be found in the Appendix A. Projects.

As it can be seen in the first half of the roadmap, 2013-2016, I have been involved in different projects where I acquired knowledge background from different sectors of NGNs. From the Smart City application field [SMCT Málaga], also focusing on Smart Grids [INTEGRIS][FINESCE], passing through the Cloud paradigm [SHECloud], to the Media application field [VSNoIPv6, MBTAP, OMBTAP]. All of them had in common the research on Communication protocols and Next Generation Networks applications. All this activities influenced directly or indirectly to the publications of this first period:

- Mecanismos de nivel de transporte para la optimización de envíos en base al ancho de banda estimado sobre Long Fat Networks [55] congress paper in 2016.
- Resource Allocation on a Hybrid Cloud for Smart Grids [48] paper in 2017.
- Security in Smart Grids [56] book chapter in 2017.

In this second half, 2016-2021, with all these experiences from the distinct backgrounds, I decided to enroll me in the PhD. I was involved in brand-new projects very focused on Smart Cities [BUSAN], and other more related to the Digital Transformation of traditional sectors, as it is the Industry 4.0 [SPRINT 4.0] or eHealth [ATHIKA]. Moreover, we started to think about a relative new concept, the Smart Campus [SmartCampus] and its evolution [DigitalTwin]. In this cross innovative solution, we merged different disciplines and concepts, as it is the Internet of Things, the environmental monitoring and the comfort measurement. Finally, all the activities undertaken during my path disposed the following publications in this second period:

- Heterogeneous wireless IoT architecture for natural disaster monitorization [49] in 2020.
- Automatic tutoring system to support cross-disciplinary training in Big Data [50] in 2020.
- An Integral Pedagogical Strategy for Teaching and Learning IoT Cybersecurity [51] in 2020.
- A Smart Campus' Digital Twin for Sustainable Comfort Monitoring [52] in 2020.

- Adaptive and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks [53] in 2020.
- Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks [54] in 2021.

1.7 Thesis outline

This thesis is structured as follows.

Chapter 1: It is the Introduction. It is focused about my motivation to start the adventure of knowledge, the background and the research questions arisen, my contributions and the roadmap followed. After put in context the reader, Chapters 2, 3 and 4 correspond to the published articles.

Chapter 2: It describes a cross-innovative Next Generation Network application field, Smart Campus, by merging different technologies and perspectives for the environmental monitorization and the comfort measurement [52].

Chapter 3: It describes the Adaptative and Aggressive Transport Protocol design, implementation and tests over Long Fat Networks [53].

Chapter 4: It presents the AATP protocol enhancement (Enhanced-AATP) which focuses its improvements in the wireless loss detection and the fairly share of the resources [54].

Chapter 5: The results from each article are presented.

Chapter 6: It concludes the thesis with the final discussion and conclusions

Chapter 7: It highlights the future work.

Appendix A. Projects: All the projects are detailed.

Appendix B. Papers: A copy of the published articles in the journal format is presented

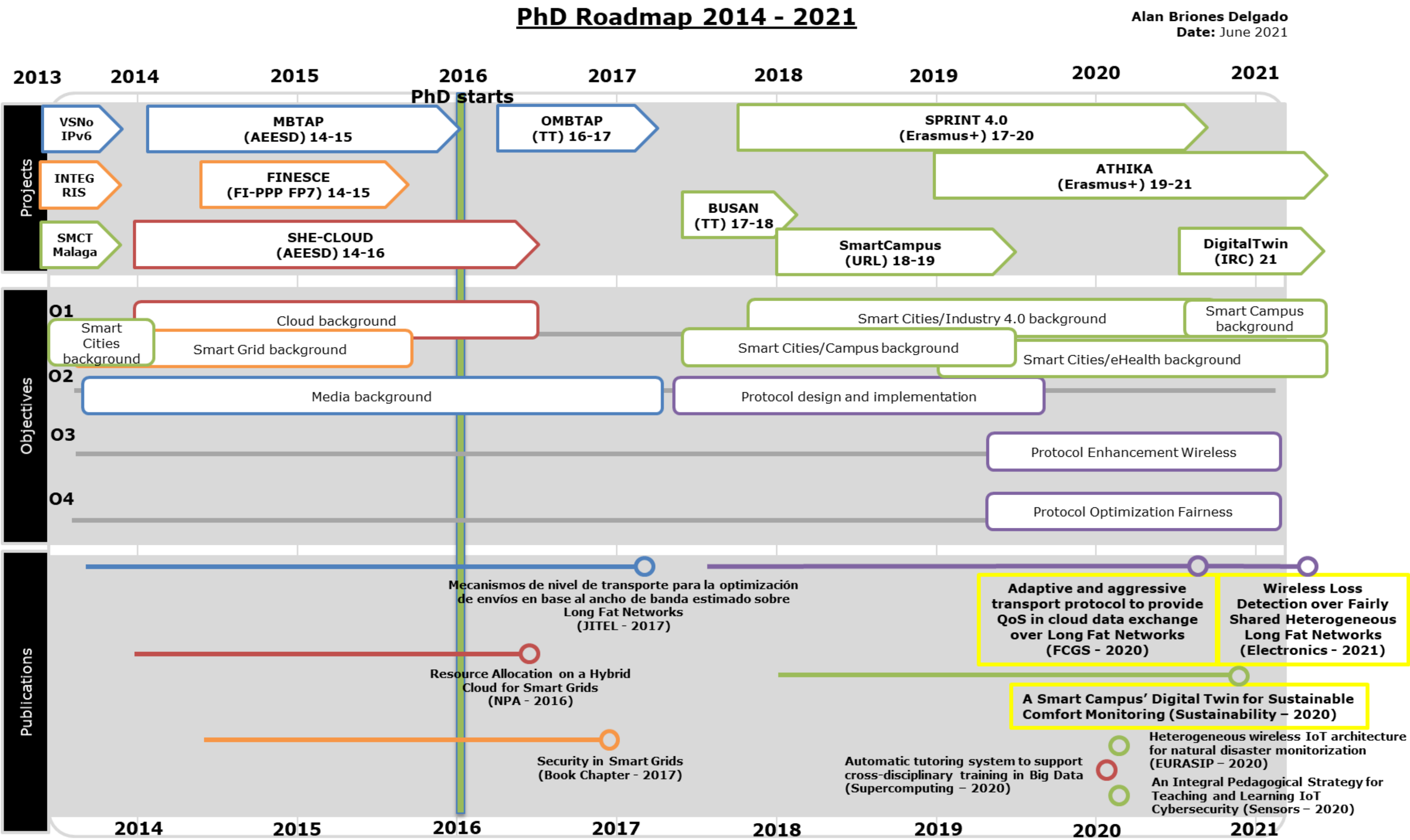

Figure 4. Alan's PhD Roadmap

2. A Smart Campus' Digital Twin for Sustainable Comfort Monitoring[4]

Interdisciplinary cross-cultural and cross-organizational research offers great opportunities for innovative breakthroughs in the field of smart cities, yet it also presents organizational and knowledge development hurdles. Smart cities must be large towns able to sustain the needs of their citizens while promoting environmental sustainability. Smart cities foment the widespread use of novel information and communication technologies (ICTs); however, experimenting with these technologies in such a large geographical area is unfeasible. Consequently, smart campuses (SCs), which are universities where technological devices and applications create new experiences or services and facilitate operational efficiency, allow experimentation on a smaller scale, the concept of SCs as a testbed for a smart city is gaining momentum in the research community. Nevertheless, while universities acknowledge the academic role of a smart and sustainable approach to higher education, campus life and other student activities remain a mystery, which have never been universally solved. This paper proposes a SC concept to investigate the integration of building information modeling tools with Internet of Things- (IoT)-based wireless sensor networks in the fields of environmental monitoring and emotion detection to provide insights into the level of comfort. Additionally, it explores the ability of universities to contribute to local sustainability projects by sharing knowledge and experience across a multi-disciplinary team. Preliminary results highlight the significance of monitoring workspaces because productivity has been proven to be directly influenced by environment parameters. The comfort-monitoring infrastructure could also be reused to monitor physical parameters from educational premises to increase energy efficiency.

Keywords: sustainable ecosystem; environmental monitoring; IEQ calculation; BIM

2.1 Introduction

2.1.1 Research Motivation and Scope

Smart cities must be large towns able to sustain their citizens' incremental needs while promoting environmental sustainability. With the emergence of new information and communication technologies (ICTs), such as the Internet of Things (IoT) and big data, smart cities are closer to this realization. However, the deployment of such an amount of technology in a wide geographical area requires experimentation and testing. Consequently, our research proposes to create smart campuses (SCs) to experiment with the deployment of these ICT technologies [1][2]. The aim is to support the efficient management of a "small" smart city. In

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the context of an SC, we consider the needs of students and campus staff while improving environmental sustainability.

This way, we narrow the scope of the present paper by focusing on two properties: students' comfort and energy efficiency. We aim to integrate the ICTs to monitor and manage both of them; therefore, IoT devices are responsible for detecting comfort levels and energy efficiency on the campus and take consequent corrective action. We propose to conceptualize groups of smart devices that could be used to achieve a determined goal by acting as physical-world proxies for agents. For instance, an agent is responsible for improving energy efficiency and comfort in a given classroom, and it senses and actuates on the physical world (e.g., classrooms) through IoT sensors and actuators.

According to Eurostat and the European Commission report in Education and Training Monitor 2019, more than 31% of the European population is currently enrolled in educational programs. This percentage only includes physical-based learning. However, in recent years remote learning and distance education have grown significantly [3]. Hence, more than 138 million European people spend a considerable amount of their time in educational facilities (schools, universities, colleges, etc.). Most of these facilities were constructed a long time ago to rapidly address the educational needs of growing local populations due to the societal changes in which young adults began to complete a full education plan: primary school, high school, and university/vocational training. At that time, educational institutions were large infrastructures to allocate all students, faculty members, and staff. However, little or no attention was paid to the overall comfort of these environments—understood as a measure that balances the wellbeing of all users, the efficiency of the processes involved, and the pro-environmental footprint of their facilities.

Recent studies have suggested that comfort in educational environments is a critical parameter for the success of learning and the evolution of society [4]. Comfort is usually related to individual and isolated parameters such as air quality, temperature, or noise [5]. Measuring these parameters can be tackled seamlessly with unobtrusive equipment as an enabler to obtaining reasonable—yet incomplete—partial conclusions [6]. Indeed, much effort has been made to improve ICT-based solutions in the direction of more accurate and more complete systems (e.g., including more local variables) [7]. However, these recurrent solutions typically fail at quantifying the side effects of measuring comfort involving external parameters to the educational environment that still have a great impact on its associated issues (e.g., overall sustainability, energy efficiency, learning and teaching performance, etc.). For instance, they are unable to address dilemmas such as whether it would be worth increasing the energy consumption to keep the optimal thermal conditions in order to ensure an improvement in the students' academic output or not.

In essence, current ICT-based proposals to monitor comfort either do not deal collectively with the vast amount of internal and external parameters to measure them, or only provide local (i.e., partial) qualitative views of comfort as they are more focused on keeping the technological paradigm of cost-effectiveness [5]. Hence, existing developments are incremental, concerning a conceptual and technological paradigm that remains unchanged. Understanding, monitoring, predicting, and optimizing comfort in educational environments requires a holistic and cross-layer view able to frame and quantify the dynamic and nonlinear relations of their involved users [8]. Indeed, addressing the comfort in educational facilities cannot be tackled in a linear way since several interdependent parts are continuously changing. Therefore, it is safe to say that comfort in educational environments has remained under-sampled for years mostly due to the complexity of objectively quantifying and acting on it.

Specifically, authors have examined, measured, and analyzed all the potential external (e.g., available open data, weather information, architectural issues, etc.) and internal (e.g., thermal or acoustic data) variables affecting such comfort to (1) quantify, monitor, predict and optimize comfort in physical and, eventually, virtual educational environments; (2) enhance overall sustainability and (3) overcome potential issues in the teaching-learning process. The proposed structural model of our SC will help to predict the impact of the distinct institutional policies on comfort and, as such, it will encourage drivers to address changes such as conducting active learning methodologies, adopting eco-friendly initiatives to reduce environmental footprint toward carbon neutrality, or incorporating renewable energies to save natural resources.

Overall, our research proposes a radical paradigm shift and the use of IoT technology in monitoring and optimizing comfort in university learning environments, where the frame for analysis and modeling of the comfort parameter holistically covers the internal and external meta-dimensions, as a whole, that characterize the socio-environmental interactions of three strategic stakeholders: teaching and learning community, facility management staff, and energy providers. If these dimensions, and their impact on comfort, were defined, quantified, and validated through innovative scientifically-grounded methods, this would drive the conception of a new technology able to transform the current generation of comfort analysis in physical and virtual educational environments. This achievement will endow them with a completely novel functionality to improve their sustainability while helping to understand, design, populate, monitor, and perceive comfortable learning environments.

2.1.2 The Importance of the University in the Promotion of Sustainability

Universities and colleges play a crucial role in the development of knowledge and innovation, especially in more environmentally benign technologies and goods to promote sustainable living [9]. They represent vital places to explore, test, develop, and communicate the necessary conditions for effective and sustainable change [10][11]. Many universities and colleges are similar to micro cities because of their population, size, and the many different types of activities happening on campus. According to the literature, a sustainable university is “a higher educational institution that addresses, involves and promotes, on a regional or a global level, the minimization of negative environmental, economic, societal, and health effects generated in the use of their resources in order to fulfill its functions of teaching, research, outreach and partnership, and stewardship in ways to help society make the transition to sustainable lifestyles” [12].

Although universities acknowledge their roles in our present culture, there is a part of university life that has been rendered a mystery and has never truly been solved universally among universities: sustainable development. Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [13]. Since sustainability is an issue of present-day and future societies, it is crucial that places of learning, such as universities, play a critical role in teaching sustainability to citizens who will be the future decision-makers. Sustainability practices begin at the university level by adapting environmentally sustainable policies and expanding to local, regional, national and international levels [14].

Since graduates of any discipline will need knowledge and skills related to sustainability, the challenges and possible solutions should be integrated within the main functions of a university: the development of an interdisciplinary curriculum, environmental literacy, sustainable academic research, sustainable physical operations of the campus, and collaboration amongst universities. The common ground of sustainable practices is the ethical and moral responsibility of universities to be leaders in promoting sustainability [15][16][17]. Campus sustainability has become an issue of global concern for university policymakers and planners as a result of the realization of the impacts the activities and operations of universities have on the environment. Generating more sustainable campus life, including actual innovative campus projects and administrative policies, creates opportunities for students within sustainability [18].

Due to their unique position, universities and colleges play a key role in educating the future generations of citizens who will have expertise in all fields of the labor market. This role includes both the promotion of environmental literacy among students and research in sustainability, as well as a contrived effort to decrease the university's impact on the environment [19]. Although universities worldwide are constantly improving their vision and curricula to address future sustainability challenges, there is still much work to do. The goal of sustainability education is to give students knowledge and skills and help them find solutions to environmental, health-related, and economic challenges [20]. Another important element in the methodology used for teaching students about sustainability is the need to undertake hands-on projects to ensure the students' understanding of the challenges and possible solutions. Self-sustainable campuses with many projects (e.g., composting, rooftop gardens and solar panels) teach students about sustainability and require the active work of the students. Students who participate in planning, building, and maintaining these projects will be more likely to develop lifelong sustainability habits.

2.1.3 The Statement for Our Smart Campus Comfort Challenge

The main goal of the Advanced Training in Health Innovation Knowledge Alliance (ATHIKA) [21] is to use knowledge transfer to duplicate, yet also locally customize, sustainability innovations undertaken by diverse institutions. The ATHIKA project will build a set of advanced training programs involving academia, public administrations, SMEs (Small and Medium Enterprises), start-ups, and health business consultants. The variety of profiles of the project partners will provide an overall perspective of the sector and will enable the identification of its most urgent challenges. They will guide and coach students and researchers during the development of novel technical and ethical-compliance solutions to implement ICT solutions in the health sector, especially the solutions related to the smart campus (SC) ATHIKA challenge. Authors envisage that the accurate monitoring, analysis, prediction, and management of comfort will lead to a reduction in the overall environmental footprint of educational environments while increasing the comfort of their users.

In this paper, we present the development and implementation of novel and advanced healthy SC by using comfort as a quality metric, based on ICT that relies on greater interaction between healthcare professionals, education communities, and technological experts. Available SC data are becoming massive, and needs to be handled in controlled environments, under proper ethical criteria. The goal is to establish a challenge-based learning program where teams of students from various disciplines and countries will compete to find solutions for our SC challenge. The devised solutions, or pretotypes, have been developed into prototypes, following a technology coaching (supported by universities) and the application-oriented coaching (conducted by the target company). This program will be used to reduce the learning and experience curve associated with targeting, developing, and implementing sustainability projects in university settings. The current paper introduces the research carried out in the smart campus challenge within the ATHIKA Erasmus+ project [21].

Reaching a comfortable and responsive SC implies focusing on the two interrelated concepts: “smartness”, mainly related to addressing the problems cities face with the aid of information and communication technologies (ICT), and “healthy sustainability”, emphasizing citizens’ inclusion (students and faculty) and social wellbeing (social dimension), ecosystem protection (environmental dimension) and boosting of the local economy (economic dimension) [22].

Nowadays, new ICTs make the real-time monitoring of university campus conditions possible. A variety of sensors and intelligent devices deployed throughout the campus can monitor pollution, noise, natural or artificial risks as well as epidemics, and manage public spaces and facilities to reduce or avoid negative impacts on educational community health. Our SC challenge also aims to build a platform capable of assisting contemporary university campuses in transforming towards sustainable and comfortable campuses by exploiting data from both existing data sets and on-field sensors. The proposed approach is based on an interdisciplinary digital twin modeling that can be integrated into existing decision support systems by providing quantitative hints and suggestions on architecting and ICT engineering sustainable policies. Using novel trends in ICTs—such as cloud computing, big data, artificial intelligence and Internet of Things—to process, visualize and analyze real-time data is now feasible to accurately monitor citizens and their interactions with the physical infrastructures, and thus, identify, learn, and act to improve the future public health conditions.

In fact, ATHIKA aims to (1) explore innovative approaches to contribute to the sustainable campus transformation, employing technologically advanced pedagogy in a multi-disciplinary way through ICT engineering and architecture frameworks, (2) propose innovative good practices for managing a university campus, involving data-driven sustainable products and service outcomes in order to support environmental policymaking and (3) use novel edge computing architectures for advanced submetering and distributed hybrid intelligence algorithms [23]. Nevertheless, in this paper, the authors introduce a quantitative and measurable definition of comfort, together with the first-ever accurate and unbiased measurement of the concept. It includes the development of computational models and low-cost infrastructures for automated, resilient, and reliable data acquisition, storage, processing, and visualization of comfort. The innovative and scientifically grounded technologies of our proposal have been validated in our real-world university campus.

2.1.4 Framework-Based Methodology

Smart cities are usually associated with complex systems [24]. Complex systems are defined as systems formed by heterogeneous elements that interact with each other and their environment [25][26][27]. The diversity of these elements, the non-linearity of relationships between them and the multiple influences of the environment determine their complexity [28]. Indeed, the level of complexity of smart cities and their ability to achieve urban sustainability has called for debate [29]. Additionally, adding smartness to the city leads to an increase in complexity—and more complexity requires more energy [30][31]. Therefore, in light of the debate surrounding the sustainability of smart cities and with the acknowledgment that smart campuses are similar to small smart cities [1][2]—thus, potentially able to shed light on the debate—the methodological framework used in this work considers the smart campus as a complex system.

Under the umbrella of complexity theory comes the framework of complex adaptive systems (CAS) [25]. CAS refers to systems that involve “a large number of components, often called agents, which interact and adapt or learn” [32]. General top-level properties and features such as self-similarity, complexity, emergence and, self-organization induce CAS to be considered as an appropriate framework for the methodological sequence of the presented research project proposal on comfort in educational environments: agents (i.e., teaching and learning community, facility managers, and energy providers) and the system (i.e., physical and virtual educational environments) are adaptive, and the system is a complex self-similar collectivity of interacting, adaptive agents.

In juxtaposition with the vision of smart campuses as CAS, some authors model the IoT—an enabler technology for SCs—as a complex system too [30][33][34][35][36]. To exemplify our SC modeling approach, we consider the increase in students' comfort and energy efficiency. We allocate each space (e.g., classroom) with an agent with two goals. The first, concerning students' comfort, the second, aiming at energy efficiency. The agent is responsible for sensing different properties of both students and classrooms through IoT sensors, gathering contextual information, and acting according to the desired level of comfort and energy efficiency through IoT devices. Therefore, we allocate several agents in the campus.

Agents in a multi-agent system (MAS) cooperate to maximize their goal [37]. For example, given a determinate number of students in a classroom, the agent sets a level of comfort for the classroom. At the same time, the agent sets a determinate energy efficiency goal. Then, the agent needs to carry out actions to achieve a reasonable level of students' comfort and energy efficiency. Additionally, the environment in which the agent operates might be modified by other agents and external factors. Modification by other agents might be due to their operation in other spaces (e.g., spaces on the same floor or building), and modification by external factors might be due to weather conditions, for example.

With regard to the characterization of the hierarchical structure of the system comprehended by IoT devices and agents (in our framework, guardians), we add a higher-level module providing a decision support system: the wise module. Therefore, IoT devices, the guardian module, and the wise module have a hierarchical relationship in the digital twin as well. IoT devices are deployed in a zone or section of an SC building, and the guardian perceives and acts on the physical world using those devices; therefore, the relationship between the guardian and the IoT devices is one-to-many. In turn, the wise module is connected to the guardians in a one-to-many relationship and contains the support decision system to coordinate the guardians, so they operate towards a common goal: students' comfort and energy efficiency.

Essentially, at a lower scale, an IoT-enabled device is a system of software and hardware components; at an upper scale, in consideration of the model we propose, devices (sensors and actuators) cooperate to enable an agent to sense and actuate on the physical world (guardian), zooming out, agents in a MAS form a system (wise module), and beyond these scales, more systems of systems arise.

In addition, regarding the interaction between agents in a CAS and their implementation using ICTs, we now set our focus on the relationship between agents. The authors in [38] compare network and complexity theories and define CAS as "a pattern of relationships among adaptive, self-organizing and interdependent elements (agents)". As stated, our technological framework is under the umbrella of IoT technologies among other novel ICTs. To frame the relationships between agents—and the organizing dynamics of their relationships—we use the Social Internet of Things (SIoT) paradigm.

The SIoT [39] promotes a scalable and flexible network structure between things. It enables things to be part of a social network to search for required services or things. The search is influenced by the trust assigned, subjectively or objectively, to each thing. In an SC, sensors and actuators might be placed at relevant locations such as classrooms. Then, according to the proposed SIoT relationships, sensors and actuators in a classroom create social relationships between each other, either by their closeness in space (called co-location relationships) or by their need to cooperate and work together to achieve a certain goal (called co-work relationships). Moreover, in the presence of an agent per classroom (the guardian), they create a hierarchical relationship; the agent on top, sensors, and actuators (things) at the bottom.

Some properties of our study (e.g., air quality, humidity, and temperature) might share a greater space than a classroom. For example, the temperature in a classroom dissipates and affects other classrooms in the same building. Consequently, when considering the spaces and locations in a building, agents need to cooperate to achieve balance and to improve students' comfort and energy efficiency, agents in different classrooms and spaces cooperate and create SIoT relationships between them by using the wise module. Furthermore, agents need to perceive the state of the physical world to validate that their acts work towards the desired behaviors in the digital twin model. In a large deployment, communication between all agents would create communication overhead. To reduce this overhead, the state of the world should be perceived within the agents' neighborhood [33].

Concluding, the SC is considered a small smart city in the scope of our research. SCs, similar to smart cities, are CAS but on a smaller scale, where heterogeneous elements adapt, interact, and create a pattern of relationships. The main elements in our SC model are IoT devices, guardians and the wise module, which have been modeled in the digital twin environment. The guardians and the wise module create relationships, interact, and adapt, whereas IoT devices (which may have limited resources) create relationships and interact. Additionally, we frame the potential relationships under the IoT paradigm called SIoT. The SIoT aims to provide a scalable and flexible network of things to facilitate their search and discovery, both processes influenced by security-related trust mechanisms. Those interactions are depicted in Figure 5.

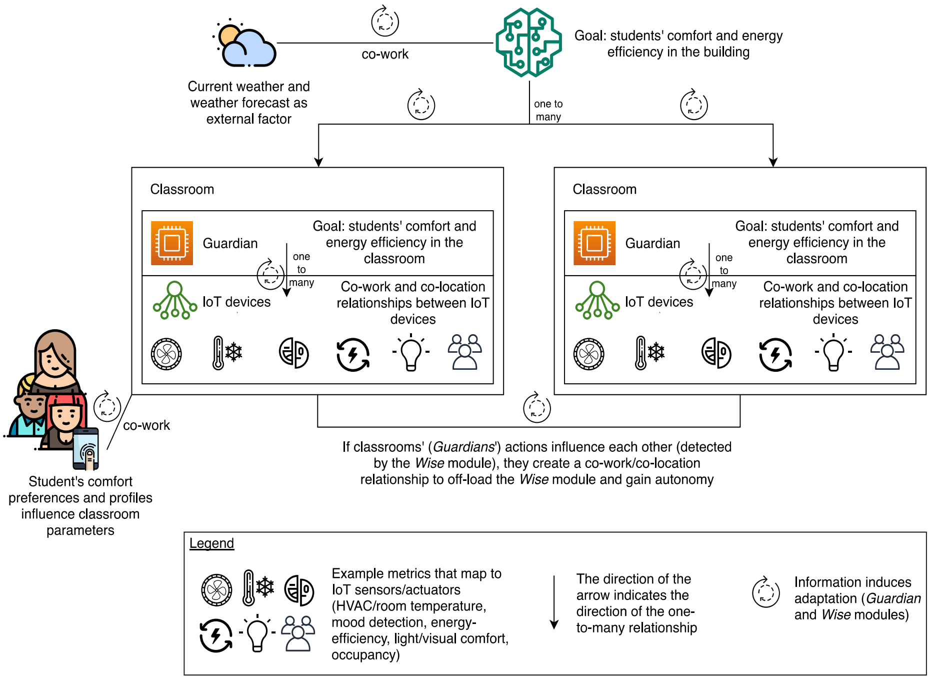


Figure 5. Complex adaptive system and Social Internet of Things (SIoT) relationships in the smart campus digital twin

2.1.5 IoT Platforms

In the literature, there are only a few papers that present descriptions of current SC proposals [8][40]. Nevertheless, authors in [41][42][43] have carried out extensive research on previous SC designs and have encountered several examples. There are SCs based on the development of an open data platform or based on cloud computing, service-oriented architecture, and IoT platforms.

As stated before, the main principle of communication inside an IoT system implies that each collector node must "speak" the same language. In IoT, this is a big issue since there is a deluge of devices, each with its own language that does not follow the standards [44]. However, this compatibility problem is solved through a middleware [37][45][46] (i.e., a software that provides interoperability between incompatible devices and applications). In the literature, IoT middleware solutions are sometimes referred to as IoT platforms or IoT middleware platforms because generally, the middleware is a platform. However, as it is proven in this project, other middleware tools exist, such as building information modeling (BIM) or computational simulation software, which can act as a middleware [47][48][49].

Various IoT platforms can be generally categorized into four categories known as (1) public traded IoT cloud platforms, (2) open source IoT cloud platforms, (3) developer friendly IoT cloud platforms, and (4) end to end connectivity IoT cloud platforms [50]. Table 3 describes various platforms in each of these categories that could be used in deployments of smart cities and IoT environments [21][50].

Table 3. Comparisons among some of the most used Internet of Things (IoT) platforms.

IoT Middleware	Type	Access Model	Data Format Supported	Programming Language Supported	Protocols	Pricing	Technologies Used
AWS IoT Platform	1	PaaS, IaaS	JSON	Java, C, NodeJS, Javascript, Python, SDK for Arduino, iOS, Android	HTTP, MQTT, Websockets	Pay when executing your own written functions	All Amazon services
Microsoft Azure IoT Hub	1	IaaS	JSON	.NET, UWP, Java, C, NodeJS, Ruby, Android, iOS	HTTP, AMQP, MQTT	Pay according to the number of devices and messages per day	Azure Cosmos DB, Azure Tables, SQL database
IBM Watson IoT Platform	1	PaaS, IaaS	JSON, CSV	C#, C, Python, Java, NodeJS	MQTT	Pay according to the number of devices and messages per day	Cloudant NoSQL DB

Google IoT Platform	4	PaaS, IaaS	JSON	Go, Java, NET, Node.js, php, Python, Ruby	MQTT, HTTP	Priced per MByte	Google's services
Kaa IoT Platform	4	IaaS	JSON	Java, C, C++	MQTT, CoAP, XMPP, TCP, HTTP	Free	NoSQL, MangoDB, Real time analytics and visualizatoin with Kaa
ThingSpeak	2	PaaS	JSON, XML	Matlab	MQTT API and REST	Free	Matlab, dashboard and Matlab analytics, MySQL
Carriots	3	PaaS	XML, JSON	Java	MQTT	Paid services	NoSQL Big-Database
Temboo	3	PaaS	Excel, CSV, XML, JSON	C, Java, Python, iOS, Android, javascript	HTTP, MQTT, CoAP	Free access for first 100 devices after that paid per device	Microsoft Power BI, Google BigQuery
Thinger.io	2	PaaS	JSON		HTTP, MQTT		MongoDB
Sentilo	3	PaaS	JSON	C, Java	HTTP	Free	Redis, Apache, PubSub, MongoDB, ElasticSearch

2.2 A Proposal for Smart Campus' Metrics to Obtain a Digital Twin Model

The term smart campus (SC) has been used to refer to digital online platforms that manage university content and the set of techniques aimed to increase university student smartness and knowledge transmission ease [51]. Several research questions have to be addressed in order to model the SC concept. In [52], a systematic literature review is performed to explain the problem by analyzing more than 300 tracked publications: (1) what are the SC features? (2) What kinds of technologies support the implementation? (3) Is there any standard model? (4) What are the main applications? (5) What are the SC contributions? The main conclusion of the research community is that the research in the smart campus area is still growing, and there is no standard used for the development of the smart campus concept and implementation. In essence, an SC is generally considered as the integration of cloud computing and the IoT, which pursues intelligent management, teaching, research, and other activities of universities [8][52][53]. As stated in [8][52], the main challenges of a sustainable SC are (1) the promotion of intelligent energy management by inner facility management, (2) the existence of a digital twin model that facilitates simulations and knowledge extraction for intelligent decision-making and (3) obtaining real-time data to render campus map information ergonomically, to generate event response and warning services, etc.

The parameters that influence the SC's environment are interconnected, so a specific component of comfort can make a space not comfortable in academic terms [54]. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Technical Committee Terminology [55], the indoor environmental quality (IEQ) is the perceived indoor experience of the building's indoor environment that includes aspects of design, analysis, and operation of energy-efficient, healthy, and comfortable buildings. Fields of specialization include architecture, heating, ventilation, and air conditioning (HVAC) design, thermal comfort, indoor air quality, lighting, acoustics, and control systems.

Thus, the term that comprises the evaluative numerical summary of IEQ performance data is known as the IEQ model [56]. To provide an outline picture of how well a workspace is performing, IEQ models require the aggregation of data by using objective physical measurements (e.g., air temperature, humidity, measurement of noise level, dioxide concentration, luminance, etc.), subjective occupant perceptions (e.g., how satisfied are you with the temperature in your workstation? Does the air quality in your workspace enhance or interfere with your ability to get your job done? etc.) collected with manual surveys or both objective and subjective data [5][17]. The measurement of subjective IEQ indexes is widely achieved by methods such as the Building Use Studies Ltd. (BUS) [57] and through the Center for the Built Environment (CBE) survey [58]. Nevertheless, surveys do not always capture IEQ issues that may have energy implications (e.g., over-lighting or economizer operation) and have incomplete diagnostic capability, and they also have a difficulty finding a general interpretation criterion of results [59].

This paper will focus on several objective measurement methods that have been developed and justified in the literature, since our goal is to quantify the comfort level experienced at the campus facilities by collecting environmental data in order to maintain the updated digital twin. The criterion followed to review the studies previously completed has been the same as the proposed by David Heinzerling et al. [56], without forgetting our introduced restrictions related to energy efficiency.

2.2.1 Comfort Modeling

As stated in [55], the indoor environmental quality models combine multiple IEQ parameters, comprised of acoustic comfort (AC), indoor air quality (IAQ), visual comfort (VC), thermal comfort (TC), and represent the relation between occupant satisfaction and objective measurements by way of a single number. Nevertheless, not all physical environments of indoor comfort are equally important to the occupants. In [56], authors have defined the weighting scheme regarding the four types of comfort that comprise the IEQ model. The existing literature on indoor environmental quality (IEQ) evaluation models is explored from previous literature studies [60][61][62][63][64]. Then, a new weighting and classification scheme is proposed.

The criteria followed in this paper to select an existing IEQ weighting and model schema are not only settled on the weighting schema closest to the one defined by experts in the field, but are also based on observations (surveying), creating a generic formula for each of the four comfort metrics. As a result of applying the above foundation, the proposed schema that our research has followed [63][64][65] is the one weighted in Figure 6 and quantified in Table 4.

Table 4. Proposed indoor environmental quality (IEQ) schema

Metric	Regression Constants	Calculation
AC	$K_0 = 4.74$	$\phi_0 = 1 - \left(\frac{1}{1+e^{(9.54-0.134\cdot dBA)}}\right)$
IAQ	$K_1 = 4.88$	$\phi_1 = 1 - \frac{1}{2}\left(\frac{1}{1+e^{(3.118-0.00215\cdot CO_2)}} - \frac{1}{1+e^{(3.23-0.00117\cdot CO_2)}}\right)$
VC	$K_2 = 3.70$	$\phi_2 = 1 - \left(\frac{1}{1+e^{(-1.017+0.00558\cdot lx)}}\right)$
TC	$K_3 = 6.09$	$\phi_3 = 1 - (\frac{\text{PPD}}{100})$
IEQ	$K_{IEQ} = -15.02$	$1 - (\frac{1}{1+e^{(K_{IEQ}+\sum_{i=0}^{3} k_i\phi_i)}})$

Figure 6. IEQ metric weighting chart

Table 5 shows our proposal for physical environmental parameters to be measured and the sensors that could be used, specifying the comfort metric.

Table 5. Possible metrics of environmental monitoring and their associated sensors

Metric	Parameter	Unit	Measurement Method	Tool or Resource
TC	Operant Temperature	°C	Temperature-humidity sensor	DHT22
TC	Relative Humidity	%	Temperature-humidity sensor	DHT22
TC	Occupant metabolic rate	Met	Pulsometer	MAX30102
TC	Mean Radiant temperature	°C	Globe thermometer	Blackglobe-L
TC	Air temperature	°C	Temperature-humidity sensor	DHT11
TC	Exterior air temperature	°C	Temperature-humidity sensor	DHT22
TC	Exterior air humidity	°C	Temperature-humidity sensor	DHT22

TC	Surface of element (wall, radiators, windows)	m^2	Thermographic camera module	Adafruit AMG8833 8×8 Thermal Camera Sensor for Arduino
TC	Person Clothing resistance	clo	Survey/infrared thermography camera	ThermaCAM s45/FLIR TG165-X
IAQ	Air velocity	m/s	CFD simulation	Ansys CFX 18.2/Visual-CFD/SolidWorks and AutodeskInventor CFD add-ons
IAQ	Specific flow of air introduced	m^3/h	CFD simulation	Ansys CFX 18.2/Visual-CFD/SolidWorks and Autodesk Inventor CFD add-ons
IAQ	Air change per hour	h-1	CFD simulation	Ansys CFX 18.2/Visual-CFD/SolidWorks and Autodesk Inventor CFD add-ons
-	Room volume	m^3	-	-
-	Number of occupants	-	Camera/PIR motion sensors	Sony IMX219 fish eye module for Raspberry/ElectroPeak HC-SR501 PIR sensor
IAQ	TVOC	mg/m^3	TVOC and eCO_2 gas sensor	Adafruit SGP30
IAQ	CO	ppm	Carbon monoxide sensor	MQ-7
IAQ	CO_2	ppm	Analog CO_2 gas sensor	DFRobot/MG-811
IAQ	Dust	$\mu g/m^3$	Grove—Dust sensor	PPD42NS
IAQ	multi-Gas (NH_3, NO_x, alcohol, Benzene, smoke)	ppm	Multi-gas sensor detector	MQ-135
IAQ	Odors	ouE/m^2	Electronic nose	zNose 4300 or 7100 model
AC	Reverberation time	s	Sound analyzer	Dual-channel Brüel & Kjaer BK 2260 real-time sound analyze
AC	Speech transmission index	-	Acoustic simulations	Odeon 9.0 software
AC	Level difference index	dB	Acoustic simulations	Odeon 9.0 software
AC	Impact sound pressure level	dB	Acoustic simulations	Odeon 9.0 software
AC	Clarity	dB	Sound sensor	Sparkfun sound sensor
AC	Sound insulation	dB	Dual-channel sound analyzer and an omnidirectional loudspeaker	Dual-channel Brüel & Kjaer BK 2260 real-time sound analyze
VC	Maintained luminance	lux	Lux meter	BH1750/PCE-170

VC	Discomfort glare	-	Image luminance measuring device/luminance meter	OP75/TES 137
VC	Daylight	cd/m^2	CAD simulations	Simulink software
VC	Dry bulb temperature	°C	Product specifications	-

2.2.1.1 Thermal Comfort (TC)

The human body tries to maintain a temperature of around 37 °C. The temperature is maintained through heat exchange between the human body and the environment through convection, radiation, and evaporation [66]. In a building, any sense of discomfort of the occupants motivates them to modify comfort parameters (e.g., those of the HVAC system or opening/closing windows) to obtain the desired comfort, usually obtaining non-optimal levels regarding energy efficiency [54]. A thermal comfort model based on the thermal balance of the human body was developed by Fanger [67] for living spaces in 1970 (see Figure 7). In this model, Fanger calculated the predicted mean vote (PMV) index (seven-point scale) by relating the net heat in the human body and the surrounding thermal equilibrium, using six different parameters consisting of four environmental factors (indoor air temperature, mean radiant temperature, air velocity, and humidity) and two personal factors (activity or metabolic rate and clothing resistance) [66][68].

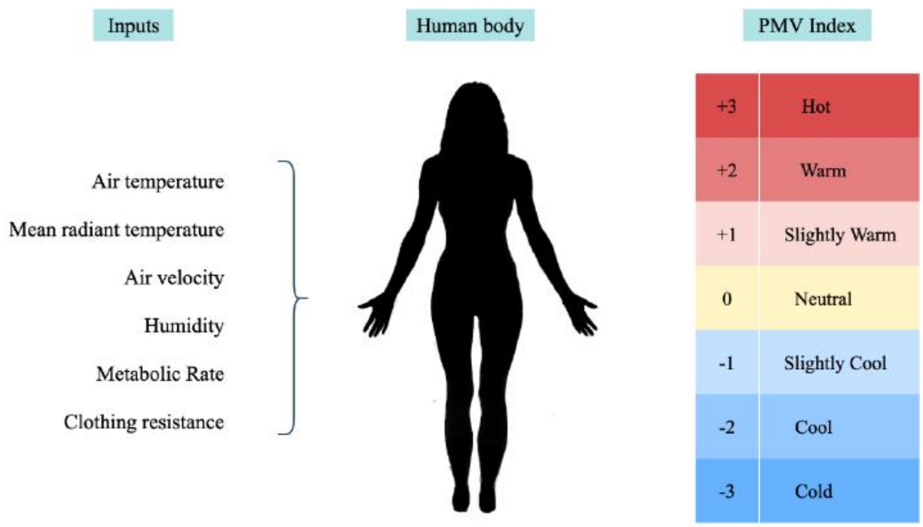


Figure 7. Predicted mean vote (PMV) index parameters and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal sensation scale

In terms of thermal preferences, various studies collected by Zheng Yang et al. [69] have shown that students easily accept slightly cool thermal conditions [70] but prefer slightly warm environments [71] (e.g., temperatures above 23.33 °C (74 °F) influence student performance in math and reading [72]).

2.2.1.2 Acoustic Comfort (AC)

In classrooms, knowledge is mainly transmitted through oral communication. The quality of this communication, and ultimately, of classroom education itself, is closely linked to the classroom's acoustic quality [73]. This acoustic quality can be characterized based on some parameters described in the International Organization for Standardization (ISO) 3382 standard [74], where methods include measuring the reverberation time [75], speech transmission index

[76], sound insulation [73], and the noise levels inside and outside the classroom [77][78][79]. According to these authors, high noise levels in the classroom impair oral communication, causing students to become tired sooner more often. This premature fatigue tends to provoke a negative effect on their cognitive skills. In fact, the recommended noise level in [77] is 40 dB(A) for classroom purposes.

2.2.1.3 Visual Comfort (VC)

The main focus on visual comfort has traditionally been light levels, contrast, and discomfort glare. Upon these, there is agreement on many principles [80], defined by the International Commission on Illumination (CIE) [81][82], the European Committee for Standardization (CEN) [83], and also lighting guides for specific building properties, such as the Lighting Guide LG5 for educational buildings [84] or the recommended practice for office lighting [85] by the Illuminating Engineering Society of North America (ANSI/IES).

The light levels are determined by the maintained luminance, which is provided by artificial lighting, and the luminous flux (either artificial or natural), which describes the quantity of light measured at 0.75 m above the ground with a lux meter (see Table 6, where the discomfort glare rating is used).

Table 6. Recommended visual comfort parameters for some of the educational spaces [84]

Space or Area	Maintained Luminance	Discomfort Glare	Observations
Classrooms for morning classes	300 lx	19	Lighting should be controllable
Classrooms for evening classes and adults education	500 lx	19	-
Lecture hall	500 lx	19	Lighting should be controllable
Black board	500 lx	19	Prevent specula reflections
Practical rooms and laboratories	500 lx	19	-
Computer practice rooms	500 lx	19	-
Student common rooms and assembly halls	200 lx	22	-
Preparation rooms and workshops	500 lx	22	-
Technical drawing rooms	750 lx	19	-

2.2.1.4 Indoor Air Quality (IAQ)

According to [55], indoor air quality is defined as the attributes of the respirable air inside a building (indoor climate), including gaseous composition, humidity, temperature, and contaminants (Table 7). Having poor indoor air quality (IAQ) is related to sick-building-syndrome (SBS), which can be tied to a lack of adequate outdoor air ventilation, improper exhaust, ventilation of odors, chemicals or fumes, or poor indoor air quality. Other sources of sick buildings may be linked to contaminants produced by outgassing of some types of building materials, volatile organic compounds (VOC), bacteria molds, etc. This syndrome does not conform to a particular illness and is difficult to trace to a specific source.

Table 7. Recommended indoor air quality comfort parameters [80,86]

Indoor Contamination	Allowable Air Concentration Levels
Carbon monoxide (CO)	<9 ppm
Carbon dioxide (CO_2)	<800 ppm
Airborne mold and mildew	<20 $\mu g/m^3$ above outside air
Total VOC	< 200 $\mu g/m^3$ above outside air

Air quality does not only affect the health status of the occupants, but it also affects the monitoring of odorous compounds in ambient air, which is an important task for environmental researchers because of the presence of some toxic volatile organic compounds (VOC) and carbonyl compounds in odorous compounds [87]. The VOC and carbonyl compounds present in malodors have adverse effects on the air quality in the surrounding areas of the sources as well as on the health of the people residing near the sources [88].

2.2.2 Energy Efficiency Monitoring

Energy efficiency is the objective of reducing the amount of energy required to provide products and services. There are many motivations to improve energy efficiency (e.g., financial cost savings and solutions to the problem of reducing greenhouse gas emissions). According to Leadership in Energy and Environmental Design standards (LEED standards [89]), the design of an energy-efficient building consists of implementing a whole-building system approach in the most efficient way to achieve an energy-efficient building. The whole-building approach treats the building as one energy system with separate but dependent parts. This means that, in order to fulfill our objective, we have to make our university campus an energy-efficient building capable of measuring and reducing its energy consumption by defining a whole-building's digital twin where IoT sensors and agents are in charge of the real-time data updating. The most relevant tactics for this objective are the following [89]:

- Design of an energy-efficient building: the implementation of a whole-building system approach to new construction is the most efficient way to achieve an energy-efficient building (see Figure 8).
- Weather usage: the design should take into consideration the building orientation. The way a structure is situated on a site and the placement of its windows, rooflines, and other architectural features is critical for efficiency. Weather data could be incorporated by outdoor sensor agents or by using a public Application Programming Interface (e.g., Meteostat's API offers historical and daily weather data from anywhere [90]).
- Ventilation: in a traditional building that uses natural ventilation or extract ventilation, 20 to 40 percent of energy consumed for heating is caused by ventilation.
- Lighting: the decision to install (1) IoT sensors such as timers and photocells that turn lights off when not in use and (2) dimmers, when used to lower light levels are good decisions to save money and energy. Light over ethernet or digital addressable lighting interfaces are smart solutions that make luminaries controllable. These methods are applied with light-emitting diode (LED) technology and allow a total control and monitoring of the whole building's luminaries [91][92].
- Heating: this concept is the largest energy expense in educational and commercial buildings. The incorporation of energy-efficient and real-time measures into a building's heating and cooling systems is essential to create an energy-efficient

accurate model of the current behavior inside the digital model. In terms of heating, a programmable or smart thermostat is one of the best options to work hand in hand with the wise module. When you install a programmable thermostat, it is easier to eliminate wasteful energy use from heating and cooling without upgrading the HVAC system or sacrificing any comfort [93].

- Monitoring: an energy modeling software is an effective way to bridge the physical and the virtual world. The digital twin could also integrate historical data from past usage to factor into its digital model. Thus, data must be transmitted seamlessly, allowing the virtual entity to exist simultaneously with the physical entity [94][95].

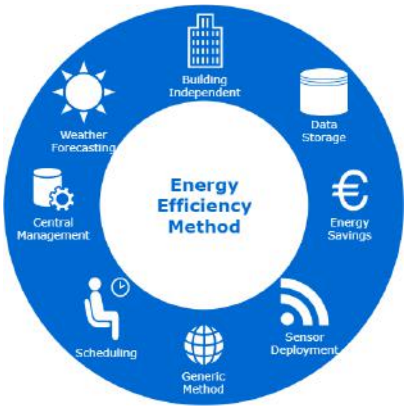


Figure 8. Subtopics for an energy efficient zone

In an SC, the integration of systems can be used to reduce operating costs through experimentation with a digital twin model. This would result from applying most of the engineering and architectural characteristics mentioned before. If we divide the whole campus into zones, the smart system can easily control each room's energy consumption [96]. We assume that the data sensed by IoT agents for the SC's comfort must be useful enough for a system that aims to find energy efficiency as well, which can use them to generate efficiency improvements. However, these benefits should not be imposed on the comfort of the occupants of the building. Our proposal aims for efficient energy usage by using the data measured by sensors deployed inside the building for the TC, AC, VC, and IAQ assessment (Section 2.2), and other accessible data such as room schedules and weather forecasting (Figure 9).

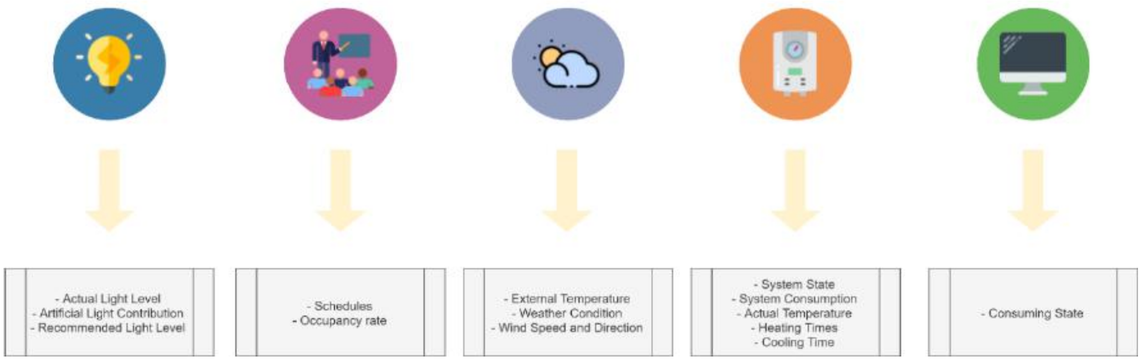


Figure 9. Sensed parameters for efficient energy and comfort assessment

In the SC that we propose, a zone defines a limited space within the building. The zone, which is usually a room or a section of the building, is described by a list of parameters such as capacity, occupancy schedules, daylight availability, current and historical occupancy, and comfort metrics (e.g., temperature and humidity). The guardian, a digital agent, is responsible for a unique zone (in a one-to-one relationship). It has the autonomy and responsibility to control the IoT devices and maximize the comfort and energy efficiency of the zone. Once the guardian gathers the data from the IoT sensors, it processes the data and stores them in the storage subsystem. Moreover, the guardians relay this information to a digital entity that aggregates them (and is on top of the hierarchy), the wise module. The wise module contains the support decision system that manages the entire building and guides each guardian, with the overarching goal of providing optimal comfort and energy efficiency (Figure 10). Thus, the wise module is the main actor for the inferred level of the smartness of the campus [97].

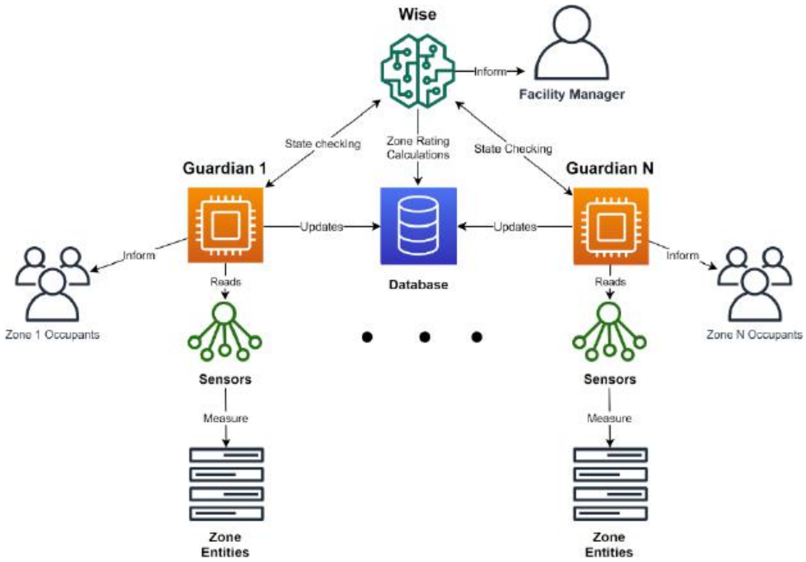


Figure 10. The decision support system for the facility manager by using the digital twin information

2.3 The Digital Twin Deployment

2.3.1 The Building Premises Modeling

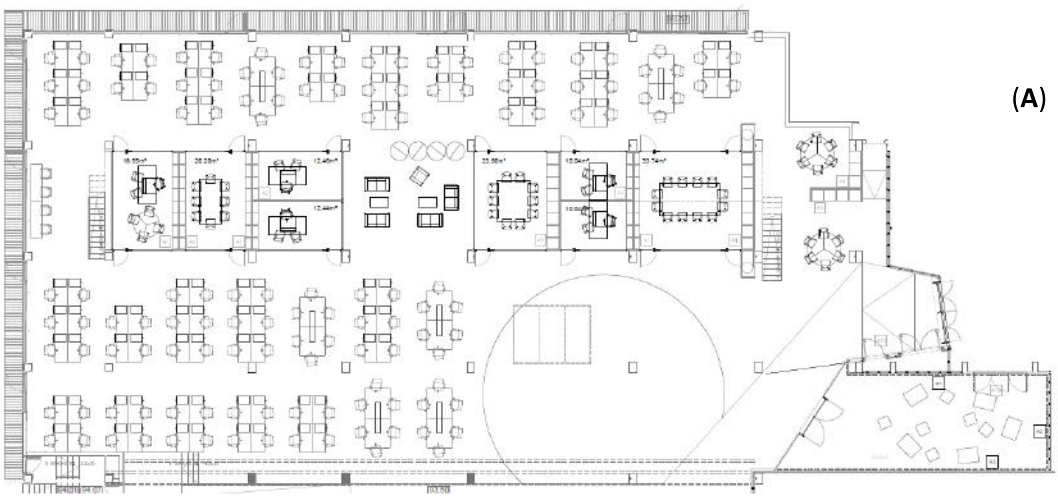
The Internet of Things Institute of Catalonia (facilities of LaSalle-URL (University Ramon Llull at Barcelona)) is the first interdisciplinary European R&D laboratory in which everything related to the interaction of people with the social and technological changes of their environment will be worked on, with a focus on the Internet of Things (digital interconnection of everyday objects with the internet). In fact, it is a space for the development of innovation initiatives and start-ups, in which business technological challenges coexist, in search of differentiating answers, with start-ups propelling new value propositions, with demonstrations of talent (researchers, professors, university students, experts, and consultants, among others) of a diverse nature and with connection to other technological parks.

The IoT institute has been co-financed since 2020 by the European Regional Development Fund (ERDF) under the framework of singular institutional projects in R&D infrastructures in the generation of excellent research, the attraction of talent, and the development of knowledge transfer activities. The laboratory is based on design, prototyping, and scaling the products and services of tomorrow for society and the business world, as well as taking students and professors toward the new realities and needs of future societies. The 2000 m² space (situated below the international students' residence) will be dedicated to research, innovation, and the promotion of talent and entrepreneurship (Figure 11 and Figure 12).

Figure 11. La Salle-University Ramon Llull (URL) (Barcelona)

Figure 12. IoT institute premises; digital twin model for automatic monitoring

The laboratory has four different areas (Figure 13):



(**A**)

Figure 13. IoT institute at La Salle-URL: (A)—architectural plan, (B)—maker Space, (C)—agora, (D)—city lab.

- A common social meeting point where people can debate, show, and even try out any idea that has been conceived during the innovation process. Ideas can later be tried out in the design and testing processes.
- Creativity room: spaces designated to fomenting creativity and information exchanges and where challenges are born into a creative and imaginative environment. These spaces can be used for structured activities, but also to facilitate an idea flow, which can be used to set off new innovation and research processes.
- Maker space: workspace designed to provide tools to develop projects for the group of researchers from the areas of architecture, management and engineering, together with designers, students, inventors, and entrepreneurs.
- City lab: space for the assembly and testing of technologies that have been developed. This is the showroom where the final products of projects are displayed, which promotes learning through overcoming challenges and is now being used all over our campus. This new laboratory will enable students to go further than case-studies, using new research and transfer techniques, with systemized processes to face tomorrow's challenges.

This paper is focused on the case-study location modeling regarding the co-creation rooms in the medium center of the laboratory. By grouping together, the aforementioned information, a global vision of the system can be obtained as follows: on the one hand, IoT agents that measure the environmental monitoring are used to calculate the IEQ index, whereas the information regarding the emotions of the occupants provided by the middleware intelligence is used for a double-check of the objectively perceived comfort. Furthermore, the middleware layer is responsible for archiving the data in a database and communicating with the visualization platform to make a predictive analysis about the monitored space's comfortability, by rendering the data into a virtual classroom model and taking into account the energy monitoring (see Figure 14).

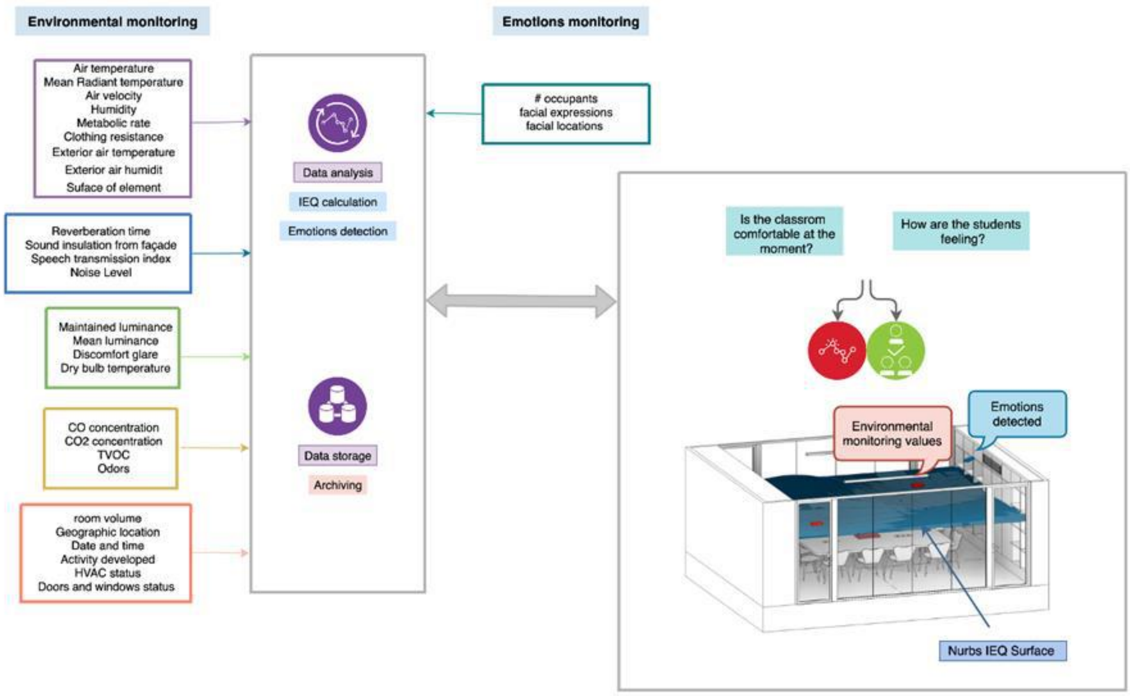


Figure 14. Conceptual system flow

We have to consider that comfort is directly related to the monitored space and the environment parameters, as analyzed in the previous sections. This relation between space and parameters is where the usual IoT platforms would limit the project, most IoT platforms only consider the readings produced by IoT devices, but they do not relate those readings with the location of production (revisit Table 1). Conversely, if building information modeling (BIM) is used [98], the collected data can be linked with the building environment parameters and characteristics (such as other indoor and outdoor characteristics) and with data from external sources, adding value to the collected data.

BIM is one of the emerging developments in architecture, engineering and construction (AEC) industries [98], and there are three main concepts regarding BIM that we cover in the project:

- BIM or building information modeling is a process, not an application, to create and manage information on a construction project across the project's lifecycle. It refers to a virtual model that contains a data-rich, object-oriented, intelligent and parametric digital representation of facilities [99], coinciding with the main benefits over conventional 3D computer-aided design (CAD) [100]. Thus, BIM enables those who interact with the building to predict performance appearance and cost, resulting in a greater whole life value for the asset.
- Revit is a modeling software to simulate, visualize, and collaborate in order to capitalize on the advantages of the interconnected data within a BIM model [98]. When one piece of datum changes in one view, it is updated in all other views automatically by Revit because each view is displaying the same data.
- Dynamo Revit is a graphical programming interface that enables the customization of the building information workflow [98]. Dynamo is an open-source visual programming platform for designers and has been installed as part of Revit since

2020, and hence it allows designers to set up automated computing processes or platforms in order to correlate processed data to structural and geometric models.

Lately, the challenge of bringing environmental monitoring of energy efficiency in buildings to BIM modeling has been discussed and designed by many researchers [47][48][49][100][101]. Consequently, the integration of IoT into BIM can be considered a fusion between physical things and virtual models—the information acquired from objects in the environment joined with information that resides in digital models of buildings. Once this fusion of information is achieved, many fields, such as facility management, assets management, environmental monitoring, energy efficiency, and the maintenance or visualization of components, among other applications, will experience potential benefits (see Figure 15).

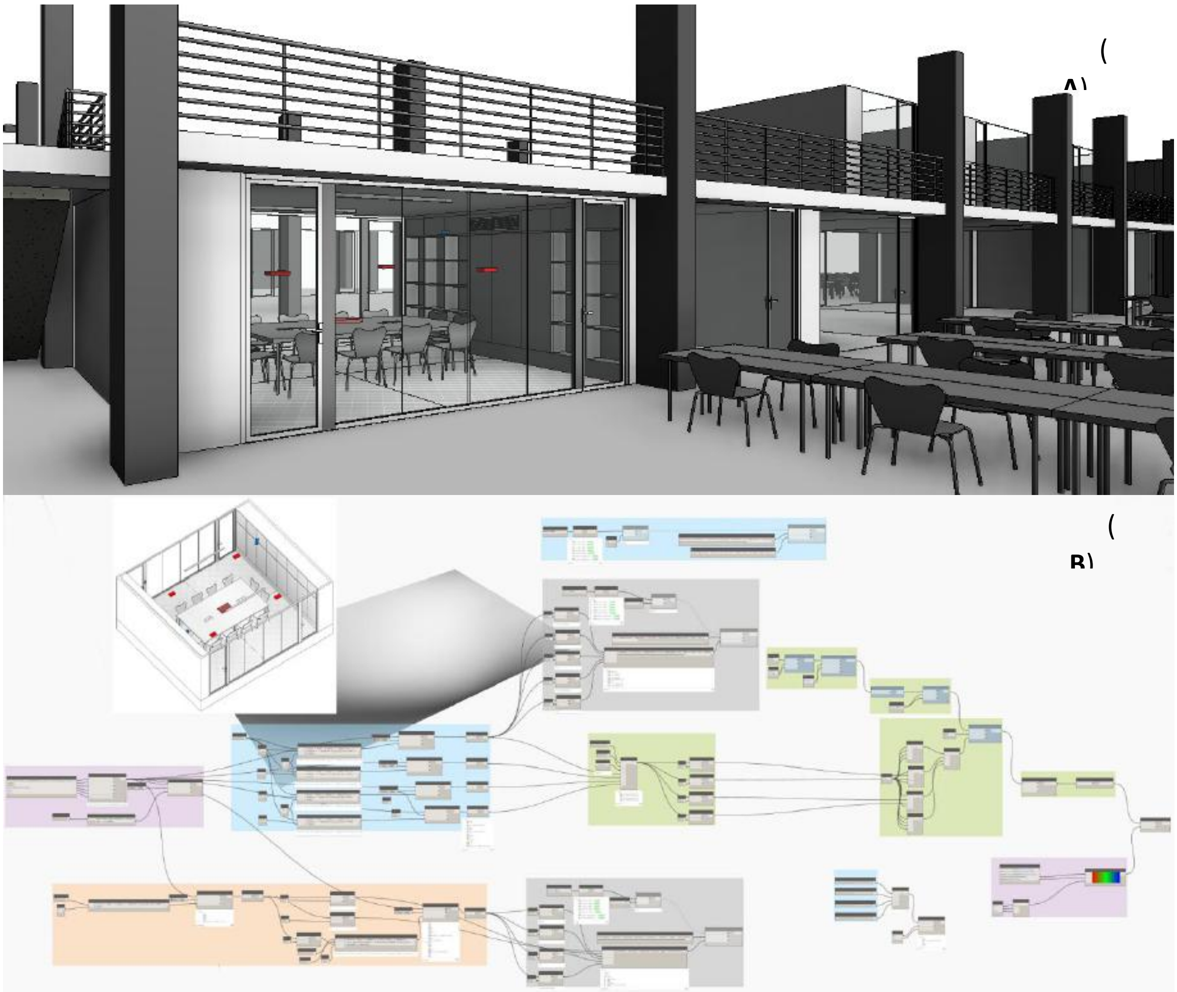


Figure 15. General overview of the digital twin developed in Dynamo Revit ((A)—spaces, (B)—sensed data and acquisition methods)

2.3.2 High-Level Design For The Sensing Level

The proposed monitoring system is divided into four main sections. They are necessary to model the behavior of the campus digital twin and make suitable recommendations to the management of the facility. This will allow us to infer the level of smartness [97] by taking into account the energy efficiency issues (see Figure 16):

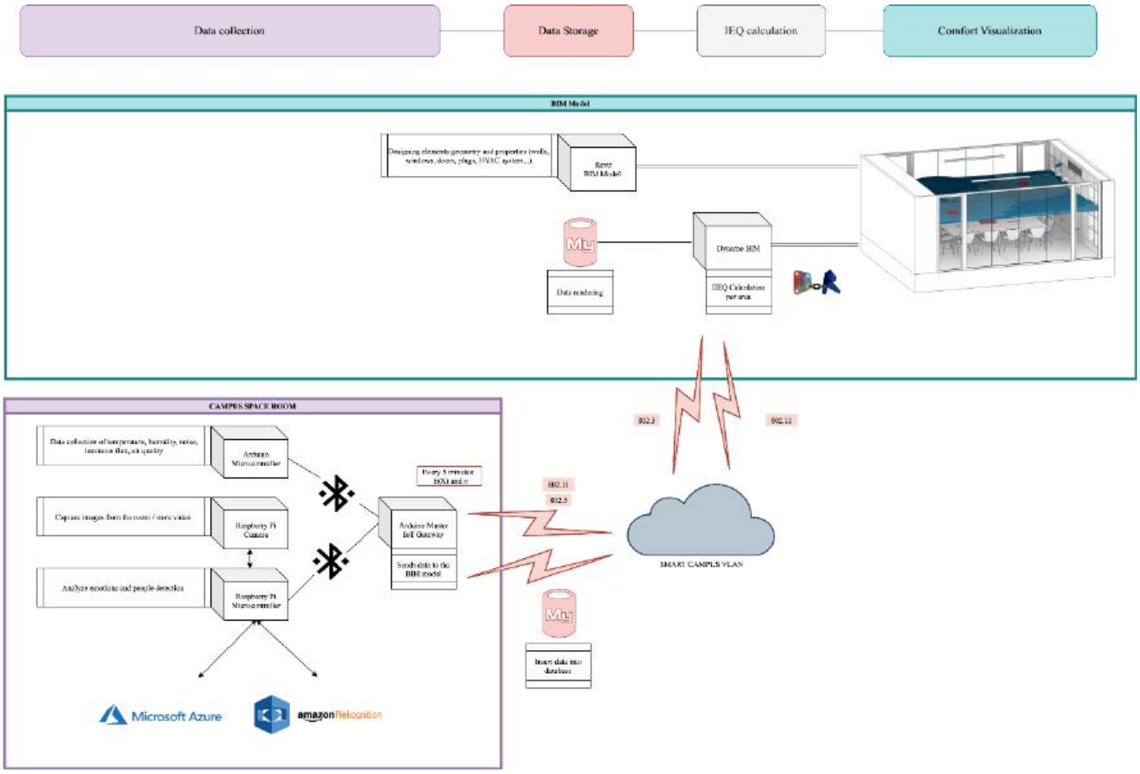


Figure 16. System high-level design

2.3.2.1 Data Collection

The environmental monitoring data are measured with sensors embedded in Arduino UNO microcontroller boards with a sampling frequency of 30 s for each node (revisit Table 5). The data collected in the nodes from every sensor are sent to an Arduino MEGA 2560 board, which corresponds to the master node (Figure 17). The latter is in charge of collecting the nodes data and calculate the mean (E(X)) and the standard deviation (σ(X)) of each metric. Once 10 metrics are collected (5 min), the master node then sends an HTTP POST (Hypertext Transfer Protocol) request to the database middleware by sending out the metrics E(X) and σ(X).

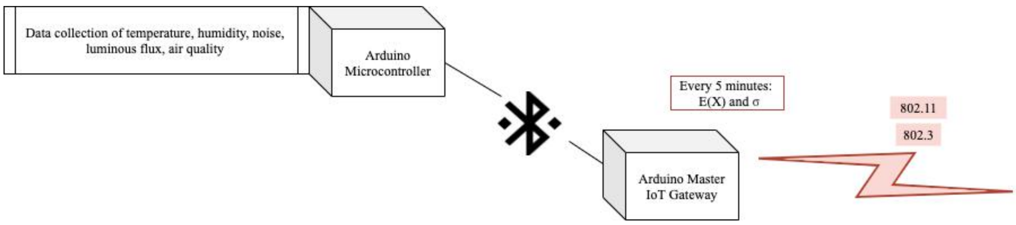


Figure 17. Environmental monitoring high-level design

The occupants' emotions are validated by an intelligent emotion detection algorithm in charge of implementing a double check to detect IEQ inconsistencies with the modeled reality. The emotion detection system consists of capturing the faces of the occupants with a camera lens assembled in a Raspberry Pi 3b+ and subsequently sending the obtained frame to the "Microsoft Cognitive Services Face API" service for a simple emotion recognition response or continuous video recording to "Amazon AWS Rekognition" for a full pattern analysis at the end of the session. The results, containing the detected emotion for each recognized occupant, are sent to the master node, which in turn will aggregate the data with the environmental data and dispatch them to the implemented middleware (Figure 18).

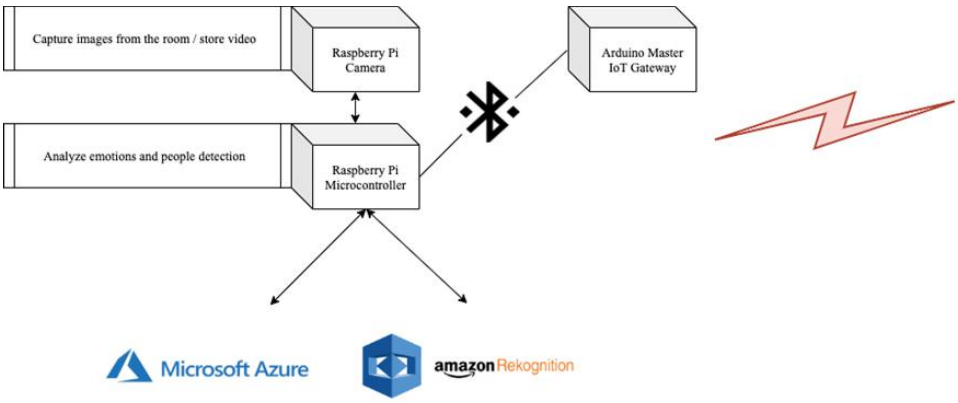


Figure 18. Occupants' emotions high-level design

2.3.2.2 Data Storage

The designed middleware encompasses customized Hypertext Preprocessor files (PHP) that permit inserting new data records into a MySQL relational database in order to store the structured environmental monitoring and emotion recognition data (Figure 19).

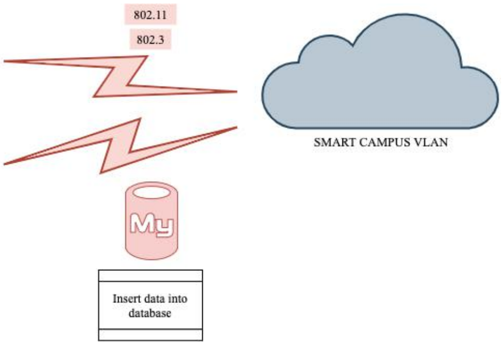
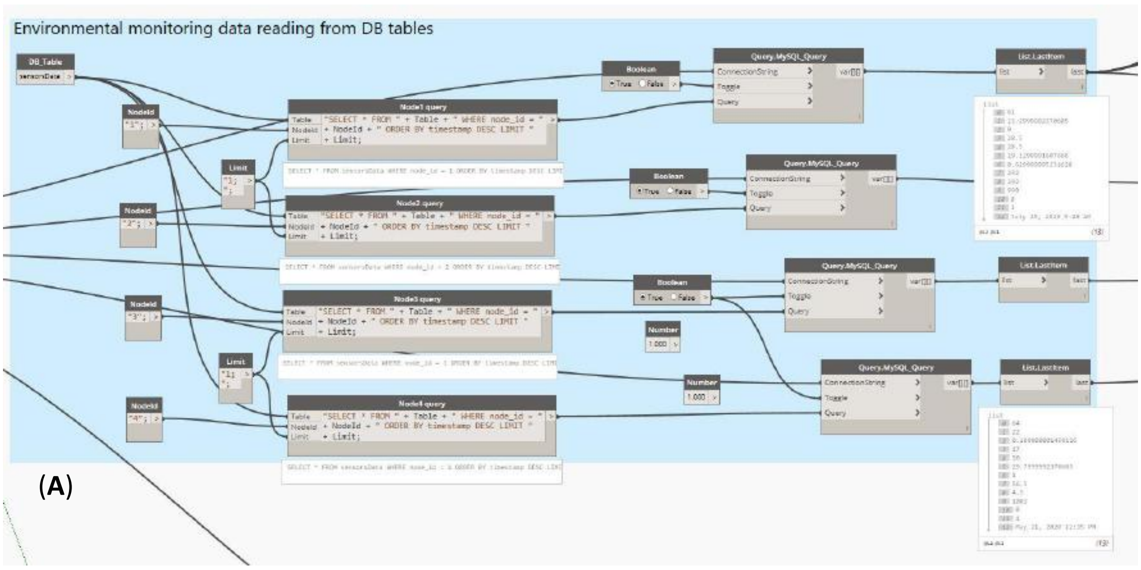


Figure 19. Data storage high-level design

If you look at Figure 15 and Figure 16 more closely, you will notice that the update of the real-time sensed data is performed from the IoT deployed physical infrastructure to the Revit model through the Dynamo interface. Thus, the digital twin of the smart campus is updated by accessing real-time stored data in the cloud (see Figure 20).



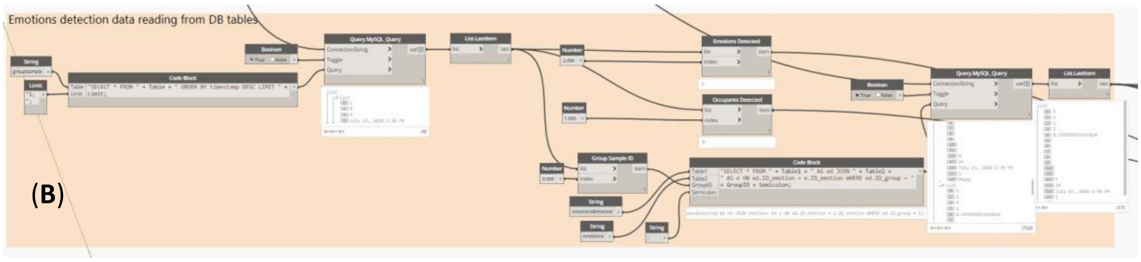


Figure 20. Dynamo flow representing (A) the current environmental data collection and rendering from each node stored in the database and (B) the current emotion data collection and rendering from each camera stored in the database

2.3.2.3 IEQ and Energy-Efficient Calculations

The guardians for each zone provide sensed information to the wise module, which aggregates the information for the final visualization application (i.e., the IoT middleware). Our middleware is based on the visual programming software Dynamo Revit, usually embedded in BIM systems. The wise module reads the database in real-time and calculates the IEQ index using a Python script (Figure 21). Furthermore, an interpolation is made by the guardian between all the resulting indexes of each node of the monitored zone and is subsequently rendered on a color scale.

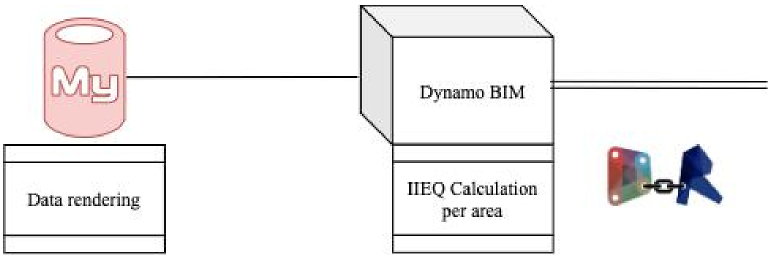


Figure 21. Data rendering and IEQ calculation high-level design

With the geometric room parameters defined in our BIM model, sensed information is collected from the database. It is then submitted into a Python-script object (Figure 22), which calculates the IEQ index based on the ASHRAE standard and figures out the proposed weighted model stated in this paper for the real-time IEQ value.

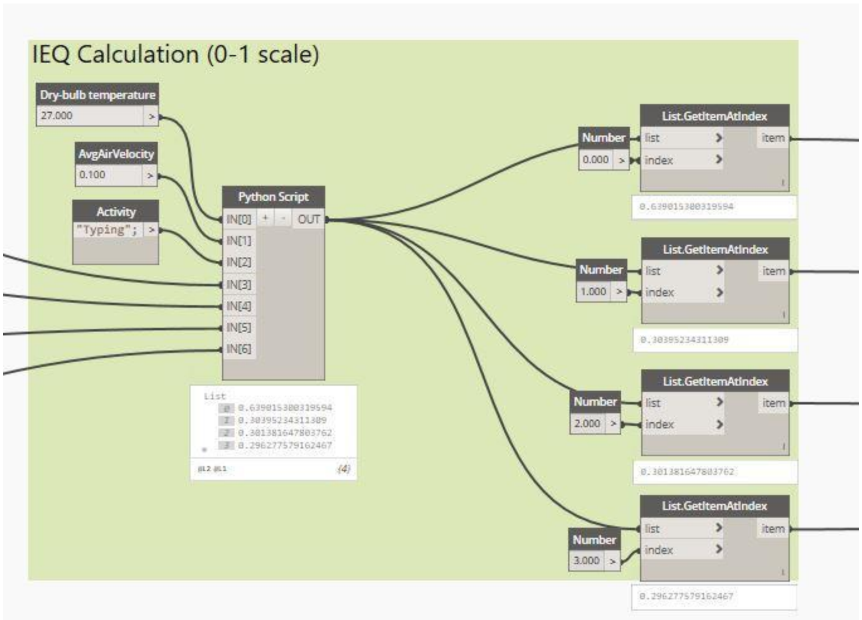


Figure 22. Dynamo flow representing the IEQ calculation

As stated before, a zone identifies a section of a building. This zone is defined by a list of parameters such as zone ID, maximum capacity, occupancy schedules, daylight availability, occupancy and temperature samples, artificial light contribution, and a digital twin zone rating. The zone rating is a quantitative parameter that tries to rate the energy efficiency of the zone in order to compare it with others and therefore establish recommendations for the facility manager. In order to formulate recommendations, the sets of data mentioned previously will be used to build a light efficiency rating (LER) and a temperature efficiency rating (TER).

For example, a LER is used for the recommended light level interval that defines the amount of light needed inside the zone. This value is constantly calculated by the zone guardian, and the state can be one out of the three following states: (1) over, (2) under, or (3) inside the recommended light level interval (Figure 23). For this reason, the guardian calculates the occupancy rate (occupants divided by maximum occupancy) and provides the actual number of occupants of the zone (Figure 24). Moreover, each sensed sample is classified considering the occupation case. For example, the machine learning algorithm should avoid comparing samples obtained on weekdays with samples obtained on weekends or holidays. If the zone is in use, the system will first measure if the current light level is inside the recommended interval in order to recommend occupants turn on/off the light, and the facility manager will be informed about the situation as well. For heating and cooling, a recommended interval has also been specified. In this case, the wise module also considers weather forecast, occupation, and temperature samples to recommend actuation of heating and cooling systems.

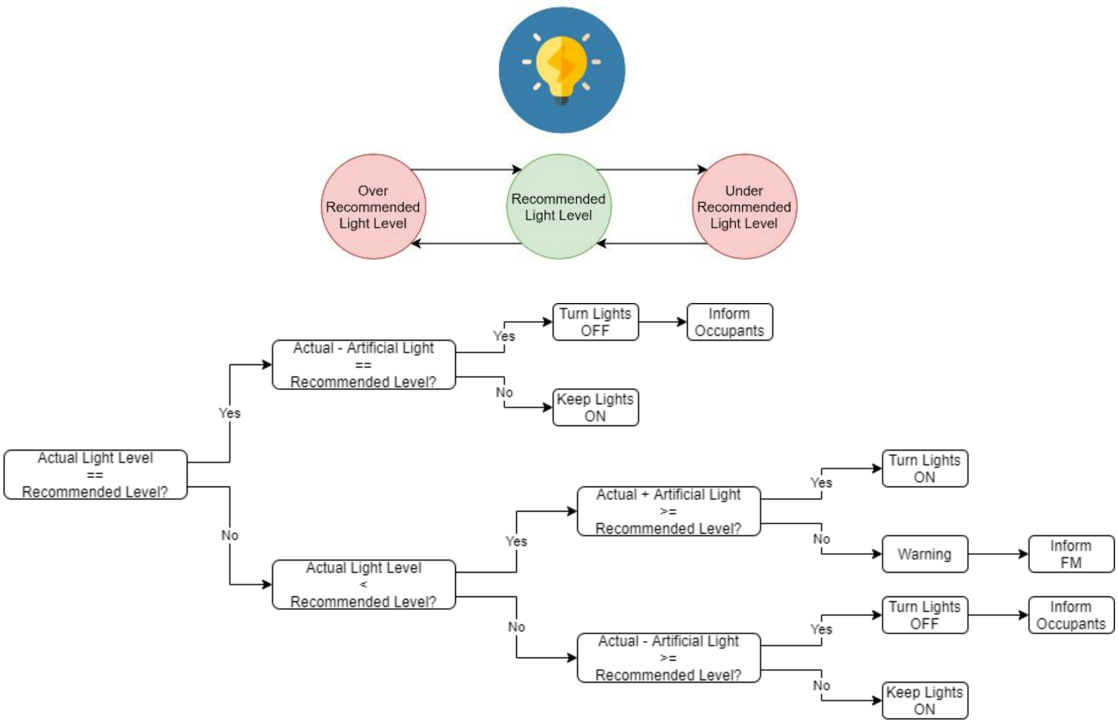


Figure 23. Finite state machine for light recommendations

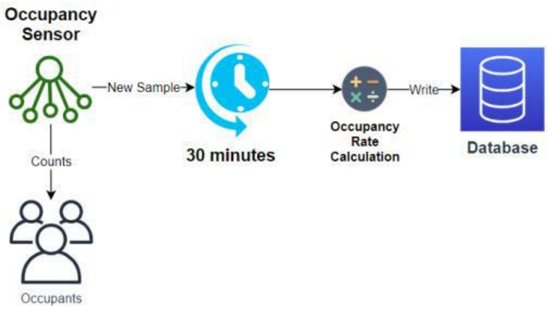


Figure 24. Occupancy monitoring

2.3.2.4 Comfort Visualization

Lastly, the resulting data (raw data, IEQ indexes, and recommendations) are represented in a virtualized model of the campus area in the Revit for BIM software. The model also represents the sensors and cameras and their location and allows the user to navigate the virtual model, enabling the mesh of points that represent the level of comfort calculated since Revit and Dynamo are directly integrated, and changes are updated in real-time (Figure 25).

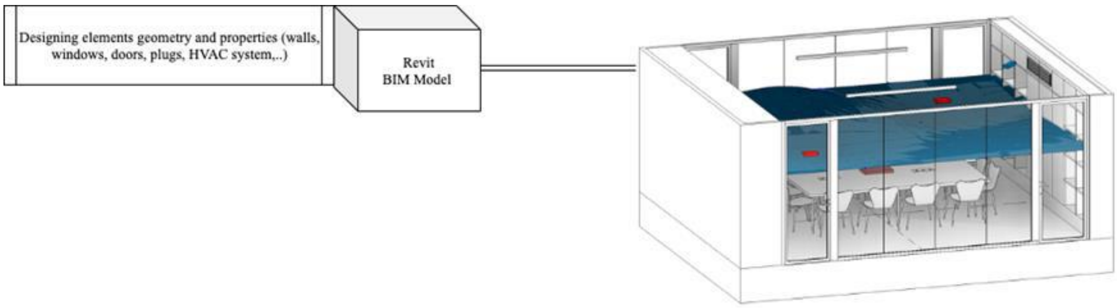


Figure 25. Comfort visualization high-level design

2.4 Discussion and Conclusions

The collaboration between the ICT engineering and architecture faculties in sustainability education and research will help students and future citizens to both understand and be a part of the solution to contemporary real-life sustainability challenges. This study explored the structures, processes, and activities related to the SC concept, which promotes sustainability from a multicultural and interdisciplinary perspective. Today, nineteen Lasallian universities are involved in a global initiative to promote sustainability through research projects focused on campus transitions via sustainability development projects. The joint efforts provide a broad range of experts and knowledge that will create innovative solutions to complex sustainability challenges, as well as creative opportunities with the hope of helping the planet through concrete and real actions, which should be the backbone on which all degrees base their teaching, research, and learning programs.

The key findings to date relate to (1) multi-disciplinary and multi-actor cooperation, where students (architects and ICT engineers), as well as researchers and teachers, are all sustainable development learners (encouraging engagement and active contribution to societal processes); (2) crossing the boundaries between education and the world of work through joint activities and common languages; (3) connecting generations, such as students, lifelong learners, and schoolchildren, by reaching out to work more closely with primary and secondary schools in developing competences in sustainability learning and (4) improving sustainability knowledge, not merely curriculum-based, but learning from practice, learning in the ecosystem (and also about the ecosystem), and making this learning accessible throughout the ecosystem.

This paper proposes an SC concept to investigate the integration of building information modeling (BIM) with IoT-based wireless sensor networks (WSN) in the fields of environmental monitoring and emotion detection systems in order to provide insights into the occupants' level of comfort. Preliminary results highlight the significance of monitoring workspaces given that it has been proven that productivity is directly influenced by environmental parameters, including thermal, visual, acoustic, and air quality comfort (our proposed primary quality goal), which could be reused to collect, store, and visualize physical parameters of educational premises for energy efficiency (our proposed secondary restrictive goal). In this way, the preliminary research presented in this paper will allow the establishment of a basis for the SC's comfort digital twin experimentation.

The designed experimentation is implemented within the software environment of Autodesk Revit 2020, which integrates the Dynamo BIM visual programming interface in order to act as an IoT middleware, by reading data stored in a remote database, processing the data, calculating the IEQ indexes and rendering the obtained comfort levels into a virtual classroom model. It has been observed that the integration between BIM and IoT provides many benefits, including: (1) real-time access to information and process automation; (2) comfort level monitoring is fully accomplished using BIM tools, the transformation of BIM data to a relational database is the basis for linking this information; (3) big data techniques are added in the construction industry for statistical analysis (machine learning, intelligent monitoring, augmented reality, virtual reality and performance in spaces) and (4) it has allowed multiple disciplines (architecture and ICT engineering) to collaborate together in the same model where data are processed and visualized in a unique model.

Nevertheless, although we have modeled, designed, and implemented the comfort-aware digital twin of the Internet of Things institute facilities to evaluate energy efficiency as well, the smartness concept of the campus has yet to be exhaustively tested. The intelligence of the deployed model, as stated before, is based on static rules and relies on recommendations for the occupants and the facility manager. Despite noticeable progress in our university campus, the concepts and principles of the smartness level are not fully clarified yet. This can be attributed to the obvious novelty of the concept and numerous types of smart systems, technologies, and devices available to students, learners, faculty, and academic institutions.

As stated in [8], these kinds of projects usually emphasize the fact that many aspects of contemporary education need new flexible organizational structures, which can be referred to as smart. In this paper, the sensing and the fundamental inferred issues of the smartness level are addressed for a comfort-aware and energy-efficient SC, where:

- Sensing level is defined as the ability to automatically identify and become aware of a phenomenon and its impact (positive or negative) by using sensors.
- The inferred level is defined as the ability to make logical conclusions based on sensed data (e.g., activate HVAC, turn off lights, and recommend administrators to take certain pro-active countermeasures).
- Further work is required to consolidate in our digital twin campus the adaptation, learning, anticipation, and self-organization smartness levels [97].
- In conclusion, we can summarize the objectives and contributions of our work in the following:
- This paper proposes a digital twin modeling procedure that merges well-known approaches used in SC to integrate a set of advanced intelligent features: the use of technology for a digital SC by using an IoT network and cloud computing to

transform university spaces into information sources for intelligent decision-making processes. SC will adopt the technological paradigm in order to support multiple tasks in multi-functional buildings (teaching, research, management, and services) and include different users (students, researchers, guests, etc.). Our proposal is to develop the SC through the efficient use of resources, thereby reducing operational costs and making life more comfortable.

- Our contributions tackle three intelligence domains that should be equipped with various capabilities [8][52]. (1) Green campus, in line with the issue of climate change, which includes the intelligent energy consumption and the implementation of sensor technology for accurate reporting. (2) Healthy campus, to monitor and promote the level of comfort by tracking and recording the status of the campus activity and (3) real-time facility management, which includes the facilities, infrastructures and people (staff, students and visitors).
- The proposed SC concept is not limited to supporting smart learning processes and can also support other aspects of campus life (the comfort of the academy community understood as a quality metric).
- In the developed model, all the smart campus devices, the energy consumption performance, and the comfort evaluation dashboard can be accessed by the stakeholders through the BIM platform. This middleware facilitates the interoperability and the co-working between engineering and architecture staff by promoting an interdisciplinary task force. We envisage that if sustainable policies have to be defined, an interdisciplinary team could easily cope with the identification of patterns and the suitability assessment of the proposed improvements.
- The main goal of our ongoing research project is to develop SC concepts, digital twin, and complex adaptive systems, and identify the main distinctive characteristics, modules, and technologies of a multi-disciplinary SC. The aim is to improve sustainability beyond that of a traditional campus with heterogeneous learning activities.

3. Adaptive and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks[5]

This paper analyses the different transport protocols used in transfers over high capacity and high delay networks, commonly known as Long Fat Networks (LFNs). After analysing relevant solutions that provide reliable communications, this article presents the design and performance of the Adaptative and Aggressive Transport Protocol (AATP) for the optimisation of data transfers in a LFN Cloud Content Sharing Use Case. Cloud server farms are geographically separated and there is a need to exchange and replicate large amounts of data. By providing calculations of the status of the network and an estimation of the bandwidth of the link, the performance rate of this protocol is high. Moreover, it also includes an adaptative sending rate in the case of packet loss and, as a result of AATP aggressiveness, only the residual bandwidth is left to other protocol flows. To demonstrate AATP performance, different tests have been carried out over a Network Simulator and a Testbed on Field.

Keywords: Transport protocol; high-bandwidth delay network; flow control; performance; cloud; quality of service.

3.1 Introduction

The usage of Internet has changed since its conception. In recent years, networks have increasingly had to deal with heavy data transfers, which may consist of multimedia files or applications from Cloud services or information gathered from millions of Internet of Things (IoT) nodes [1].

Current society needs data anywhere, anytime and that can be adapted to the context of the end-users. Increased user demands, as well as the rise of Cloud platforms and Big Data, have created the need for a network [2] that can move large amounts of information from one point to another, both efficiently and reliably. In addition, the need for effective data management has increased in response to the millions of IoT devices producing data [3].

For these reasons, Quality of Service (QoS) is a key factor in effective communications in terms of bandwidth performance and reliability [4][5].

The wide range of content has evidenced the need to have networks with higher bandwidth for end-to-end connections, especially when great distances separate the networks.

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[5] The work reported in this chapter was published as the paper entitled "Adaptive and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks" in the Future Generation Computer Systems journal, 115, 34-44, 2020 https://doi.org/10.1016/j.future.2020.08.043 Authors: Alan Briones, Adrià Mallorquí, Agustín Zaballos, Ramon Martin de Pozuelo

Authors contributions: Alan Briones: Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Project Administration. Adrià Mallorquí: Software, Resources Data Curation, Visualization. Agustín Zaballos: Conceptualization, Methodology, Validation, Supervision. Ramon Martin de Pozuelo: Conceptualization, Formal analysis, Investigation.

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Within the classification of high capacity links, there is a type of network known as the Long Fat Network (LFN)[6]. The main characteristic that defines this type of networks is its high Bandwidth (BW) and high values of Round Trip Time (RTT). A network is considered LFN if its Bandwidth-Delay Product (BDP) is greater than 12,500 bytes (10^5). For example, a link of 1 Gbps and 1 ms of RTT, obtains a BDP of 10^6, being classified as LFN.

These characteristics of the LFNs lead to lower performance rates when using the Transmission Control Protocol (TCP), which is the most commonly used transport protocol in the network, and have led to the need to define an extension of the protocol [7].

Moreover, the friendliness of the protocol creates an equitable distribution between several flows which share a link, regardless of its priority (unless Quality of Service is applied, which is not controllable outside the local network).

For these reasons, Cloud companies are trying to find a protocol which allows them to achieve a high throughput between their networks in order to optimise data exchange and replication.

The purpose of this paper is to present the design and show the performance of the AATP (Adaptive and Aggressive Transport Protocol) for a Cloud Data Sharing Use Case. In order to demonstrate its effectiveness and behaviour, different tests have been carried out over a Network Simulator and a Testbed on Field.

The rest of this paper is structured as follows. In Section 2, the use case is presented. In Section 3, the related work is summarised. Section 4 introduces the protocol specification. Section 5 presents the QoS objectives to be achieved and the tests deployed, and shows the reliability and efficiency of the design when tested in a Network Simulator and on a Testbed. Section 6 analyses the results obtained from the proof-of-concept implementation. Finally, conclusions and future works are presented in Section 7.

3.2 Cloud Data Sharing Use Case

A specific Cloud company has set high-level data exchange requirements between their servers' farms deployed in Storage Area Networks (SANs) from remote branches in different regions. The main requirement of the company is a protocol that achieves the maximum link capacity, adapting its behaviour to the status of the network. Moreover, in order to leave the residual bandwidth for other non-critical flows, this protocol has to act aggressively on other protocols, given that it is not possible to apply Quality of Service in intermediate nodes.

In order to shape the protocol behaviour, a non-oriented connection protocol is needed to overcome the main TCP constraints. However, it is necessary to implement a flow control that can adapt its behaviour to the network status. Finally, some security features are requested, although they are not in the scope of this paper.

The typical company network values for wired connections are presented in Table 8. Wireless connections are out of the scope of this first specification.

Table 8. Cloud Data Sharing Network Use Case - Network requirements

Link	Bandwidth (Mbps)	Delay/RTT (ms)	Packet Loss Rate (%)
WAN	[20..2000]	[1..100]	[0..3]

The use case network physical topology is shown in Figure 26. This topology exhibits a data transfer of hundreds of GB from a server in Region 1 to another server in Region 2. An additional requirement of the company is the efficient transfer and replication of data. This traffic has to be prioritised in order to send the data as quickly as possible since there is no control beyond the gateway.

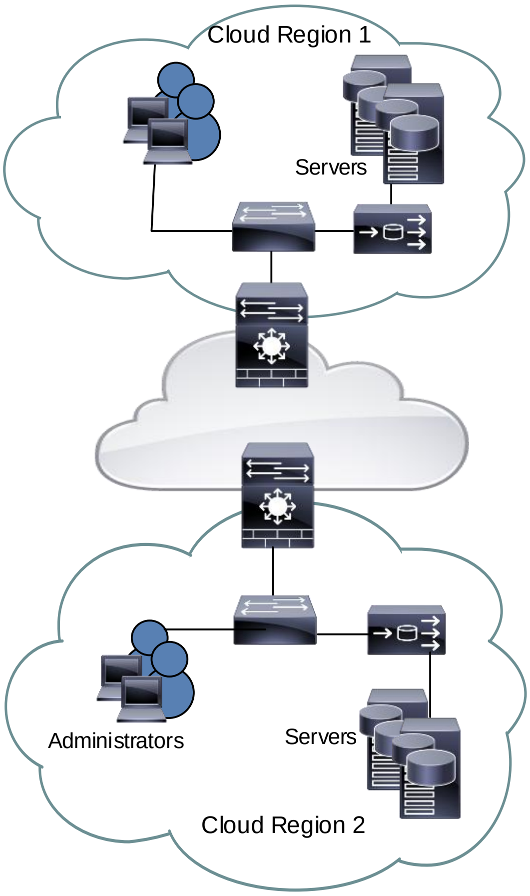

Figure 26. Cloud Data Sharing Network Use Case

In the following section, different protocols are analysed in order to extract the mechanisms to be adopted and integrated into the design of the AATP protocol.

3.3 State of the Art

This state of the art will focus on the aforementioned characteristics related to the specific purpose of the proposed protocol in order to achieve more efficient and reliable transfers of large amounts of data from Cloud networks.

3.3.1 Congestion Control

Congestion control aims to detect the network status before it collapses [8].

There are two main strategies to detect and mitigate network congestion [9]:

- Preventive, which is generally used in circuit-switched networks. Resources are reserved during connection set-up to prevent congestion during data transfer, limiting the number of users and monitoring the flow so that it does not exceed a predetermined limit.

- Reactive, typically used in connectionless packet-switched networks, in which no resource reservation is made prior to data transfer and techniques are used to resolve the congestion once it is detected.

They could be classified into two classes:

  - Direct feedback: intermediate network nodes detect congestion risk and notify the sender and receiver of the end-points of the communication by tagging the packets or sending specific notifications.
  - Indirect feedback: end nodes detect the congestion, based on packet losses and delays (jitter) and notify the other end-nodes.

Although protocols that use direct feedback congestion could provide an improvement in high bandwidth-delay environments, the proposed cross-layer solution in real scenarios implies revolutionary changes to routers and end devices which would make them difficult to deploy on a large scale.

On the contrary, protocols that use indirect feedback congestion control are the most broadly used, with TCP being the most common, and the basis of many congestion controls.

3.3.2 TCP

TCP is currently the most widely used transport protocol [9]. Its main characteristics are reliability and information integrity. The receiver informs the sender of the receipt of the packet using acknowledgement packets (ACK). TCP adjusts transmission throughput employing an Additive Increasing Multiplicative Decreasing (AIMD). The main two mechanisms that control the throughput of the transmission are Slow Start (SS) and Congestion Avoidance (CA). This AIMD congestion control causes a sawtooth effect in the transmitted flow that renders it inefficient over error-prone links. However, some solutions have been presented to smooth this effect by splitting the transmission into multiple parallel connections.

Other legacy TCP variants [10], such as TCP Tahoe [6], have been released to improve TCP performance by implementing SS, CA and Fast Retransmit. In addition, TCP Reno [7] included Fast Recovery. Finally, New Reno [8] has tried to solve the main problems by estimating the optimal sending rate at the start of the transmission using the Packet Pair algorithm [9][10].

TCP SACK [11] implements all the mechanisms explained in previous variants, and it incorporates additional ones to adapt the congestion control to larger networks which are often error-prone and incur an elevated use of traffic. When a receiver detects that a packet is lost, it sends a duplicate ACK (DUACK) indicating that it has received the rest of the packets correctly. It allows the sender to know which segments should be retransmitted.

TCP Vegas [12] emphasises packet delay rather than packet loss, as a signal to determine the sending rate. Instead of looking for a change in the throughput slope, it compares the measured throughput rate with an expected throughput. The idea is to measure and control the amount of extra data this connection has in transit, that is to say, the data that would not have been sent if the bandwidth used by the connection exactly matched the available bandwidth of the network.

As a result, TCP Vegas is able to achieve between 40% and 70% better throughput than Reno, allowing transmission at an almost constant data rate. However, the aggressiveness of the protocol can cause inefficient use of the bandwidth.

3.3.3 Fast long-distance TCP variants

Other types of TCP are proposed, especially in two specific fields where the performance of standard TCP and explained variants is still poor, namely wireless and fast long-distance networks.

Given that the study of wireless networks is out of the scope of this paper, a brief summary of the most outstanding protocols focused on long-distance is presented.

FAST TCP

FAST-TCP [13] is a modification of TCP Vegas, conceived for networks with high latency. It works with the concept of not penalising the CWND and detects the delay of the communication.

Binary Increase Control TCP (BIC-TCP)

BIC-TCP [14] is a version of TCP that combines an additive growth of CWND when the congestion window is medium or high and a binary growth when the window is small. The protocol starts the transmission with an Additive Increase, increasing the window more slowly than with Slow Start. Next, the Binary Search mechanism is used, which updates the value of CWND to the midpoint between W_{max} (value of CWND where the last losses have occurred) and W_{min} (last value of CWND where no packets have been lost). Finally, the Max Probing mechanism is applied, which causes an exponential growth of the window. In addition, when losses are detected, the congestion window is reduced by a factor β. The main drawback of this protocol is that it takes a long time to reach a high throughput level, although when it does so, the bandwidth of the link is maximised and is highly stable.

CUBIC

CUBIC [14] is an improvement of BIC-TCP that stands out for its high stability in high-speed transfers.

This protocol replaces the BIC-TCP Binary Search for a cubic growth function, so when the value of CWND is much lower than W_{max}, the increase is higher. On the other hand, when the value of CWND is close to W_{max}, small increments are made, which attempt to overcome the value of W_{max}.

Regarding the reduction of the congestion window after losses, the Multiplicative Decrease of BIC-TCP with a factor $\beta = 0.2$ is maintained. Additionally, it incorporates a mechanism of Fast Recovery that BIC-TCP does not. The main drawback of CUBIC is the same as that of its predecessor - the time of convergence that is needed to reach a stable and high sending rate.

Bottleneck Bandwidth and Round-trip propagation time protocol (BBR)

BBR [15][16] is the evolution of CUBIC. This protocol bases its congestion control on the management of the maximum bandwidth and the minimum round-trip times. Taking into account these metrics and their values, BBR tries to maintain performance at its optimal level. Figure 27 shows the behaviour of the RTT and the delivery rate of a transmission. The idea works on the point where the RTT is the minimum, which means that buffers are not saturated, and there is no queueing, at the same time that the delivery rate is sending at the maximum capacity of the link.

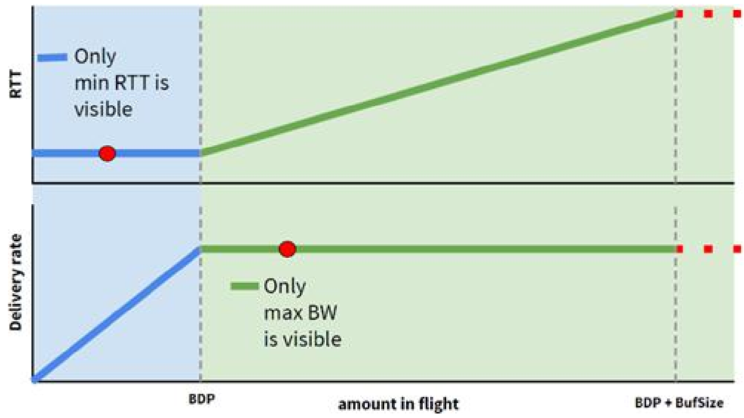

Figure 27. BBR graph function (RTT & Delivery rate)[15][16]

3.3.4 UDP-Based protocols

Besides the TCP variants mentioned, a set of UDP-based protocols attempt to provide efficient congestion control and reliability functions.

UDP-Based Data Transfer Protocol (UDT)

The UDT presents a better throughput [17][18] and some improvements beyond the state of the art of the standard UDP in terms of throughput utilisation, implementation flexibility and security. In addition, it presents some guidelines for its implementation, which take into consideration the operating system limitations that can hinder the development and operation of the standard UDT.

High-Performance and Flexible Protocol (HpFP)

Another protocol to highlight is HpFP [19]. HpFP sends asynchronous ACK messages for received packets every 200ms, solving the problem of delay in LFNs. Data burst packets are sent independently from the ACK reception.

This protocol works by adapting its throughput to the available bandwidth and is friendly to the other flows. The authors do not detail the congestion control mechanism.

3.3.5 Other Transport protocols – Stream Control Transmission Protocol (SCTP)

Finally, specific protocols have emerged in the last decade in an aim to make up for the inefficiencies of TCP and UDP.

The most commonly known is SCTP [20], which provides a series of additional mechanisms and functionalities that TCP does not offer. It significantly increases the obtained throughput and achieves a more optimal behaviour by adding new functionalities (security, multistream and multipath capacities, among others). For example, the protocol uses a 4-way handshake instead of the 3-way handshake of TCP, thus offering protection against denial of service attacks (DoS).

Many SCTP variants have appeared during the last years. Some of the most relevant are New-Reno SCTP [21], HSP-SCTP, CMT-SCTP [22], MPSCTP [23] and cmpSCTP [24].

3.4 AATP protocol design

This section presents the Adaptive and Aggressive Transport Protocol (AATP) design, which considers the Cloud Data Sharing Network Use Case requirements (Table 8). Concretely, this section is focused on explaining the workflow of the protocol by detailing the phases of the AATP and the selected mechanisms for each phase.

First, according to the requirements, this protocol is UDP-based but connection-oriented (in-band control). The idea is to avoid the synchronous locking of TCP and other associated problems analysed in the previous section.

In general, the AATP is inspired by UDT flow control and SCTP phases and messages.

The use case highlights the need for an aggressive protocol to reach the maximum capacity of the link. Furthermore, the AATP is conceived as an unfriendly protocol. It is created to leave residual bandwidth to the other protocols of the network due to the priority of the data to be sent so that the transmission of data is accomplished as quickly as possible.

AATP includes two differentiated phases after session establishment:

- Network Status Estimation
- Data Transfer

Regarding the aforementioned phases, this protocol is designed to add some additional security features, such as a 4-way handshake session establishment, encryption and authentication methods; and keepalive mechanisms, which are out of the scope of this paper.

3.4.1 Network Status Estimation

The Network Status Estimation process enables us to determine the potential bandwidth of the connection, which specifies the maximum bandwidth that will be available in that specific association. It is calculated at the beginning of the transmission and provides a rapid set-up of the sending rate, thus creating an immediate benefit in the throughput usage and optimising its convergence. In this phase, unlike other estimation mechanisms that focus on finding the residual (free) bandwidth of the link, it aims to estimate the total bandwidth of the communication (link capacity).

As shown in Figure 28, this process consists of sending bursts in order to generate different representative samples at the time of calculating the total bandwidth. The blocks are arranged in groups of 2 to 20 packets, where the number of packets per burst is chosen according to the estimated speed of the link in the previous iteration. Therefore, the more packets are used, the lower the probability of error in the estimated bandwidth (avoiding potential deviation caused by packet losses or a high jitter during the estimation process).

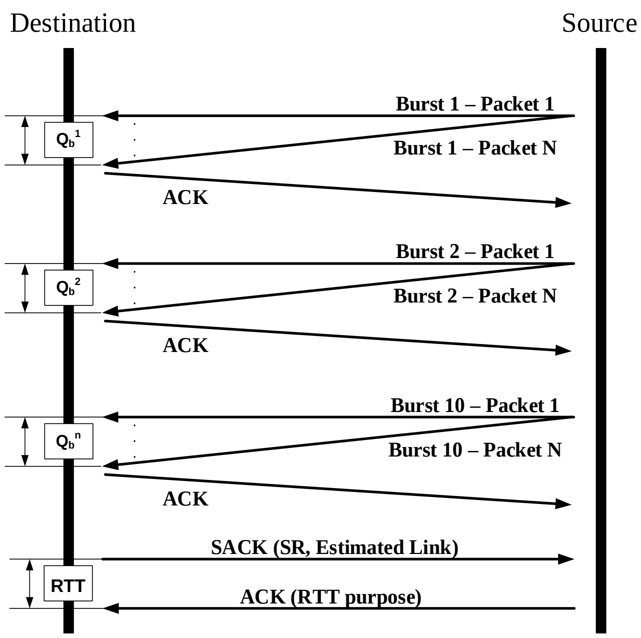

Figure 28. AATP - Network Status Estimation process

The packets to be sent are data messages (DATA) that, depending on the communication situation, can be empty (initial BW estimation) or contain information on the transfer (periodical in-band estimation).

For the initial BW estimation, once the Source-Destination connection is completed, 10 bursts are sent. The Source sends the packets of each block (burst) consecutively. After that, the Destination sends a confirmation message (ACK) on receipt of the last packet of the block, which is flagged by the Source at the header.

For each burst, the reception times of the first and last packets are recorded, and the difference (Qb_i) is calculated. Once information on the size of the packets (b) in bits and the number of packets has been received (N), the bandwidth of the link (BW_i) for that burst can be calculated (Eq. 1a). Once the Destination has received the ten bursts, ten values of the estimated bandwidth are obtained, using the arithmetic mean (Eq.1b) of these values as the definitive one($BW_{estimated}$).

$$BW_i = \frac{b\cdot(N-1)}{Qb_i} \qquad (Eq. 1a)$$

$$BW_{estimated} = \frac{\sum_{i=1}^{10} BW_i}{10} \qquad (Eq. 1b)$$

Finally, the Destination sends a message (SACK) indicating the Estimated Bandwidth ($BW_{estimated}$) in Mbps and the Sending Rate in packets per second, while the Source responds with a confirmation message (ACK). The Round-Trip Time (RTT) will be the difference between the sent SACK and the reception of the ACK at de Destination.

For the bandwidth calculation during the session, some data packets from information bursts can be used to calculate Eq. 1c & 1d.

$$BW_{LastBurst} = \frac{b\cdot(N-1)}{Qb_{LastBurst}} \qquad (Eq. 1c)$$

$$BW = 0{,}7\cdot BW_{LastBurst} + 0{,}3\cdot BW_{Historical} \qquad (Eq. 1d)$$

In Eq.1d a formula is proposed to stabilise the BW, where $BW_{Historical}$ is the mean of the last 100 samples of BW_i calculated.

3.4.2 Data Transfer

This section describes the operation of exchanging messages between the Source (sender) and the Destination (receiver) once it starts the Data Transfer process.

At the beginning of the data transfer, the initial transmission speed (Sending Rate - SR) should be set, fixing it at a percentage of the maximum bandwidth ($BW_{estimated}$). Depending on the desired aggressiveness, a higher or lower value can be established.

The data is sent by bursts, separated by a period (T_{burst}) determined by the RTT or the minimum temporal resolution that can be offered by the operating system (OS) and the hardware (HW) on which the process operates. This time will be calculated by Eq.2 in milliseconds or microseconds.

$$\mathrm{T_{burst}} = \max(OS/HW\ \text{res.}, \mathrm{RTT}) \qquad (Eq. 2)$$

Once we know the speed at which the packets are sent initially (in packets per second) and have determined the separation between bursts, the number of packets sent in each burst ($Packets_{\mathrm{burst}}$) is defined by Eq.3.

$$\mathrm{Packets_{burst}} = \mathrm{SR}\cdot \mathrm{T_{burst}} \qquad (Eq. 3)$$

Figure 29 shows the process of sending the data. The receiver saves the information that it receives and simultaneously lists the lost packets (sorted by gaps), which are requested in the confirmation message (SACK) of the received data. The SACK messages are sent asynchronously in relation to the bursts. Moreover, the SR and $BW_{estimated}$ are indicated in the message.

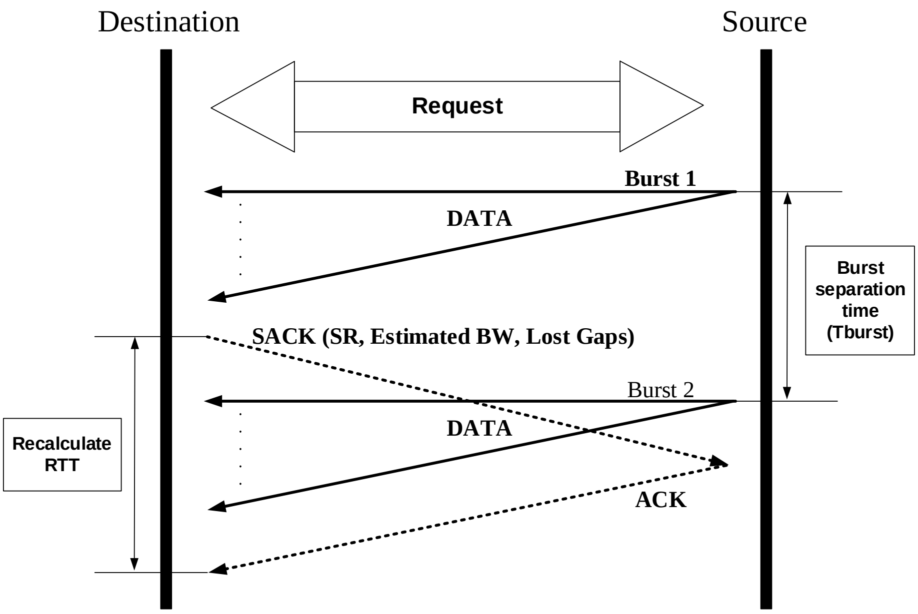

Figure 29. AATP - Data Transfer process

The receiver decreases or increases the SR value depending on whether or not any packets have been lost in the last burst (Eq.4). P_{size} is the size of the packet in bytes:

$$SR = \begin{cases} \dfrac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}, & LostPackets = FALSE \\ \\ \dfrac{SR}{1 + 0.125 \cdot \dfrac{SR \cdot P_{size} \cdot 8}{BW}}, & LostPackets = TRUE \end{cases} \qquad (Eq.4)$$

When losses are detected, the higher the use of the link, the greater the reduction in the SR.

The value of the Inc_p, packet increment (packets), is determined by (Eq.5):

$$Inc_p = 10^{\log(BW - (SR \cdot P_{size} \cdot 8)) - M} \qquad (Eq.5)$$

This method of calculation causes a logarithmic growth of the SR. When the use of the link is low, the increase in the speed of transmission is greater, and vice versa.

The value M is a magnitude modifier (Eq. 6) in order to apply a dynamic increase based on the efficiency of the link. It is more aggressive when efficiency is worse than 80% with the objective of achieving a high throughput without saturating the connection.

$$M = \begin{cases} 7, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} < 0.8 \\ \\ (\dfrac{SR \cdot P_{size} \cdot 8}{BW} \cdot 10) - 1, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} \geq 0.8 \end{cases} \qquad (Eq.6)$$

In the following section, in order to test the goodness of the designed protocol, a proof-of-concept implementation has been undertaken.

3.5 Performance Tests

Based on the analysis and design described in the previous sections, the protocol is implemented, and performance tests are deployed in different scenarios in order to validate the objectives proposed during the design phase.

3.5.1 QoS Objectives

The QoS objectives to be demonstrated from the results of the tests based on the use case are:

(O1) Efficiency

Maximum average bandwidth reached (Mbps) over different link speeds (>95% of the link capacity).

(O2) Adaptability

Modification of the Sending Rate to maximise the useful bandwidth used (Mbps) without causing congestion on the link (no losses objective during the recovery phase, immediate recovery after no losses in the last burst).

(O3) Friendly Aggressiveness

Aggressiveness against other TCP, UDP and AATP flows. The protocol contemplates the status of the network in order to let the other protocols use the residual bandwidth capacity of the link (>75-80% of the bandwidth for AATP protocol, thus leaving the 20% of residual one to other flows).

3.5.2 Tests

Three different groups of tests are set to demonstrate the objectives related to the Cloud Content Sharing Use Case described before:

(T1) Single flow without losses and cross-traffic

Transmission of a single flow in order to demonstrate the efficiency of the communication at different speeds (O1).

(T2) Single flow with losses, without cross-traffic

Transmission of a single flow in order to demonstrate the efficiency of the communication at different loss levels and congestion (O2).

(T3) Single flow with cross-traffic

Transmission of a flow sharing link with other protocols, in order to demonstrate the Friendly Aggressiveness against these (O3):

a. TCP

b. UDP

c. AATP

In order to deploy these tests, two different phases were planned. First, an AATP implementation is done in a Network Simulator to analyse its behaviour and performance.

After analysing and verifying the results, an AATP prototype is deployed as a proof of concept in a Testbed on Field to check it over a real scenario.

Network Status estimation and *Data Transfer process* building blocks for the sender and the receiver have been coded in protoC (Simulator) and C (Testbed).

3.5.3 Phase 1 - Network Simulator

The Riverbed Modeler [25] is used to implement the protocol in a simulator. It is a programme that allows the design of scenarios of data networks of any size and type.

These processes are programmed as a finite state machine in C or C++ language, where each state is responsible for implementing a specific part of the functionality of each process.

The end-to-end BDP in all tests is 10^6 or greater to simulate an LFN and the base scenario that has been deployed.

The outcomes shown are the mean results of different executions, assuring a confidence interval of 99% with a maximum error deviation of ±1.5%. The results of the aforementioned tests performed are as follows:

3.5.3.1 Phase 1 – T1 – Single Flow without losses and cross-traffic – Efficiency (O1)

Different links are set in order to test the estimated bandwidth and the throughput of the protocol.

T1.1a) WAN SONET-3 (148.608 Mbps)

In a SONET-3 network, the mean estimated bandwidth is 145.93 Mbps (98.2%), and the mean throughput is 142.68 Mbps (95.99%).

T1.1b) WAN SONET-12 (601.344 Mbps)

In a SONET-12 network, the mean estimated bandwidth is 573.03 Mbps (95.29%), and the throughput is 568.44 Mbps (94.53%).

T1.1c) WAN SONET-48 (2.405 Gbps)

In a SONET-48 network, the mean estimated bandwidth is 2.34 Gbps (97.37%), and the mean throughput is 2.32 Gbps (96.6%).

The results of the test show an efficiency rate of around 95% of the bandwidth for different links.

3.5.3.2 Phase 1 - T2 – Single Flow with losses, without cross-traffic – Adaptability (O2)

For this test, random losses are set in order to test the adaptability of the protocol in a lossy network.

To check the adaptability of the protocol in the simulator, a packet discarder is configured to generate random packet losses. The simulation software limits the configuration of the packet discarder.

T2.1a) 3.5% random losses

A Packet Discarder is configured to generate 3.5% of random packet losses, which is the worst-case loss scenario of the use case requirements described in this paper.

Given that the objective is to show how the protocol adapts its behaviour to random loss episodes and not performance, these losses are considered sufficient. In Figure 30, the result is shown. The blue line represents the estimated bandwidth, the green one represents the Sending Rate and the red line the throughput accomplished.

Figure 30. Random Loss – T2.1a - Simulator – Blue: Estimated Bandwidth; Green: Sending Rate; Red: Throughput accomplished

It is observed that the throughput starts at around 147 Mbps and when the losses begin, it oscillates between 126 and 128 Mbps (84.8-86.1%). Finally, when the losses disappear, the speed of the connection returns to 136.75 Mbps (92% usage). It is also possible to verify that the operation of the calculation of the Sending Rate is correct, with a logarithmic increase when losses are not detected and a linear reduction when detected.

3.5.3.3 Phase 1 – T3 – Single Flow with cross-traffic – Friendly Aggressiveness (O3)

Three comparisons are proposed in order to check the aggressive behaviour of AATP when it shares a link with other transport protocols. These protocols are TCP (friendly), UDP (aggressive-inflexible) and AATP (aggressive).

To generate additional traffic between the end nodes, the following flows are used:

- TCP Flow: Riverbed node running FTP traffic (3 GB of data).

- UDP Flow: Riverbed node running UDP traffic (30 Mbps).

- AATP flow: AATP instance to generate AATP traffic (No speed fixed).

Due to the limitations of the simulator, it is not possible to configure the characteristics of the TCP and UDP flows.

T3.1a) TCP flow - SONET-3 (148.608Mbps)

In this test, the link is shared between a TCP flow and an AATP flow (Figure 31). The blue line is the AATP flow and the red one is the TCP flow.

In this case, AATP forces TCP to use the residual BW (20%). AATP maintains the BW established first with fluctuations (80%). After sending the AATP, FTP takes the full bandwidth.

Figure 31. TCP Flow – T3.1a – Simulator - Blue: AATP flow; Red: TCP Flow

T3.1b) UDP flow - SONET-3 (148.608Mbps)

For this test, a UDP flow of 30 Mbps is launched (Figure 32). The blue line is the AATP flow and the red one is the UDP flow. Neither flow lets the other take the bandwidth because of its aggressiveness. This situation causes packet loss in both flows.

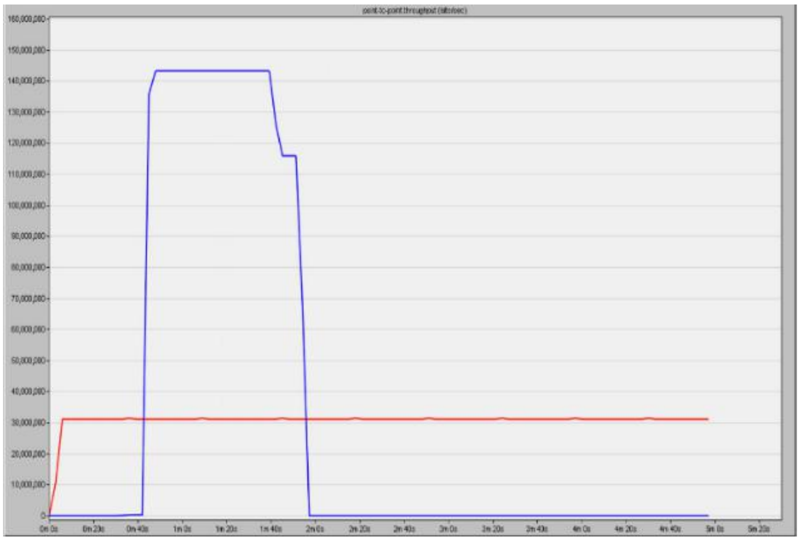

Figure 32. UDP Flow – T3.1b – Simulator- Blue: AATP flow; Red: UDP Flow

T3.1c) AATP flow - SONET-3 (148.608Mbps)

Finally, in this test, two AATP flows share a link. The result of this test (Figure 33) shows that the first flow launched uses almost the entire bandwidth. Meanwhile, the other flow does not obtain more than 10% of the bandwidth. The blue line is the first AATP flow and the red one is the second AATP flow.

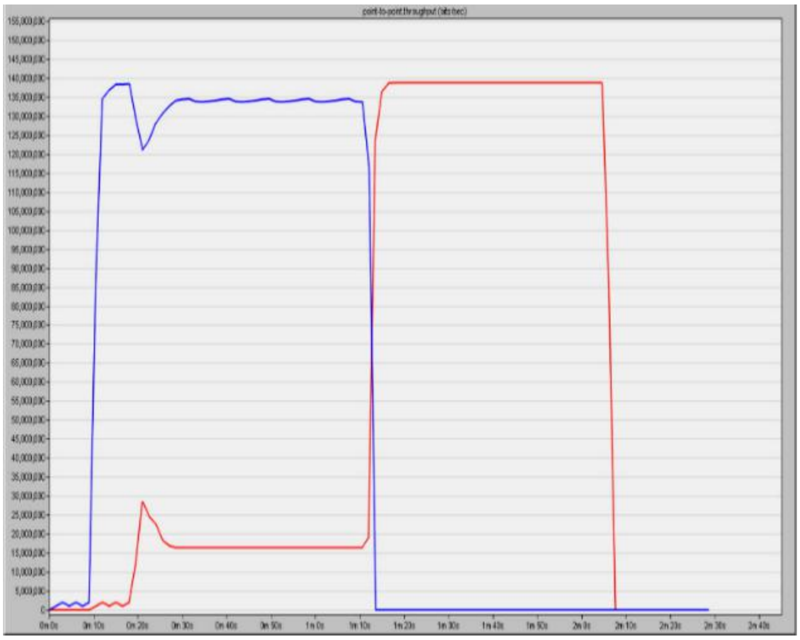

Figure 33. AATP Flow – T3.1c – Simulator - Blue: AATP flow 1; Red: AATP flow 2

After deploying the protocol in the Riverbed Simulator, a first analysis has been carried out to improve the implementation of the protocol before the final implementation of the proof of concept.

3.5.4 Phase 2 - Testbed on Field

With the objective of testing the protocol in a real environment as a proof of concept, a Testbed on Field is deployed. The Testbed consists of two extreme nodes (Source and Destination) which are interconnected through a central node that emulates the behaviour of a WAN network with LFN characteristics.

The physical connections between devices are made by twisted pairs CAT-5 at 100 Mbps Full Duplex and latencies of up to 100ms. To simulate different network characteristics, the *WANem* software [26] is used in the central node.

During the entire test, a total of 1GB is sent and a BDP greater than 12,500 bytes (10^5 bits) is fixed. In the graph, the blue colour indicates the estimated bandwidth (Mbps), the green colour the throughput (Mbps) and the red colour the losses (%).

The results of the aforementioned tests performed are shown.

3.5.4.1 Phase 2 – T1 – Single Flow without losses and cross-traffic – Efficiency (O1)

The maximum speed is set in order to check the efficiency.

T1.2) 100Mbps - 1 GB of data

In a 100 Mbps scenario, the estimated bandwidth is 97 Mbps (97%) and the throughput is around 96Mbps (96%).

95% of link utilisation is exceeded. It should be noted that the actual sending speed of the protocol is, in most situations, below the estimated one. This is due to the step used when increasing the sending speed, the one defined by the size of the packages that are sent.

3.5.4.2 Phase 2 – T2 – Single Flow with losses, without cross-traffic – Adaptability (O2)

Two main tests are set in the Testbed using WANem to check the behaviour of the protocol during a random loss scenario.

T2.2a) From 0% to 5% random losses

First, the result of the throughput accomplished in a range from 0% to 5% random packet losses (Table 9).

Table 9. From 0% to 5% random losses - T2.2a - Testbed

Random losses (%)	Average efficiency (%)
0	96
0.001	96
0.01	96
0.1	90
1	40
3	35
5	18

The results with up to nearly 0.1% random losses show an efficiency of 90% for AATP. From this point to 3% losses, the efficiency decreases to 40%. After that, where losses are over 3%, the throughput of the protocol drops to 20% of the link capacity.

T2.2b) Bandwidth occupation from 0% to 100%

A test divided into different stages is proposed. The objective is to show how AATP modifies its throughput depending on the network congestion by introducing contention traffic using an Iperf flow [27]. The sequence of execution of flows is described below:

(1) The test starts with an initial link occupation of 70%. The AATP flow starts shortly after.

(2) Interfering traffic is added, transmitting at 100% of link capacity.

(3) An interfering flow is introduced and progressively increased in steps from 20% to 100% occupancy.

(4) Increasingly, an interfering flow in steps of 20% occupancy to reach 100% and decrease to 0%.

(5) Interfering traffic from 100% to 0% occupancy is gradually decreased, in steps of 20%.

In Figure 34, the results of (T2.2b) can be observed and the previously defined sections can be identified. The blue line represents the estimated bandwidth (Mbps), the green line the throughput (Mbps) and the red line the Loss Rate (%).

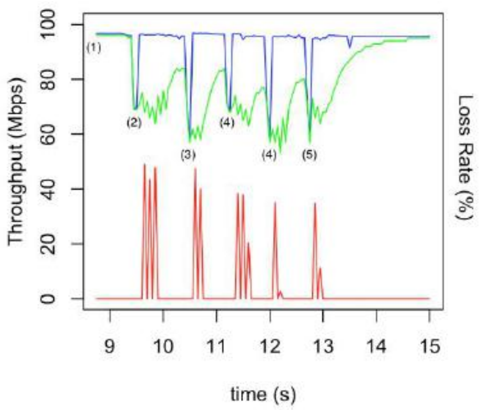

Figure 34. Congested Network – T2.2b – Testbed - Blue: Estimated Bandwidth; Green: Throughput; Red: Losses

It is observed that the mechanisms react to both congestion and losses. Congestion causes a decrease in the Sending Rate, which occurs continuously to decongest the link and is reflected in the throughput. Losses cause throughput decreases, which prevent the mechanism from recovering until the channel is ready. It is also capable of recovering the sending speed as soon as the channel allows it in less than half a second.

3.5.4.3 Phase 2 – T3 – Single Flow with cross-traffic – Friendly Aggressiveness (O3)

In order to check the friendly aggressiveness of the protocol, three sets of tests are proposed over the Testbed. The following flows are set to generate additional traffic between the end nodes:

- TCP flow: File Transport Protocol (FTP) to generate TCP traffic [28]. 1 GB of Data.

- UDP flow: Iperf [27] to generate UDP traffic. 1 GB of Data.

- AATP flow: AATP instance to generate AATP traffic. 1 GB of Data.

T3.2a) TCP flow - 100 Mbps

This test shows how the protocol AATP shares the link with a non-aggressive protocol.

Figure 35 evidences the throughput achieved by the designed protocol. AATP reaches around 93% of the link capacity, allowing TCP to only obtain the residual bandwidth of the link (7%), without generating losses.

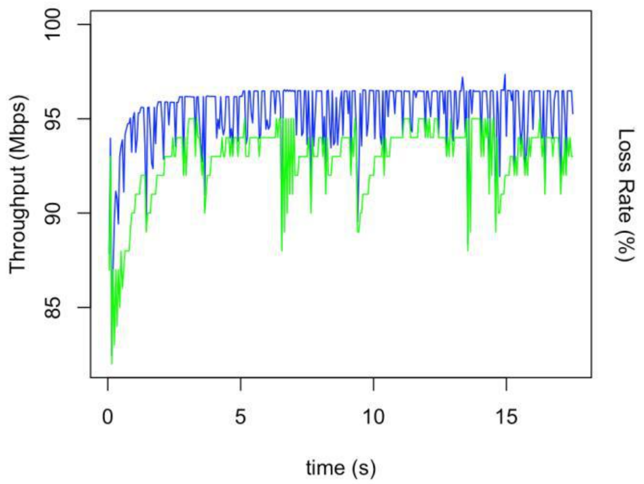

Figure 35. AATP sharing with TCP Flow – T3.2a – Testbed - Blue: Estimated Bandwidth; Green: Throughput

T3.2b) UDP flow - 100 Mbps

The UDP flow performed in this test is inflexible. The software used to simulate UDP (*Iperf*) does not decrease the sending rate even if losses are generated.

In this context of aggressiveness, this test shows the throughput achieved by AATP sharing a 100Mbps link with a UDP flow (Figure 36).

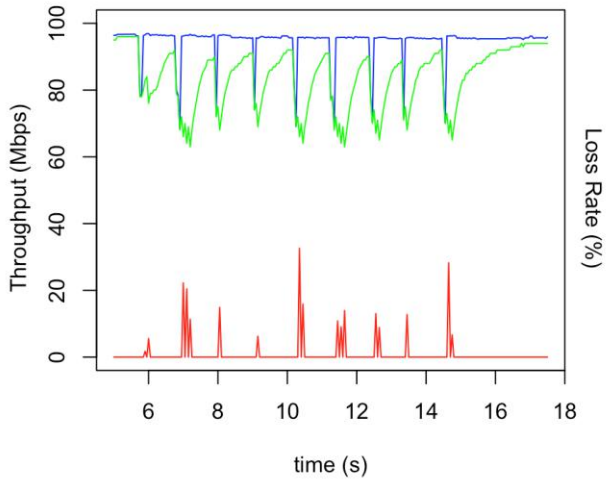

Figure 36. AATP sharing with UDP Flow – T3.2b - Testbed - Blue: Estimated Bandwidth; Green: Throughput; Red: Losses

Under these circumstances, the congestion control is not capable of occupying the entire channel since the UDP flow is highly aggressive and inflexible. This situation generates considerable losses, meaning that the large number of retransmissions to be made results in a significant decrease in the real speed of data transmission. However, it does achieve an average throughput of 75Mbps. This is because the UDP flow is invariable even when saturation losses of the link occur.

T3.2c) AATP flow - 100 Mbps

In this final test, two AATP instances share the same link. Figure 37 shows the behaviour of one of the two AATPs transmitting simultaneously in which we can observe a struggle for the total bandwidth of the channel (100Mbps), where each one achieves a distribution of 50% but incurs losses.

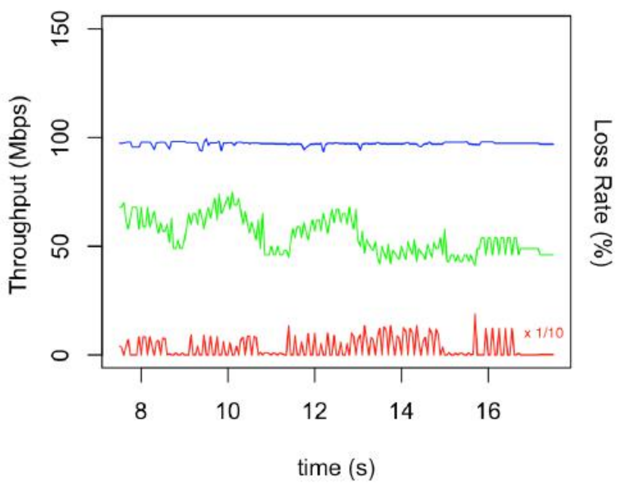

Figure 37. AATP Flow – T3.2c – Testbed - Blue: AATP flow 1 Bandwidth; Green: Throughput; Red: Losses

Both flows compete for the available bandwidth without considering the presence of other flows, which generates congestion due to the aggressiveness of the protocol.

3.6 Tests Output Analysis

In this section, the output of the tests deployed in both phases (Network Simulator and Testbed) is analysed in order to meet the QoS objectives.

It is necessary to highlight that the implementation in both scenarios differs slightly depending on the programming language and the simulation (Riverbed Modeler) or emulation (WANem) options available of the software used.

The main reason for deploying the protocol in these two phases is to cover the maximum number of possible cases and situations in order to prove and demonstrate the real behaviour of the designed protocol.

3.6.1 Efficiency (O1) - Analysis from Tests 1

The objective of deploying this first set of tests is to check the Efficiency (O1) of the protocol to use all the bandwidth of the link capacity (>95%).

The AATP is designed with a Bandwidth Estimation mechanism. It is launched during the connection establishment, calculating the bandwidth of the communication. With this information, the initial Sending Rate is set directly to the maximum capacity, depending on the aggressiveness set in the protocol behaviour.

As shown in Table 10, the protocol uses around 95% of the link in all tests deployed over links without losses and cross-traffic, accomplishing the Objective 1 – Efficiency.

Table 10. Results from T1

Test	Link Capacity (Mbps)	Estimated BW (Mbps)	Throughput (Mbps)	Efficiency (%)
T1.1a	148.6	145.9	142.7	95.9%
T1.1b	601.3	573.0	568.4	94.5%
T1.1c	2405.4	2342.2	2323.5	96.6%
T1.2	100	97	96	96%

3.6.2 Adaptability (O2) – Analysis from Tests 2

This set of tests helps to demonstrate the adaptability (O2) of the protocol in lossy or congested networks. It is necessary to highlight that Packet Discarder (Simulator) and WANem (Testbed) have different implementations and behaviour in terms of random losses, which consequently affects the results.

The protocol is designed to react to network losses, without differentiating the cause. This reaction causes a reduction of the Sending Rate, which is proportional to its use of the link at that moment.

After detecting the end of the lossy event, the protocol aggressively increases its Sending Rate with the objective of reaching an efficiency rate of 80%. As a consequence, the Sending Rate is increased gradually, in order to avoid causing congestion.

With the results from T2.2a (Table 9), the AATP is compared with other protocols (TCP Vegas, Tahoe and New Reno) deployed over the same scenario. The comparison is shown in Figure 38:

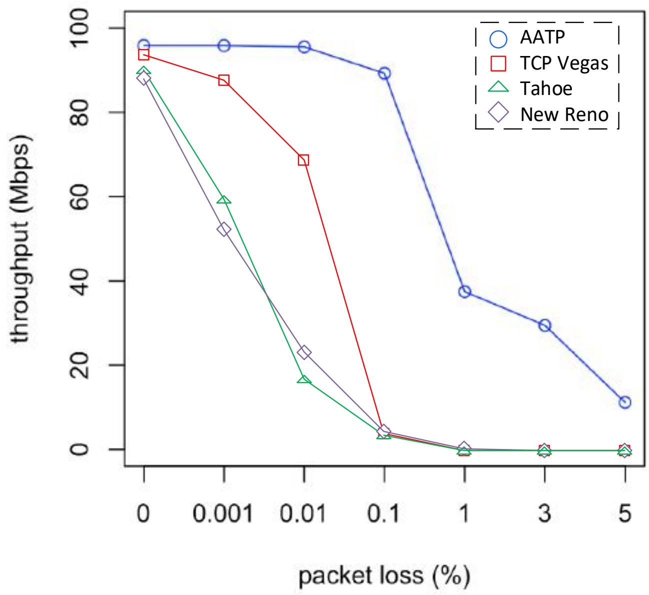

Figure 38. Comparative between AATP, TCP Vegas, Tahoe, New Reno

The results, of up to nearly 0.1% random losses, show an efficiency of 95% for AATP. This situation is considered inefficient for other protocols. From this point to 3% losses, the efficiency decreases to 40%. After that, where losses are over 3%, the throughput of the protocol drops to 20% of the link capacity.

Focusing on the adaptability of the protocol, a detailed study of the results (T2.2b -Figure 34) shows how the reactivity to the losses can be decomposed into three phases (between seconds 10 and 12), observable in Figure 39.

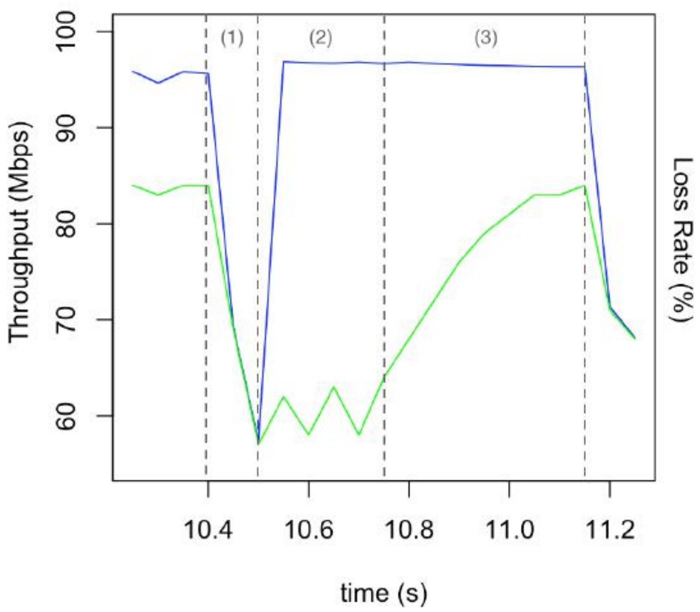

Figure 39. Congested Network – Recuperation process – T2.2b – Testbed - Blue: Estimated Bandwidth; Green: Throughput

In the first place, the initial sending speed is decreased until the aggregate sending speed stops causing congestion (Figure 39 - (1)).

The congestion control then detects that the available bandwidth is the maximum of the channel. At this point (second 10.5), it enters a second phase in which it experiences the losses generated by the previous congestion period (Figure 39 - (2)), where the efficiency is around 60%.

Moreover, in that same phase, since the estimation of the link no longer detects congestion, the sending window is increased.

Finally, once the losses have been treated, the recovery process is started (Figure 39 - (3)).

It is shown that the protocol tries to modify its behaviour when it detects a packet loss. Because the losses are random and not caused by the traffic generated, packet losses continue to occur, even though the protocol tries to reduce its sending rate (60%).

On the one hand, the results of T2 were useful to check the accomplishment of the Objective 2 (O2) - Adaptability of the protocol. On the other hand, these tests cannot be used to check the efficiency (O1) of the protocol, since they do not focus on efficient behaviour over a random loss network such as a wireless scenario. LFNs are not characterised for their loss ratio in the same way as wireless networks.

3.6.3 Friendly Aggressiveness (O3) - Analysis from Tests 3

In the final set of tests, the main objective is to demonstrate the behaviour of the protocol when coexisting with other reference protocols, such as TCP or UDP, and also with other AATP flows (O3).

The design of the AATP protocol is focused on the maximum use of the capacity of the link (>80%), and the residual bandwidth is left for the other protocols (20%). This is accomplished with the Bandwidth Estimation mechanism and the aggressive behaviour of the Data Transfer process.

3.6.3.1 AATP vs TCP

In this case, most of the capacity of the link is occupied by AATP (around 80-85%) and as a consequence TCP is left with the residual bandwidth without causing losses (from 20% to 5%). This is because of the aggressiveness of AATP, which does not share the link equally with other non-aggressive protocols such as TCP.

3.6.3.2 AATP vs UDP

In this case, AATP competes against another aggressive protocol, UDP. This is the most aggressive case scenario because UDP does not modify its sending rate even though losses occur. ATTP tries to modify its sending rate (from 95% to 60%) in order to reduce losses in the link. As UDP flow does not modify its behaviour, this situation causes congestion over the link and packet losses during the data transfer, which results in inefficiency.

3.6.3.3 AATP vs AATP

In this last case, two AATP flows share the bandwidth of the link. The first flow launched experiences a greater link utilisation and fewer packet losses than the second one. The conflict between the two flows produces inefficiencies in the network, reaching 50% of sharing but without control.

After achieving the goals and demonstrating the objectives set, the AATP is currently undergoing an implementation process to be deployed in a production environment.

3.7 Conclusions and future work

The growth of Storage Area Networks in Cloud platforms has arisen from the need to share large amounts of information all over the world. Therefore, the need for a network that can transfer or move this information from one point to another both efficiently and reliably has increased. The context exhibits a Cloud Content Sharing Use Case where several limitations appear over Long Fat Networks due to their Bandwidth-Delay Product (high Bandwidth and high Round Trip Time). This causes problems in the existing TCP and UDP protocols.

On analysis of the requirements, the transport protocol is required to send large amounts of data (to the order of Hundreds of Gigabytes) due to the exchange of information between cloud environments. Furthermore, it is necessary to reach the full capacity of the connection efficiently and, due to the Bandwidth-Delay Product, to overcome the main TCP constraints in long-distance communications. In addition, this protocol has to act aggressively towards other transport protocols while, at the same time, adapt to network losses by performing a flow control.

In order to fulfil the aforementioned requirements, the AATP protocol has been designed and implemented to be efficient (O1), adaptable (O2) and friendly aggressive (O3). The two main characteristics to highlight from the AATP are (1) the mechanism to calculate the maximum bandwidth capacity of the communication through a Bandwidth Estimation process and (2) the capacity of the protocol to adapt its behaviour using an efficient Data Transfer process. Furthermore, this process is aggressive towards other protocols and adaptative to the changes in the network during and after a lossy episode.

The different tests (T1, T2 and T3) from both deployment phases (Phase 1 - Network Simulator and Phase 2 - Testbed on Field) are set to demonstrate the performance of the AATP protocol.

Efficiency is around 95% in the different scenarios deployed, accomplishing the O1 – Efficiency, shown in T1. It is noted that minor inefficiencies are caused by headers and implementation issues.

After a lossy episode, the protocol rapidly recovers 80% of its maximum sending rate and gradually increases until it reaches full capacity, being O2 – Adaptative, demonstrated in T2. Moreover, a comparison between the AATP with other protocols is made. Improved efficiency over the same link with different random losses (0% to 5%) is observed.

In comparison with TCP, AATP takes up almost all of the bandwidth (80%), leaving the residual bandwidth to TCP (20%). In another case, versus UDP-aggressive, both protocols try to take all bandwidth without sharing it, producing losses. This is because the UDP version used does not modify its sending rate in the same way as AATP. In the last case, where two AATP flows share the link, the results show that the protocol behaves aggressively and causes losses because both flows try to achieve the maximum bandwidth. It can be concluded that the AATP protocol accomplishes O3 – Aggressiveness, proved in T3.

After analysing all the tests results, it can be concluded that our objectives to provide Quality of Service for a Cloud data exchange use case are achieved. Future work aims at:

- Improving the protocol performance in lossy episodes by differentiating random losses from congestion losses in heterogeneous scenarios.
- Applying fairness flow prioritisation between AATP flows to fairly share the whole bandwidth of the network efficiently without causing losses and instabilities.

4. Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks[6]

The quality of inter-network communication is often detrimentally affected by the large deployment of heterogeneous networks, including Long Fat Networks, as a result of wireless media introduction. Legacy transport protocols assume an independent wired connection to the network. When a loss occurs, the protocol considers it as a congestion loss, decreasing its throughput in order to reduce the network congestion without evaluating a possible channel failure. Distinct wireless transport protocols and their reference metrics are analyzed in order to design a mechanism that improves the Aggressive and Adaptative Transport Protocol (AATP) performance over Heterogeneous Long Fat Networks (HLFNs). In this paper, we present the Enhanced-AATP, which introduces the designed Loss Threshold Decision maker mechanism for the detection of different types of losses in the AATP operation. The degree to which the protocol can maintain throughput levels during channel losses or decrease production while congestion losses occur depends on the evolution of the smooth Jitter Ratio metric value. Moreover, the defined Weighted Fairness index enables the modification of protocol behavior and hence the prioritized fair use of the node's resources. Different experiments are simulated over a network simulator to demonstrate the operation and performance improvement of the Enhanced-AATP. To conclude, the Enhanced-AATP performance is compared with other modern protocols.

Keywords: Transport protocol; heterogeneous long fat networks; wireless; fairness; loss episode; bottleneck

4.1 Introduction

Nowadays, communications take place over heterogeneous networks composed of wired and wireless sections. The number of wireless end devices connected to the Internet is increasing exponentially because of the massive use of mobile phones. Moreover, the bandwidth required is also increasing because of the global presence of the latest multimedia technologies such as 4K and Virtual Reality/Augmented Reality (VR/AR) [1]. The presence of the wireless sections directly influences the network's characteristics and data transmission quality. The main inconveniences of using wireless connection for communication protocols are bandwidth degradation, the interruption of the transmission caused by the nature of the media, and the network resource inefficiency caused by obstacles, interferences, or the mobility of the node [2].

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[6] The work reported in this chapter was published as the paper entitled "Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks" in the Electronics journal, 10(9):987, 2021. https://doi.org/10.3390/electronics10090987. Authors: Alan Briones, Adrià Mallorquí, Agustín Zaballos, Ramon Martin de Pozuelo.

Authors contributions: Conceptualization, A.B. and A.Z.; methodology, A.B. and A.M.; software, A.M.; validation, A.Z. and R.M.d.P.; formal analysis, A.B. and R.M.d.P.; investigation, A.B., R.M.d.P. and A.M.; resources, A.Z.; data curation, A.M.; writing—original draft preparation, A.B.; writing—review and editing, A.Z., R.M.d.P. and A.M.; visualization, A.M.; supervision, A.Z.; project administration, A.B. All authors have read and agreed to the published version of the manuscript.

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The presence of access wireless sections in the last mile of the Long Fat Networks (LFN), networks composed of core wired sections with high Bandwidth (BW), high values of Round-Trip Time (RTT), and a Bandwidth-Delay Product (BDP) greater than 12,500 bytes (10^5 bits) [3] is increasing the complexity of this type of networks, which are also denominated Heterogeneous Long Fat Networks (HLFNs).

Concretely, the transport layer protocols are affected because their semantics are end-to-end, meaning that there is a lack of awareness of the sections of the network at the endpoints. During the design of the first transport protocols, in the course of the Internet conception in the 1970s [4], some premises were assumed. First of all, legacy transport protocols are not able to distinguish the cause of a packet loss episode, assuming that the packets are discarded by an intermediate router because of congestion; the possibility of this being caused by media inefficiencies is not considered. Furthermore, these traditional protocols assume that independent connections are wired without contemplating the possibility of sharing the media, as is the case in wireless environments. Finally, other related problems include the random multiple packet losses caused by interferences or the fading of a channel, or the introduced delay due to asymmetric link capabilities.

Consequently, increased traffic volumes and the large deployment of wireless networks are detrimentally affecting the transport protocol basis and its performance [5][6][7][8], as is the case of the worldwide used Transmission Control Protocol (TCP) [9][10] and some of its variants [11][12][13]. These limitations also affect Adaptative and Aggressive Transport Protocol (AATP) [14].

The goal of this work is to achieve a high-performance data transmission over a wired-wireless communication that fairly shares the network resources of a node, although real-time transfers are out of the scope because of the packet-burst operation of the AATP.

The main contributions of this paper are as follows. First, distinct wireless transport protocols are analyzed, and different metrics are examined to design a mechanism to differentiate between congestion and channel losses. Similarly, different fairness indices are considered to define a procedure for the fair distribution of the bandwidth among distinct flows connected to an endpoint. Second, the AATP is upgraded (Enhanced-AATP) by introducing the aforementioned features for wireless loss detection and for the controlled fair distribution of the network resources of an end-device. For this, the designed Loss Threshold Decisor (LTD) mechanism, based on the Jitter Ratio metric, is proposed for the decision-making process of the protocol to discern between the losses caused by network congestion or those caused by channel fault. In addition, the defined Weighted Fairness mechanism is introduced to enable the fair coexistence of multiple flows. Finally, the protocol is deployed over the network simulator Steelcentral Riverbed Modeler [15]. A set of tests are designed and run to demonstrate how the Enhanced-AATP outperforms HLFNs and its capacity to manage different flows from the point of view of an endpoint. In conclusion, its performance is compared with modern transport protocols.

The rest of this paper is structured as follows. In Section 2, the background of the paper is explained. In Section 3, the related work is presented, focusing on wireless transport protocols, their reference metrics, and their wireless mechanisms, also including distinct fairness indices. A review of the AATP protocol basis is provided in Section 4. Section 5 describes the Enhanced-AATP with the modifications and mechanisms introduced. Section 6 details the experiments deployed over the network simulator, showing the results of the improvements. Finally, Section 7 concludes the paper.

4.2 Background

The Adaptative and Aggressive Transport Protocol (AATP) [14] protocol was designed to work over LFNs, focusing on solving the Cloud Data Sharing Use Case defined by a Cloud company. Within this Use Case, servers from far separated Storage Area Network (SAN) regions exchange large amounts of data over high-speed networks through a private wired WAN. For recent deployments, this Cloud company decided to evolve the Use Case by introducing wireless access in the last mile of their client edges (Figure 40). A similar Use Case, more focused on processing, is discussed in [16].

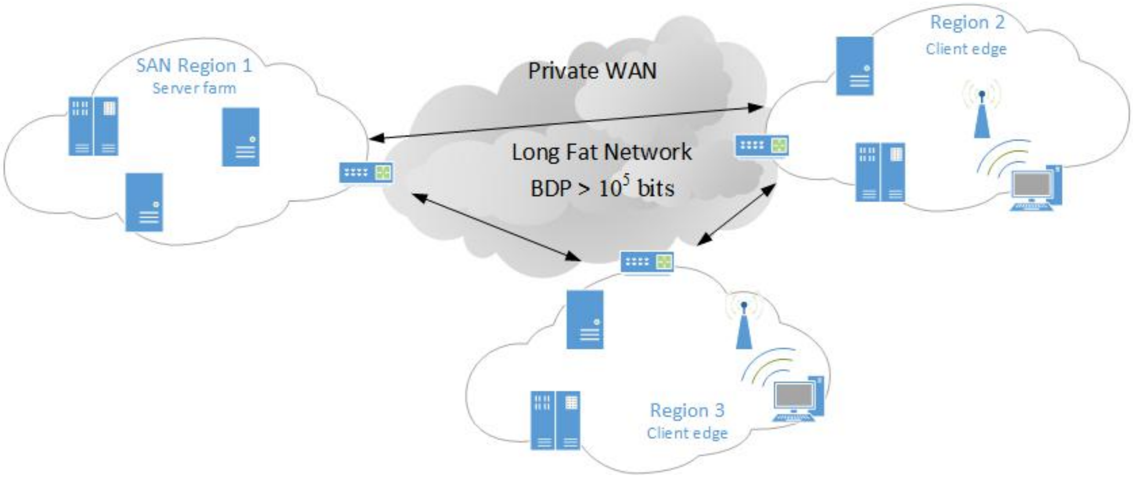


Figure 40. Cloud Data Sharing Use Case over Heterogeneous Long Fat Networks (HLFNs)

In addition to transferring information between servers from different server farms, it also exchanges large amounts of stored data between cloud servers and endpoints. These end nodes can be connected through a wired or a short-range wireless connection. Given the short-range wireless connection and the endpoints' data transfer profile (large amount of stored data), mobility during the transfer is not expected, nor are there a high number of intermediate nodes due to the network topology.

On the one hand, the AATP protocol provides a high-performance data transmission and quick recovery in case of a loss episode. However, on the other hand, its performance is affected over lossy wireless networks because the protocol does not recognize random channel losses. Its lower operation requires an adaptation to deal with the complexity of the Cloud Data Sharing Use Case over Heterogenous Long Fat Networks. In addition, given the possibility of having different AATP flows connected to the same end-device or server, the unfriendly behavior of the AATP is required to be modified to achieve intra-protocol fairness. To overcome these drawbacks, it is necessary to propose solutions for the paradigm of HLFNs.

For these reasons, a review of the State-of-the-Art of the most outstanding transport protocols designed for wireless networks is detailed. Specifically, it focuses on the operation of these protocols, the reference metrics, and their mechanisms to deal with the inconveniences of the radio media. Finally, different fairness indices are considered to define a mechanism for the fair distribution of the bandwidth among the distinct flows connected to an endpoint.

4.3 Related Work. Metrics Selection Process

The main cause of losses in wired networks is the congestion of one of the intermediate devices [17]. To correct this situation, the endpoint reduces its sending rate to reduce network saturation. However, when a loss occurs in a wireless network, it can be caused by a change in channel conditions (fading, interferences) [2]. In HLFNs [3], these drawbacks are more critical.

In this section, distinct metrics are analyzed and are selected to be included in the protocol for the decision-making process. Moreover, in the case of wireless shared media, the fair distribution of the network resources, from the nodes' point of view is more difficult to control [18] because of its channel characteristics.

4.3.1 Wireless Oriented Transport Protocols. Wireless Channel-Loss Metric

Relating the actions taken by a protocol to network statistics is an interesting approach for the decision-making process on network events. The Performance-oriented Congestion Control (PCC) [19], defined by Mo Dong et al., makes controlled decisions based on empirical evidence, pairing actions with directly observed performance results.

In order to evaluate the metrics and mechanisms for wireless loss-tolerant transmissions, diverse transport protocols solutions and their congestion controls have been studied. Cheng Peng Fu and S.C Liew proposed TCP Veno [20], based on TCP Reno and TCP Vegas [21][22]. This protocol calculates the Round-Trip Time (RTT) periodically, recording the minimum RTT of the communication, known as Base RTT or Best RTT, and the last RTT, known as Actual RTT. TCP Veno bases its loss episode decision on the comparison of these two RTT values, also taking into account the Congestion Window and the bottleneck of the connection.

A multipath feature is introduced in mVeno [23] by Pingping Dong et al. to improve the performance of the protocol by using the information from the subflows that belong to a TCP connection. The objective is to adaptively adjust the transmission rate of each subflow and acting over the congestion window, decreasing one-fifth of it, in the case of a packet loss event.

With reference to the TCP Reno mechanism, Taha Saedi and Hosam El-Ocla proposed the Congestion Control Enhancement for Random Loss (CERL) [24][25] and its revisited version, CERL+ [26], to improve the performance over wireless networks. CERL+ proposes a modification of TCP Reno at the sender-side by using a dynamic threshold of the RTT. With the average RTT, the protocol calculates the length of the bottleneck's queue to evaluate the congestion status and distinguish a random loss. The main drawback pointed out by its authors is the requirement of precise time synchronization between the sender and receiver.

Saverio Mascolo et al. built TCP Westwood [27] and its evolution TCP Westwood+ [28]. This protocol differentiates the loss episodes by defining a coarse timeout for congestion loss and by setting the reception of three duplicated ACKs (DUPACKs) as the indicator of channel loss during the bandwidth estimation process. An upgraded slow-start for Westwood was proposed to improve its performance [29].

The Dynamic TCP (D-TCP) [30], proposed by Madhan Raj Kanagarathinam et al., extracts the end-to-end performance statistics (traffic intensity, link capacity, packet sending rate) of the connection to calculate the available bandwidth of the network. In case of abrupt changes or lossy conditions, D-TCP can adapt its operation by fixing a dynamic congestion window factor N. By adaptatively modifying the CWND, based on the factor N, the protocol avoids losing performance during a spurious packet loss event.

Venkat Arun and Hari Balakrishnan defined Copa [31], a practical delay-based protocol. Even if it is not focused on wireless environments, this protocol proposes a mechanism by fixing a target rate. This target rate provides a reference for high throughput and low delay. By relating the minRTT (the minimum RTT calculated in a long period of time) to the standing RTT (the smallest RTT over a recent-time window), the protocol adjusts its congestion window in the direction of the reference target rate. Moreover, Copa has a competitive mode to compete with buffer-filling protocols, based on the information extracted from the last 5 RTTs to check if the queue has been emptied.

Yasir Zaki et al. presented Verus [32], which is a protocol that focuses on the delay over high variable cellular channels. This protocol establishes a delay profile, which reflects the relationship between the congestion window and the delay variations, which is determined through the RTT, over short epochs. Verus uses this relationship to increment or decrement the congestion window based on short-term packet delay variations.

Neal Cardwell et al. presented TCP BBR [33], one of the most high-performance TCP protocols, which manages the maximum BW with the minimum RTT. Given the inefficiency of BBR in exploiting the Wi-Fi bandwidth, a modification is proposed by Carlos Augusto Grazia et al., which is called BBRp [34]. This inefficiency lies in the impossibility of performing frame aggregation because TCP BBR implements its own solution of the TCP pacing algorithm. Tuning the BBR pacing speed allows the congestion control to correctly aggregate packets at the wireless bottleneck with almost optimal TCP throughput.

To fulfill the needs of high-bandwidth requirements of last multimedia technologies (4K, VR/AR) over wireless connections, Li Tong et al. presented the protocol TCP-TACK [35]. This protocol bases its operation on two types of ACKs, the Instant ACK (IACK) and the Tamed ACK (TACK). The first one, IACK, is meant to get rapid feedback, which provides information about instant events (loss, state update.). The second one, TACK, is more focused on statistics (losses, available bandwidth, receipts, etc.). In this way, the number of ACKs sent to the network is reduced by over 90%, decreasing the overhead control and leading to an improvement of the goodput around 28%. Furthermore, TCP-TACK proposes an advanced way of calculating the minimum RTT using the smooth One-Way Delay (OWD) using relative values, reducing the information sent to the network without affecting the performance.

E. H. K. Wu and Mei-Zhen Chen designed Jitter TCP (JTCP) [36], which is based on the concept of the Jitter Ratio. Considering the sending time and receiving time of the packets, the Jitter ratio relates to the effect of the queued packets at the bottleneck the delay introduced between packets at the destination. The Jitter Ratio is compared to the Queue Decision maker (k/w), which is defined as the number of queued packets (k) considered as a congestion trace after all the packets of a congestion window (w) have been sent. If the Jitter Ratio is greater than the Queue Decision maker, this implies that the loss episode is due to congestion. If it is lower than Queue Decision maker, the loss episode is caused by the channel. JTCP defines one queued packet (k = 1) as a trace of congestion because TCP control flow increases its throughput by one packet per iteration. The operation with k > 1, more than one packet, is not analyzed or evaluated.

Jyh-Ming Chen et al. proposed an enhancement for the Stream Control Transmission Protocol called Jitter Stream Control Transmission Protocol (JSCTP) [37]. The JSCTP keeps the semantics and operation from the SCTP, adding a calculus of the aforementioned Jitter Ratio proposed in the JTCP for the loss episode decision. To filter the case Jr = 0, the Jitter Ratio is smoothed.

The TCP Jersey, presented by Kai Xu et al. [38], and its evolution, TCP New Jersey, estimate the total bandwidth of the connection and, with the information provided by the timestamps of the ACK received, decide if the loss episode is due to congestion or the channel. These protocols include the flag Explicit Congestion Notification (ECN), which uses the information provided by the intermediate routers on their queue status to make the final decision. Different protocols rely on these feedback mechanisms from the network devices, which are out of the scope of this paper because these functionalities are not usually enabled on the intermediate routers. V. B. Reddy and A. K. Sarje proposed TCP-Casablanca [39] for these types of mechanisms to decide the type of losses by considering the flag set by the intermediate routers. These routers have a biased queue management to identify the retransmitted packets.

New data-driven designed protocols are out of the scope of this work, as is the protocol algorithm Indigo [40] from Francis Y. Yan et al., which applies machine learning, given the requirements needed to train the protocol and the amount of data needed for this process. Indigo uses a machine-learned congestion control scheme from the data gathered from Pantheon [41], which is a community evaluation platform for academic research on congestion control from Stanford University. Indigo observes the network state each time an ACK is received, adjusting its congestion window every 10 ms while updating its internal state.

After analyzing the most outstanding transport protocols for wireless loss-tolerant transmissions, Table 11 depicts the wireless loss decision metrics used by each analyzed protocol. The analyzed protocols propose the combination of different metrics related to the Round-Trip Time (or Delay-based), Jitter, information from different flows and the queue, buffer, or congestion, and status of the network or the intermediate routers to find out the cause of a loss over a wired-wireless network.

Table 11. Wireless loss decision elements from the wireless loss-tolerant transport protocols

Transport Protocol	Network Status	RTT	Intermediate Queue Length	Jitter	ACK Action	ECN	Machine Learning
PCC [19]	X						
TCP Veno [20]		X	X				
mVeno [23]		X					
CERL+ [26]		X	X				
TCP Westwood+ [28]	X				X		
D-TCP [30]	X		X				
Copa [31]		X					
Verus [32]		X					
BBRp [34]	X	X					
TCP-TACK [35]		X			X		
JTCP [36]			X	X			
JSCTP [37]			X	X			
TCP New Jersey [38]			X			X	
TCP-Casablanca [39]			X			X	
Indigo [40]	X						X

The metrics related to the information provided by the network nodes (ECN) are discarded from the metric decision due to the fact that this information from the network may not be accessible. Data-driven machine learning techniques are also discarded, given the requirements requested to train the protocol and the amount of data needed for this process.

In addition, delay-based solutions are not considered because of the buffer-fill profile of the AATP protocol. The use of the Round-Trip Time is also discarded, given the high delay of HLFNs, the ACK actions, and the synchronization requirement.

Finally, given the packet burst operation of the AATP, the time difference among the packets received provides information about the status of the bottleneck, which can be directly related to the jitter. The jitter provides information about the intermediate nodes packet queue. None of the Jitter Ratio-based protocols consider the possibility of adding more than one packet per iteration.

In this paper, in order to overcome the aforementioned drawbacks, the Enhanced-AATP proposes a Loss Threshold Decision maker (LTD) mechanism. The LTD is compared to the Jitter Ratio, considering the possibility of adding more than one packet per iteration. The Jitter Ratio increments its value as the saturation of the intermediate nodes increases, providing information about a possible congestion episode.

4.3.2 Fairness Indices. Intra Fairness Multi-Flow Metric

The concept of fairness is analyzed, and distinct indices are evaluated by the AATP enhancement to obtain a controlled fair share of the network's resources by different flows connected to the same node.

The fairness concept refers to how fair the treatment is between the different nodes that are sharing a specific resource. In the environment of networks and the Internet [42], the concept refers to the fairness in the distribution of the throughput that can reach each of the flows that share a point-to-point connection. Modern protocols have required the introduction of a fairness system as in the case of BRR [43].

Usually, most of the networks are IP best-effort, in which there is no point-to-point control of the resources and in which losses can occur due to congestion or channel failure, directly affecting the quality of the connection. However, to achieve proper fairness, the different flows must be treated fairly, equally, and impartially. Another possible approach is to give preferential treatment to the flows that require more resources at the request of the system or the user [44].

Shi, H. established in [45] a way to measure the fairness of a system (or of the individuals in a system), where various types of indices are used to quantify this notion of equality and fair treatment. These indices quantify fairness based on certain metrics (throughput is one of the most used) that are evaluated by each of the flows. In this way, the initial assumption is made that there is a type of resource whose total is C_x, which has to be distributed among *n* individuals. In this way, the location $X = \{x_1, x_2, \ldots, x_n\}$ is obtained, where x_i is the amount of the resource provided to element *i*. Thus, $\sum_{i=1}^{n} x_i \leq C_x$ must be satisfied, where C_x is the total amount of the resource that can be provided. In this way, a function f(X) must be defined to give a quantitative value of the system's fairness. Said function f(X) should meet the following requirements:

- R1: f(X) should be continuous in $X \in \mathbb{R}_n^+$.
- R2: f(X) should be independent of *n.*
- R3: The range of values of f(X) should be mappable to [0,1].
- R4: f(X) should be scalable to multi-resource cases.
- R5: f(X) should be easy to implement.
- R6: f(X) should be sensitive enough to the variation of X.

To compare the different fairness indices, other significant aspects are defined to consider:

- Definition: The index must meet the definition of fairness.
- Measurable: Fairness must be measurable quantitatively.
- Unfairness: The method should make it possible to detect which individuals are not treated fairly.
- Priorities/Weights: The method must allow weight assignation to give priority to some individuals over others.

- Control: Fairness control and possible index requirements for information on system data are also considered.
- Function f(X) requirements: The definition of the function f(X) meets the six aforementioned requirements (continuous, independent, mappable, scalable, implementable, and sensitive).

The indices analyzed are Jain's Fairness Index, Entropy Fairness, Max-Min Fairness, Proportional Fairness, Tian Lan's Index, and Envy-Based Fairness, which are compared in Table 12.

Table 12. Fairness indices comparison [45]

Index	Jain's	Proportional	Entropy	Tian Lan's	Max-Min	Envy-Based
Definition	Yes	Yes	No	Yes	Yes	Yes
Measurable	Yes	No	Yes	Yes	No	Yes
Unfairness	No	No	No	No	No	Yes
Priorities/Weights	No	Yes	No	No	Yes	No
Control	Centralized	Centralized	Centralized	Centralized	No	No
Function f(X) requirements	R1, R2, R3, R5, R6	No	R1, R2, R5, R6	R1, R2, R3, R6	No	R1, R2, R3, R4

The index that meets the most requirements is Jain's Fairness Index. The fairness calculation, according to Jain's Fairness Index (JFI) is calculated from the J function:

$$J = \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{N \cdot \sum_{n=1}^{N} r_n^2} \tag{1}$$

here r_n is the amount of the resource that is given to flow n for each of the N flows that make up the system. The values that the function can take are in the range [0, 1]. A value of J = 1 indicates that there is total fairness in the whole system, while a value of J = 0 indicates that the system is totally unfair. From this function, samples can be taken periodically to obtain a discrete function that depends on time and is able to analyze the trend of the system, obtaining the following equation:

$$J(t) = \frac{\left(\sum_{n=1}^{N} r_n(t)\right)^2}{N \sum_{n=1}^{N} r_n(t)^2}. \tag{2}$$

Although this method helps to give a general idea of the fairness of the system, not giving weights to the flows does not help us to find at which points the fairness is not fulfilled [46]. For example, it has been found that a difference between J = 0.9 and J = 0.8 has a different effect on the behavior of the different flows compared to a difference between J = 0.6 and J = 0.5; although in both cases, the difference is 0.1 [42]. Furthermore, the JFI assumes that all flows are equally capable of consuming the resources for which they are competing, although in reality, this may not be the case.

In this paper, a modification of the JFI is proposed for a Weighted Fairness (WF) calculation in the Enhanced-AATP, which considers the possibility of prioritizing flows.

The modifications proposed in this section for the improvement of the AATP over heterogeneous networks directly affect the base operation of the protocol, which is reviewed in the following section.

4.4 AATP Review

In this section, the Aggressive and Adaptative Transport Protocol (AATP) [14] is reviewed to provide a recap of the protocol operation and its mechanisms before introducing the improvements.

A specific Cloud company set high-level data exchange requirements between their servers' farms deployed in Storage Area Networks (SANs) from remote branches in different regions. The AATP protocol was designed to overcome the limitations of transport protocols over Long Fat Networks [3]. In order to achieve an optimal communication performance, the protocol was designed with the following characteristics:

- Connection-oriented: The objective is to avoid TCP's synchronicity and its rigid overhead. For this reason, the AATP proposes an in-band control of the packets over IP. Compared to TCP and UDP, the use of the Selective ACK and its control of the gaps (lost packets) provides an asynchronized controlled data exchange and lost packets are requested.
- Efficient: The Bandwidth Estimation process calculates the maximum bandwidth capacity of the communication, reaching the upper limit of the link during data transfer (>95%).
- Adaptable: The protocol reacts to a loss episode, reducing its throughput. After detecting the end of the loss episode, the protocol increases its throughput directly to reach 80% of the calculated link capacity. After that, the protocol increases it gradually to avoid causing congestion.
- Friendly aggressive: The protocol is focused on the maximum use of the capacity of the link (>80%), and the residual bandwidth is left for the other protocols (<20%).

For the initial BW estimation, 10 bursts are sent following the technique of packet trains (groups of two to 20 packets). The Source sends the packets of each block (burst) consecutively. After that, the Destination sends a confirmation message on receipt of the last packet of the block.

For each burst, the reception times of the first and last packets are recorded, and the difference (Qb_i) is calculated. Once information on the size of the packets (*b*) in bits and the packets that have been received (*N*) is obtained, the bandwidth of the link (BW_i) for that burst can be calculated

$$BW_i = \frac{b \cdot (N-1)}{Qb_i} \tag{3}$$

Once the Destination has received the ten bursts, ten values of the estimated bandwidth are obtained, using the arithmetic mean of these values as the definitive one (BW).

$$BW = \frac{\sum_{i=1}^{10} BW_i}{10} \tag{4}$$

At the beginning of the data transfer, the initial transmission speed (Sending Rate—SR) is set, fixing it at a percentage of the maximum bandwidth one (BW). It depends on the desired aggressiveness.

The data are sent by bursts, which are separated by a period ($\mathrm{T_{burst}}$) determined by the *RTT* or the minimum temporal resolution that can be offered by the operating system (*OS*) and the hardware (*HW*) on which the process operates. This time will be calculated in milliseconds or microseconds.

$$\mathrm{T_{burst}} = \max(OS/HW\ \text{res.}, RTT) \tag{5}$$

Once we know the speed at which the packets are initially sent (in packets per second) and have determined the separation between bursts, the number of packets sent in each burst is

$$\mathrm{Packets_{burst}} = SR * \mathrm{T_{burst}}\,. \tag{6}$$

The receiver decreases or increases the *SR* value depending on whether or not any packets have been lost in the last burst, which is calculated by

$$SR = \begin{cases} \dfrac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}, & LostPackets = FALSE \\ \dfrac{SR}{1 + 0.125 \cdot \dfrac{SR \cdot P_{size} \cdot 8}{BW}}, & LostPackets = TRUE \end{cases}, \tag{7}$$

where P_{size} is the size of the packet in bytes. When losses are detected, the higher the use of the link, the greater the reduction in the *SR*.

The value of the Inc_p, packet increment (packets), follows the philosophy of UDT [47] and uses a DAIMD (AIMD with decreasing increases) logarithmic function. This function is based on the usage of the estimated link capacity. On the one hand, when the *SR* value (converted to bps) is far from the estimated link capacity (meaning low efficiency), the increase of packets per each burst is high to achieve greater throughputs fast. On the other hand, as the link utilization keeps growing (meaning higher efficiency), and the increase of packets to be sent per each burst gets smaller. This strategy has been proved to be stable and efficient [48]. The Inc_p value is determined by

$$Inc_p = 10^{\log\left(BW - (SR \cdot P_{size} \cdot 8)\right) - M}, \tag{8}$$

causing a logarithmic growth of the *SR*. In relative terms of the link's capacity usage, the growth of the *SR* always experiences the same behavior (in a zero-loss scenario) thanks to the logarithmic function. P_{size}—in bytes—and 8 are conversion factors to get the *SR* value in bps. When the use of the link is low, the increase in the speed of transmission is greater, and vice versa.

The value *M* is a magnitude modifier that reduces the orders of magnitude of the power function. It is necessary to reduce these orders of magnitude because if they were not reduced, the final *SR* value would be enormous and vastly surpass the estimated bandwidth. Thus, the *M* value aims to adapt the number of packets to be increased per burst depending on the estimated bandwidth utilization. It is a design value that can be fine-tuned, but it should be large enough to moderate the results of Equation (8) and get reasonable *SR* values. As an example, the logarithmic function of UDT is always reduced by nine orders of magnitude. We do not use the same value because the UDT formula calculates packets per second, while the AATP formula calculates packets per burst. In our case, after several iterations of simulations, we found that a value of 7 was big enough to achieve high increases in *SR* values in situations where the estimated link utilization was below the 80% of its estimated value. When the link's utilization is equal to or greater than 80%, the order of magnitude to be reduced must decrease linearly as efficiency increases. This way, the M value helps to shape the *SR* logarithmic growth more aggressively at low-performance episodes and more steadily at high-performance ones. The calculation of M is based on the following formula

$$M = \begin{cases} 7, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} < 0.8 \\ (\dfrac{SR \cdot P_{size} \cdot 8}{BW} \cdot 10) - 1, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} \geq 0.8 \end{cases}, \quad (9)$$

being more aggressive when efficiency is worse than 80% to achieve high-throughput levels without saturating the connection. Figure 41 shows the growth of the *SR* value (in Mbps) over a 1 Gbps link in an ideal situation without losses and an estimated bandwidth of 1 Gbps.

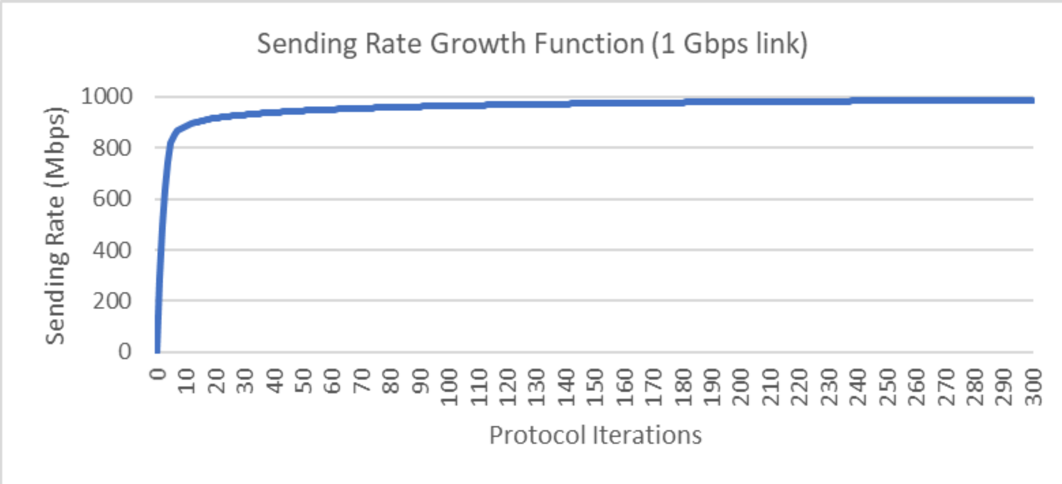


Figure 41. Sending Rate Growth Function over 1 Gbps link in an ideal situation without losses. Sending Rate (Blue).

Although the objectives of the protocol are clear (efficient, adaptative, and friendly aggressive) and accomplished, the AATP presents two main drawbacks if the protocol is used over Heterogeneous Long Fat Networks:

- Lossy episodes are all assumed as a congestion episode, without differentiating channel losses from congestion losses in heterogeneous scenarios. The efficiency of the protocol decreases because the Sending Rate is reduced in a channel loss episode and the time to recover the high-performance throughput directly affects its capability.
- There is no fair flow prioritization to fairly share the node network resources efficiently without causing losses and instabilities because there is no control between both flows.

4.5 Enhanced-AATP

The Enhanced-AATP is an improvement of the AATP protocol, which proposes solutions to solve the aforementioned drawbacks of the protocol over Heterogeneous Long Fat Networks. As stated before, the protocol AATP is efficient and adaptable in networks with high bandwidth and high delays (LFNs), but when it is used in heterogeneous networks, it is not able to differentiate distinct types of losses. Moreover, because of its aggressiveness, the protocol is unfair with other AATP flows.

The objective of the Enhanced-AATP is to adapt the protocol to achieve high performance over HLFNs and fairly sharing the network resources with the other flows that coexist in the same node. In this section, the operation of the Enhanced-AATP, together with its two new functionalities, is presented:

Loss differentiation mechanism. The protocol identifies if the loss episode is due to congestion or a channel failure through a Loss Threshold Decision maker (LTD), which bases its operation on a Jitter Ratio comparison.

Prioritized fair share of node network resources. This mechanism manages the Enhanced-AATP flows exchanged information with one node to achieve the deserved speed for each of them regarding their prioritization.

These imply a modification of the data exchange process of the protocol and its mechanisms, introducing the Loss Threshold Decision maker functionality and the Weighted Fairness mechanism.

4.5.1 Data Exchange Process

The Enhanced-AATP data exchange process is detailed to show the data process and how the metrics are measured. Figure 42 shows the protocol operation and how the information is sent and processed.

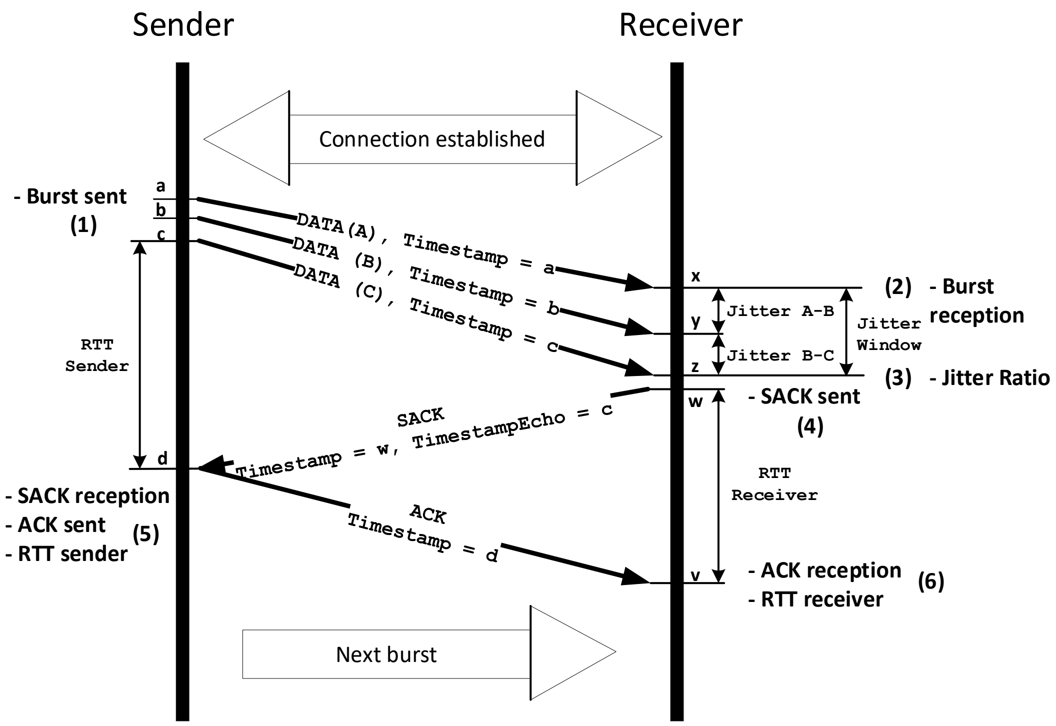


Figure 42. Enhanced-AATP data exchange process

Following the numbers (1) to (6) of Figure 3, the data exchange process of the Enhanced-AATP is explained:

(1) After the connection is established and the Estimated Bandwidth is measured, the Sending Rate is decided (% of the Estimated Bandwidth). The Sender sends a burst to the Receiver, recording the timestamp of each packet sent.
(2) The Receiver registers the time reception of each packet.
(3) After receiving the last packet of the burst, the Jitter Ratio is calculated

$$Jr = \frac{(t_{rxLastPkt} - t_{rxFirstPkt}) - (t_{txLastPkt} - t_{txFirstPkt})}{(t_{rxLastPkt} - t_{rxFirstPkt})} = \frac{(z-x)-(c-a)}{(z-x)}. \quad (10)$$

Given the aforementioned limitation of the case *Jr* = 0, the Enhanced-AATP will use the $smooth_{jr}$.

$$smooth_{jr} = (1 - \alpha) \cdot smooth_{jr} + \alpha \cdot Jr \quad (11)$$

where α is an arbitrary value between 0 and 1. Depending on it, the weight of the last iteration will count proportional to the defined value.

(4) At this point, the Receiver sends a SACK message confirming the reception of the burst and the Jitter Ratio.
(5) The Sender registers the Jitter Ratio and the reception time to calculate its *RTT*. At the same time, he replies to the Receiver with an ACK message to confirm that it will adjust the $\mathrm{Packets}_{\mathrm{burst}}$ to the new SR and $\mathrm{T}_{\mathrm{burst}}$ (*RTT*).

$$RTT_{Sender} = t_{rxSACK} - t_{txLastPkt} = d - c \quad (12)$$

(6) The Selective ACK is acknowledged. The Receiver records the reception time to calculate its *RTT*. This information is taken for network statistics in case a transfer is initiated in the other way. The next burst is sent.

$$RTT_{Receiver} = t_{rxACK} - t_{txSACK} = v - w \quad (13)$$

4.5.2 Loss Differentiation Mechanism—Loss Threshold Decision Maker (LTD)

After detailing the data exchange process, the operation of the loss differentiation mechanism is defined. The Enhanced-AATP introduces the Loss Threshold Decision maker (LTD) as a way to distinguish the cause of the losses produced during the communication. At this point, given the HLFNs characteristics, it is necessary to obtain a reference metric that is not affected by the high delay of this type of networks and that is asynchronous to the endpoints. The metric used for the loss decision is the smoothed Jitter Ratio ($smooth_{jr}$), which is defined in (11).

Since the Jitter Ratio is the reference metric to check the origin of a loss episode, it is necessary to determine the threshold. As soon as a queue is formed in the bottleneck device due to a saturation episode, it is detected by the Destination node through the value of the Jr, thus preventing an overflow in the buffer and packet discard. The Jr value calculation is increased because the time between packet arrivals at the Destination is greater as a result of the formation of queues at the bottleneck. Following the network's operation process, if the bottleneck device is fully saturated after a new burst is sent and it starts to drop packets; these additional packets will provoke an overflow in the intermediate device, causing a congestion loss episode.

In the case of the aforementioned JTCP and JSCTP, the *Jr* is fixed to one packet over the congestion window because the basis is TCP. In the case of the Enhanced-AATP, this design value is different because of the way the protocol operates as it can increase its Sending Rate by more than one packet per burst. The Loss Threshold Decision maker (LTD) is defined by the number of increased packets in the burst over the total number of packets of the burst.

$$LTD = \frac{\#Inc_p}{\#Packets_{burst}} \quad (14)$$

The reason for this *LTD* proposal is because in each iteration without losses, a number of new packets ($\#Inc_p$) are included in the burst ($\#Packets_{burst}$). If a congestion loss occurs, it means that the buffer of the bottleneck is overflowing as a result of the new packets included in the last burst.

The defined LTD is compared to the $smooth_{jr}$. This comparison will differentiate when a loss episode is because of a misfunction of the channel or the congestion in the network or when the $smooth_{jr}$ rises as the intermediate router generates a packet queue caused by saturation. When the $smooth_{jr}$ remains stable because there are no packet queues in the intermediate router (no saturation), the channel has most likely suffered a failure (fading, interference).

Depending on the situation detected, the Enhanced-AATP reacts differently to the loss episode. Four different states are defined, which are detailed in Table 13 and described below.

Table 13. Enhanced-AATP operation states

State	Loss Episode	$Smooth_{jr}$ vs. LTD	Process	Actions
S0	No	$smooth_{jr} \leq LTD$	Sending Rate ↑	No loss episode Throughput increased
S1	No	$smooth_{jr} > LTD$	Sending Rate ↗	No loss episode Jr indicates possible congestion Throughput moderately increased
S2	Yes	$smooth_{jr} \leq LTD$	Sending Rate ≡	Loss episode due to channel Throughput kept Lost packet requested
S3	Yes	$smooth_{jr} > LTD$	Sending Rate ↓	Loss episode due to congestion Throughput reduced Lost packet requested

(S0) **No loss episode and $smooth_{jr} \leq LTD$.** The sending rate is increased, depending on the efficiency registered.

$$SR = \frac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}};$$
$$Inc_p = 10^{\log(BW-(SR \cdot P_{size} \cdot 8))-M};$$
$$M = \begin{cases} 7, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} < 0.8 \\ (\dfrac{SR \cdot P_{size} \cdot 8}{BW} \cdot 10) - 1, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} \geq 0.8 \end{cases}; \tag{15}$$

(S1) **No loss episode and $smooth_{jr} > LTD$.** On receipt of this information, the sending rate is moderately increased (M = 9), as if the sending rate was reaching the limit.

$$SR = \frac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}};$$
$$Inc_p = 10^{\log(BW-(SR \cdot P_{size} \cdot 8))-9}; \tag{16}$$

(S2) **Loss episode and $smooth_{jr} \leq LTD$, meaning a channel loss episode.** The sending rate is kept at the same speed. As soon as the communication starts working again without losses, the lost packets are requested again.

$$SR = \frac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}; \quad Inc_p = 0 \tag{17}$$

(S3) **Loss episode and $smooth_{jr}$ > LTD, meaning a congestion loss episode.** The sending rate is reduced. As soon as the communication starts working again without losses, the sending rate is increased.

$$SR = \frac{SR}{1 + 0.125 \cdot \frac{SR \cdot P_{size} \cdot 8}{BW}}; \tag{18}$$

4.5.3 Fairness Mechanism

In order to procure a fair share of network resources from the destination, the fairness mechanism is presented. The adopted Fairness index is the Jain Fairness Index (JFI). The only requirement that is not fulfilled by the JFI is the weighted priorities of the flows. As a result of this reason, the JFI is modified to provide it to the Enhanced-AATP. The metrics to consider in the Weighted Fairness calculation are:

- Internal factors.
  - Number of Flows (N).
  - Priority of each flow n (p_n). Its value can be any integer between 1 and 8 (both inclusive). This way, the priority value can be mapped to other QoS classifications (IP Precedence and 802.1p).
- External factors.
  - Estimated Bandwidth (BW) [bps].
  - Network status (characteristics, statistics, and behavior).
- Real throughput of a flow n (V_n) [bps]. Where SR is the packets sent per second [packets/second], P_{size} is the packet size [Bytes] and 8 to convert bytes to bits.

$$Vn = SR \cdot P_{size} \cdot 8 \tag{19}$$

- Allocated throughput for a flow n (Vm_n) [bps]. This formula provides the allocated throughput assigned to the flow n regarding its priority (p_n), the sum of all priorities ($\sum_{i=1}^{N} p_i$), and the available bandwidth (BW).

$$Vm_n = \frac{p_n}{\sum_{i=1}^{N} p_i} \cdot BW \tag{20}$$

- Efficiency (r_n) of a flow n. It determines the percentage of the throughput achieved by the flow regarding the allocated speed.

$$r_n = \frac{V_n}{Vm_n} \tag{21}$$

With these defined metrics, the Weighted Fairness (WF) can be calculated as follows, being the JFI the base:

$$WF = \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{N \cdot \left(\sum_{n=1}^{N} r_n^2\right)} = \frac{\left(\sum_{n=1}^{N} \frac{V_n}{Vm_n}\right)^2}{N \cdot \left(\sum_{n=1}^{N} \left(\frac{V_n}{Vm_n}\right)^2\right)} = \frac{\left[\sum_{n=1}^{N} \frac{V_n}{\frac{p_n}{\sum_{i=1}^{N} p_i} \cdot BW}\right]^2}{N \cdot \left[\sum_{n=1}^{N} \left(\frac{V_n}{\frac{p_n}{\sum_{i=1}^{N} p_i} \cdot BW}\right)^2\right]}. \tag{22}$$

If the WF value is 1, there is a fair share of the resources. Otherwise, if the WF value is 0, the system is not working properly. In contrast to the JFI, this way of calculating the fairness considers the real throughput of each flow, the priority provided to these flows, and their allocated throughput decided by the system, considering the estimated bandwidth.

The protocol is able to modify its operations and flow behavior because of the WF and its performance.

The main modification is the number of packets to be increased or reduced at the time of calculating the Sending Rate (no lossy episode; S0 and S1) to adapt the flow to the deserved speed. It is done with the Adapter ($\boldsymbol{\Delta_n}$).

$$SR = \frac{(T_{burst} \cdot SR) + Inc_p + \Delta_n}{T_{burst}}; \tag{23}$$

$$\Delta_n = A \log_2 \left(\frac{Vm_n}{V_n}\right), \tag{24}$$

where Vm_n is the allocated throughput of the flow, V_n is the real throughput of the flow, and A is the Transcendence factor. A logarithmic function is used to shape three different behaviors. Firstly, if the current throughput of the flow is below its maximum, packets per burst should be increased. This is achieved because, in this case, $\frac{Vm_n}{V_n} > 1$ so $\log_2\left(\frac{Vm_n}{V_n}\right) > 0$. Secondly, if the current throughput of the flow is above its maximum, the number of packets per burst should decrease to achieve fairness. This is also possible because when $\frac{Vm_n}{V_n} < 1$, $\log_2\left(\frac{Vm_n}{V_n}\right) < 0$. Thirdly, if the throughput of the flow is equal to its maximum, it behaves fairly, so packets per burst should not be increased or decreased. This behavior is also satisfied because when $\frac{Vm_n}{V_n} = 1$, $\log_2\left(\frac{Vm_n}{V_n}\right) = 0$. A simple quotient $\left(\frac{Vm_n}{V_n}\right)$ could not be used, because the result would always be positive, so packets per burst would always increase. A subtraction $(Vm_n - V_n)$ would satisfy the three behaviors, but it would depend on the absolute values of throughput instead of relative values of utilization, which would result in excessive values of Δ_n. For this reason, the use of a logarithmic function was chosen.

Despite that, the values obtained in the logarithmic function might be too small when compared to the values of Inc_p, making the fairness mechanism insignificant when compared to the congestion control. Thus, the Transcendence factor A is needed to give relevant importance to the fairness mechanism, with a comparable influence on congestion control. The higher the value of A, which should be related to the WF, the higher the value of Δ_n. This implies a more aggressive increase in the Sending Rate or a decrease when Δ_n is negative and $|\Delta_n| > Inc_p$, reducing the convergence time to balance the weighted distribution of resources. This fact can affect the stability of the system due to sudden changes.

The value of *A* is a design parameter that can be adjusted. The greater the value is, the greater the importance of the fairness mechanism over the congestion control. In our case, the A factor is defined by

$$A = \frac{\gamma}{N} * BW^{1+\beta} \cdot (WF - 1)^2, \tag{25}$$

thus, relating it to the WF, the number of flows (*N*), and the estimated bandwidth (*BW*). The *A* factor is directly proportional to the estimated bandwidth because more packets can be sent per burst at a higher bandwidth. Moreover, it is inversely proportional to the number of flows because the packets to be increased or decreased per burst should be distributed among all flows. It is related to the WF too, in a way that when the system is behaving more fairly (WF value close to 1), the fairness mechanism has less relevance, while in unfair scenarios (WF value not close to 1), it has a greater impact.

γ and β are design parameters that help to fine-tune the degree of aggressiveness of the Transcendence factor (*A*). $\gamma = 1$ and $\beta = 0$ are standard values to relate the *A* factor directly to *BW* and inversely to *N*. In our case, after several iterations of simulations, $\gamma = 5$ and $\beta = 0.05$ are the used values in our tests that provide a suitable balance between the Inc_p and Δ_n parameters as well as faster convergence in fairness.

Instability occurs when the designation of a Sending Rate is higher or lower than the ideal one, thus requiring a new iteration to achieve the ideal speed of each flow. The degree of instability is related to the suddenness of the change in the Sending Rate. If the value of *A* is not high, the convergence time is longer, since slight modifications are made on the *SR*. However, the probability of instability in the system is reduced since there are no sudden changes in the Sending Rate, causing a fine-tuning.

Once the Weighted Fairness mechanism is introduced, the congestion control needs to slightly modify Equations (7)–(9) as each flow aims to reach its allocated throughput (Vm) and not the total Bandwidth of the link (*BW*).

$$SR = \begin{cases} \dfrac{(T_{burst} \cdot SR) + Inc_p + \Delta_n}{T_{burst}}, & S0|\,S1|\,S2 \\ \dfrac{SR}{1 + 0.125 \cdot r}, & S3 \end{cases} \tag{26}$$

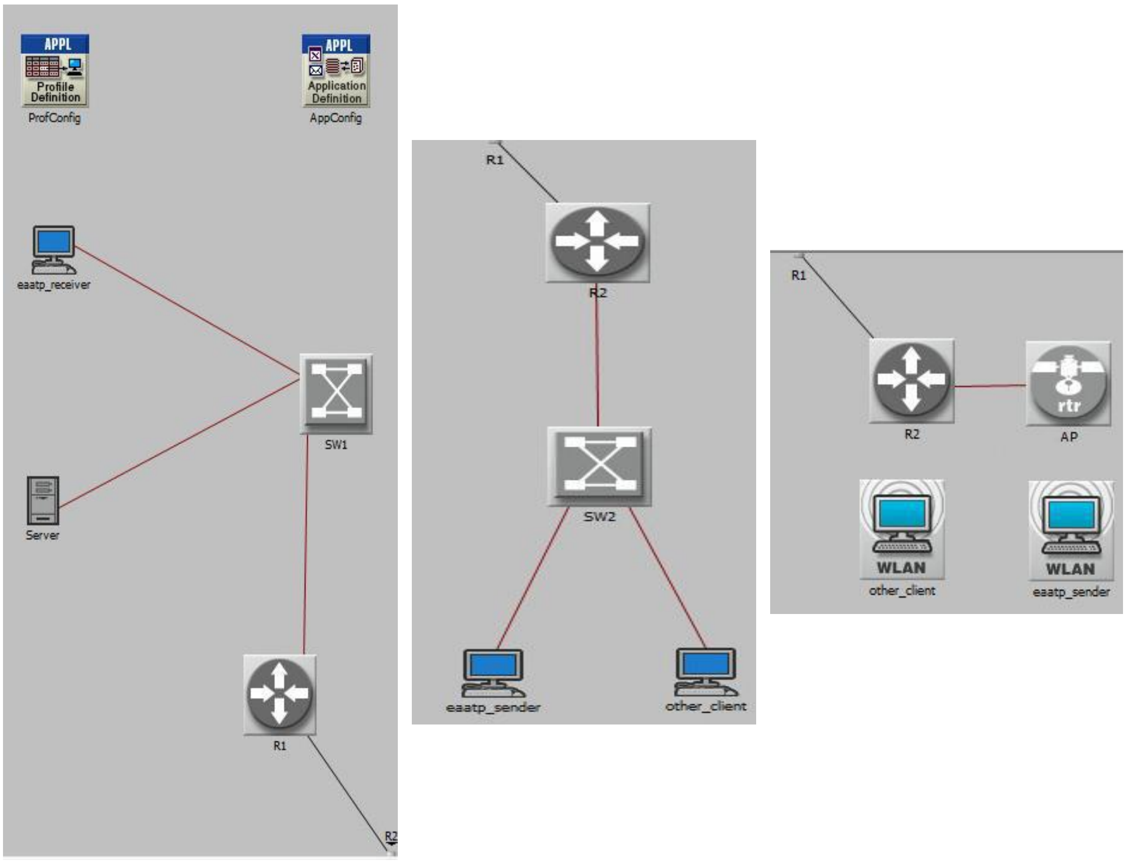
$$Inc_p = \begin{cases} 10^{log(Vm-V)-M}, & S0 \\ 10^{log(Vm-V)-9}, & S1 \\ 0, & S2 \end{cases} \tag{27}$$

$$M = \begin{cases} 7, & r < 0.8 \\ (r \cdot 10) - 1, & r \geq 0.8 \end{cases} \tag{28}$$

4.6 Enhanced-AATP Evaluation and Performance Simulations

In this section, the Enhanced-AATP protocol is simulated and evaluated by the Steelcentral Riverbed Modeler [15]. The new functionalities are tested through different experiments to validate its operation and performance.

The Riverbed Modeler testbed scenario is detailed in Figure 43, which simulates a Long Fat Network with different possible configurations. In most scenarios, the bottleneck has a bandwidth of 148.608 Mbps (OC-3 link), and the maximum bottleneck capacity tested in the simulations is 1 Gbps. The packet size is fixed at the MTU of the media technology, and the propagation delay is the speed of light in the backbone. The minimum base RTT of the WAN link is 20 ms, so the Bandwidth-Delay Product (BDP) is always greater than 12,500 bytes (10^5 bits)).



(a) (b) (c)

Figure 43. Testbed scenario over a Steelcentral Riverbed Modeler. (a) Storage Area Network (SAN) side and Client edge with (b) wired endpoints or (c) short-range wireless endpoints

Although the connection between both routers consists of a single link, distinct random generation seeds are defined in the simulator to introduce variability in the network. The environment is configured to simulate the characteristics and behavior of a Heterogeneous Long Fat backbone, depending on the requirements of the experiment (different speeds, random losses, delay depending on the distance).

The Testbed is composed of a Storage Area Network (SAN) region and a Client edge. In the SAN side, there are servers from the server farm connected through a wire to the gateway that gives access to the WAN (a), and in the Client edge, two nodes are deployed. One is an Enhanced-AATP node (eaatp_sender), and the other node (other_client) is introduced to provoke different scenarios (different types of cross-traffic, interference generation). The cross-traffic can be a TCP flow with a Variable Bit Rate (VBR) or a UDP flow with a Constant Bit Rate (CBR). These nodes from the Client side can be connected through a wire (b) or a short-range wireless (WiFi—802.11n) (c), while the speed and Ethernet technology can be varied depending on the experiment and the objective to be achieved.

The experiments and their objectives are listed below:

1. **Maximum performance in wireless.** The objective is to verify the efficiency of the protocol over wireless. This experiment exhibits the maximum performance of the Enhanced-AATP protocol over different wireless speed connections without other flows or random losses. The scenario is Figure 43a connected to Figure 43c.

2. **Random loss episode detection.** The objective of this experiment is to demonstrate the channel loss identification and the proper operation of the protocol in this specific case (Table

3—(S2) Channel loss). This experiment shows that the protocol identifies the different random loss episodes occurred and reacts by keeping its Throughput and Sending Rate. The scenario is Figure 43a connected to Figure 43c.

3. Loss Threshold Decision maker (LTD). The objective is to prove the correct differentiation of distinct types of losses. Moreover, the optimal LTD value is evaluated. In this experiment, distinct cross-traffic (load) and different random losses are introduced. The operation of the protocol and the LTD performance are presented, differentiating congestion losses and channel errors that occurred during the communication. The scenario is Figure 43a connected to Figure 43c.

4. Fairness mechanism. The objective of this experiment is to demonstrate the fair share of the network resources through the implementation of the weighted fairness mechanism. In this experiment, different flows are set in order to share the media. The scenario is Figure 43a connected to Figure 43b.

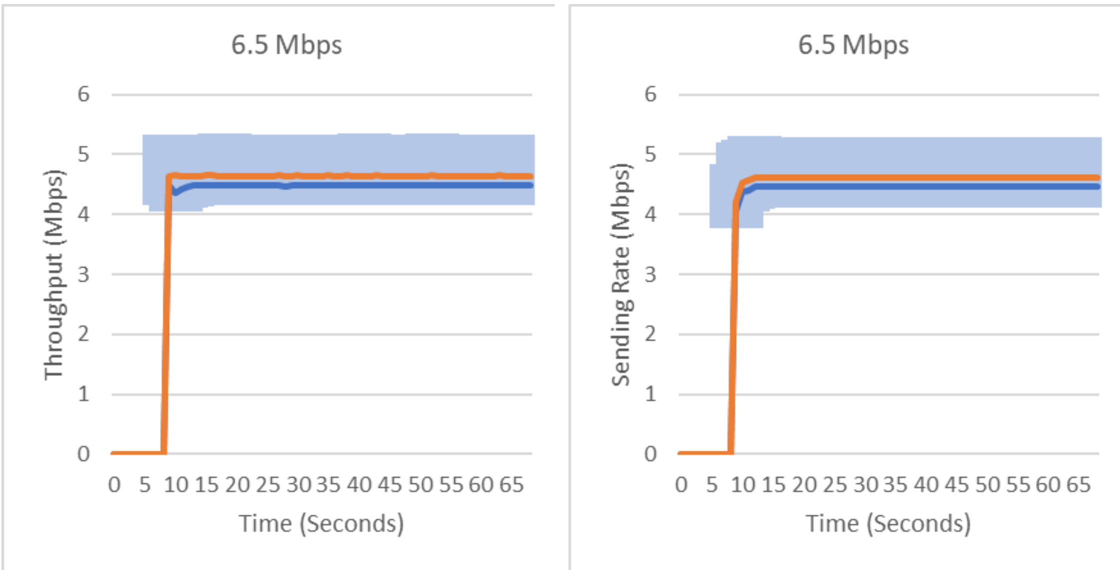
5. Enhanced-AATP performance comparison. The objective of this last experiment is to compare the Enhanced-AATP performance (throughput, one-way delay and losses) with the modern protocols analyzed. A specific scenario is deployed.

The outcomes shown are the mean results of different executions (around 1000 in total, 30 simulations run per test, except the LTD value test, which implied 650 simulations), assuring a maximum error deviation of ±1.5% with a confidence interval of 99%.

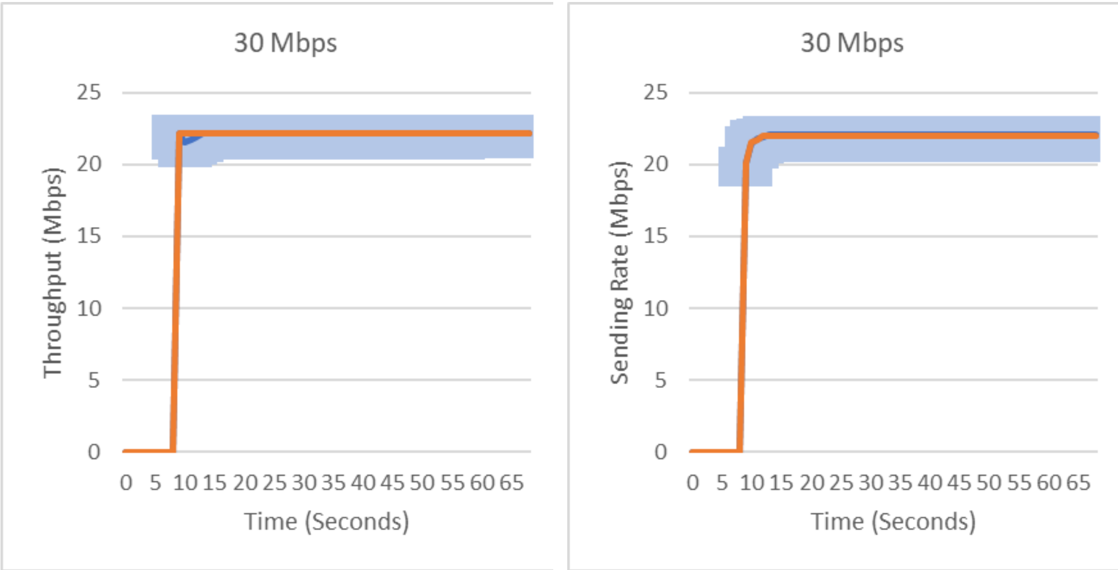
4.6.1 Maximum Performance in Wireless Connections

The performance of the Enhanced-AATP over heterogeneous networks without cross-traffic nor random losses is studied in this set of tests, where the bottleneck is the wireless section at different link speeds. The scenario is Figure 43a connected to Figure 43c.

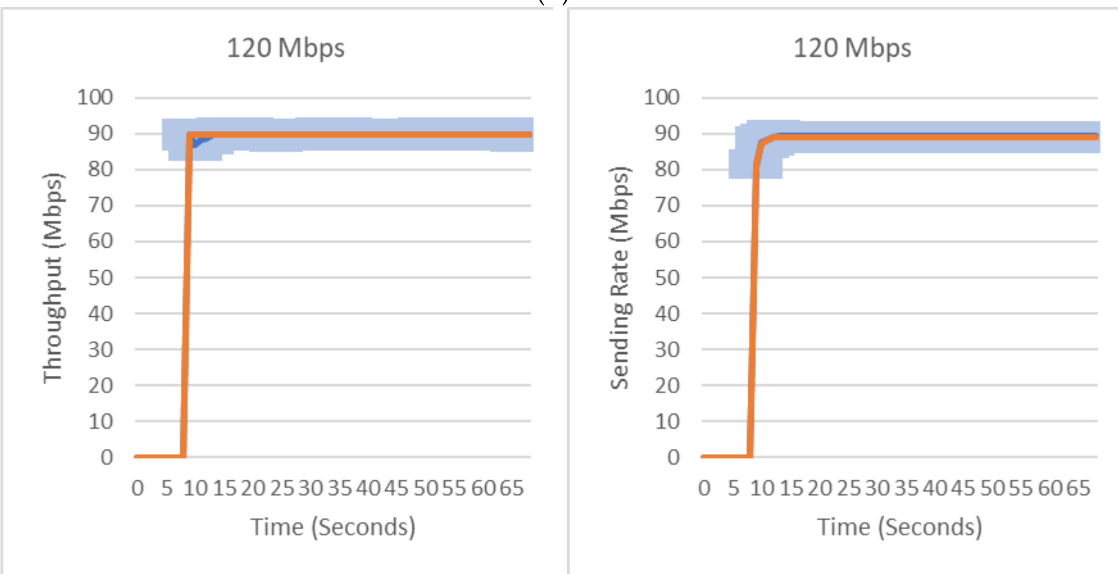
Figure 44 exhibits the Enhanced-AATP performance, showing the average (orange) and the median with second and third quartiles (blue) of the Throughput and Sending Rate over different link speed scenarios. The selected wireless link speeds are 6.5 Mbps (a), 30 Mbps (b), 120 Mbps (c), 300 Mbps (d), and 600 Mbps (e). The duration of the transfer is 60 s.



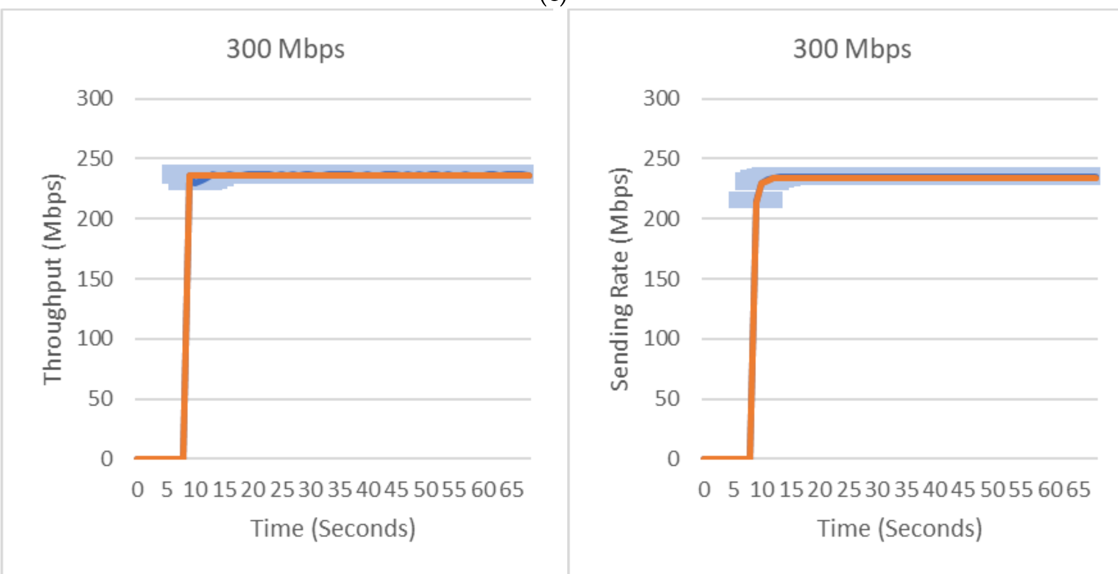
(a)


30 Mbps
Throughput (Mbps)
Time (Seconds)
30 Mbps
Sending Rate (Mbps)
Time (Seconds)

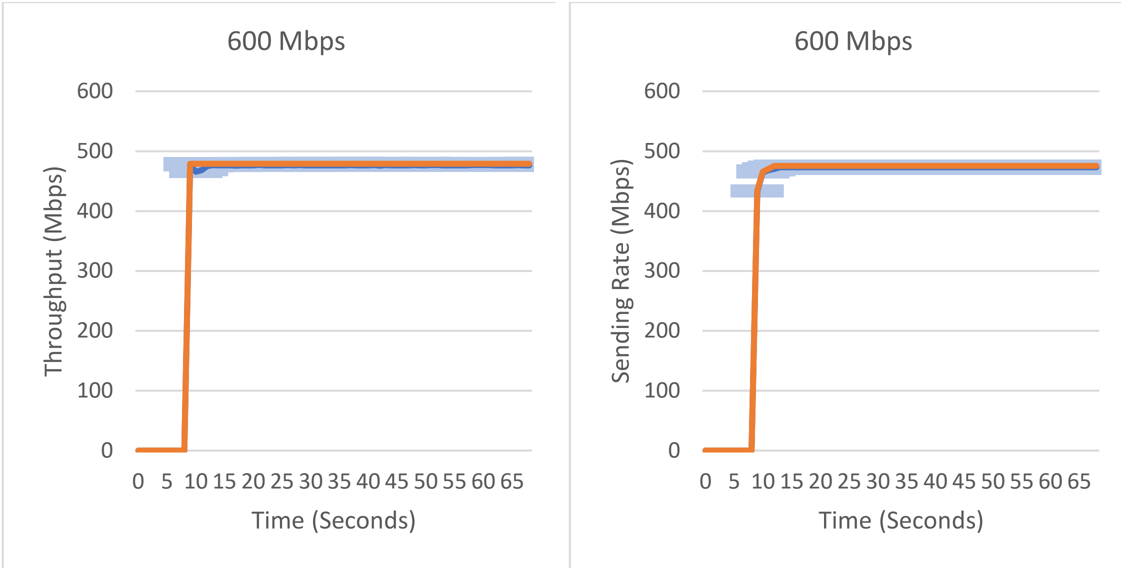
(**b**)


120 Mbps
Throughput (Mbps)
Time (Seconds)
120 Mbps
Sending Rate (Mbps)
Time (Seconds)

(**c**)


300 Mbps
Throughput (Mbps)
Time (Seconds)
300 Mbps
Sending Rate (Mbps)
Time (Seconds)

(**d**)



(e)

Figure 44. Enhanced-AATP performance over different wireless networks without cross-traffic and random losses. Average Throughput and Sending Rate (orange), the median with quartiles (blue). (a) 6.5 Mbps link capacity, (b) 30 Mbps link capacity, (c) 120 Mbps link

From Figure 44, the summary in Mbps is extracted in Table 14 to compare them with the maximum capacity of the link in each bottleneck situation. Given the limitation of the CSMA/CA, as Apoorva Jindal and Konstantinos Psounis presented in [49], in any realistic topology with geometric constraints because of the physical layer, the CSMA-CA is never lower than 30% of the optimal used to access the media in wireless. In the case of Enhanced-AATP, the maximum bandwidth used in these links goes from 72% to 80%, keeping to the aforementioned limitation and working with higher efficiency over high-bandwidth links due to the design of the protocol for Long Fat Networks.

Table 14. Enhanced-AATP performance over different wireless networks

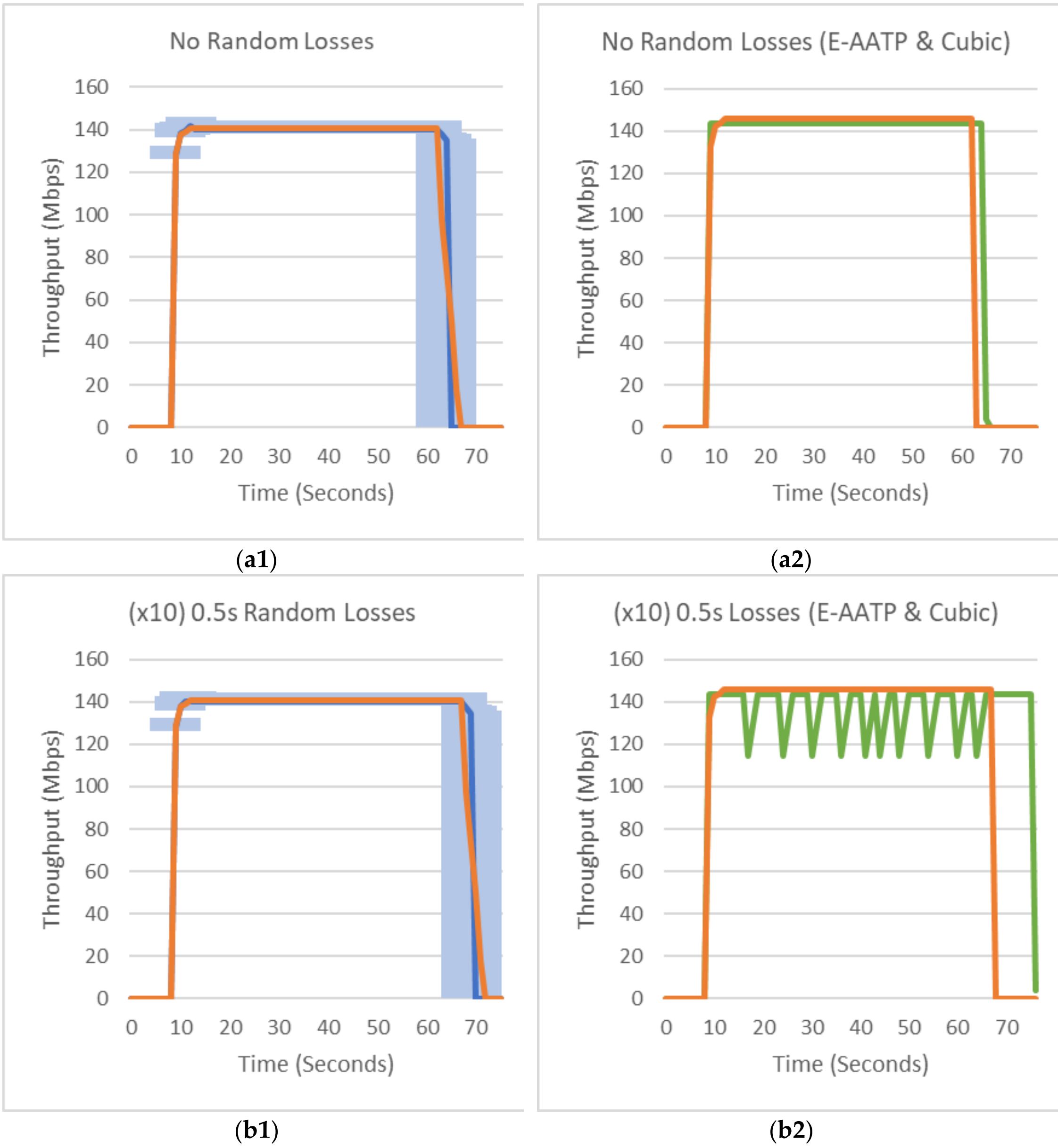
Link Capacity (Mbps)	Average Sending Rate (Mbps)	Efficiency (% over Maximum Link Capacity)
6.5	4.68	72.03%
30	22.31	74.37%
120	90.47	75.39%
300	237.89	79.30%
600	482.71	80.45%

4.6.2 Random Loss Episode Detection

In order to check the Enhanced-AATP mechanism to detect random losses, distinct tests are run simulating loss episodes of different periods of time. In this case, the bottleneck is placed on the wired section (OC-3 (148.608 Mbps)) to avoid the effect of the CSMA/CA shown in the previous set of tests, without affecting the loss detection mechanism and its performance. The scenario is Figure 43a connected to Figure 43c.

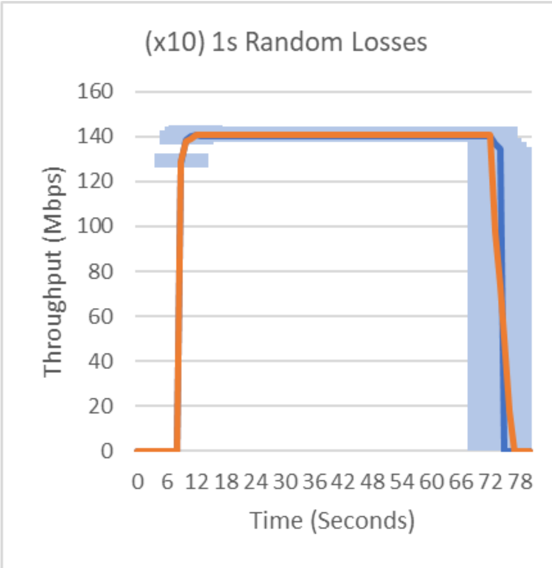
In order to depict the Enhanced-AATP's random loss identification and behavior using the LTD mechanism, its operation is shown together with other TCP protocol's behavior without the LTD maker (TCP Cubic). The main goal of this comparison is to show how the Enhanced-AATP identifies the channel losses occurred (fadings with 100% of losses), while TCP introduces load to the network and also reacts to the fading, reducing its throughput as it was caused due to a congestion in the network. It also affects the transmission time.

Figure 45 illustrates the Throughput obtained by the Enhanced-AATP, average (orange), and the median with second and third quartiles (blue) and TCP Cubic (green), and the time required to send 1 GB in different channel loss situations. First, a case without losses is shown (a) to be the reference in time spent and Throughput performances. After that, the random loss episodes experiments are 10 random losses of 0.5 s (b), 10 random losses of 1 s (c), and 5 random losses of 2 s (d).

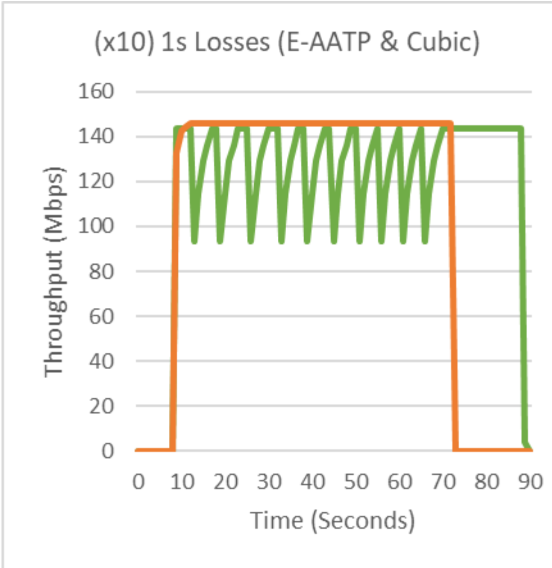


(a1) (a2)

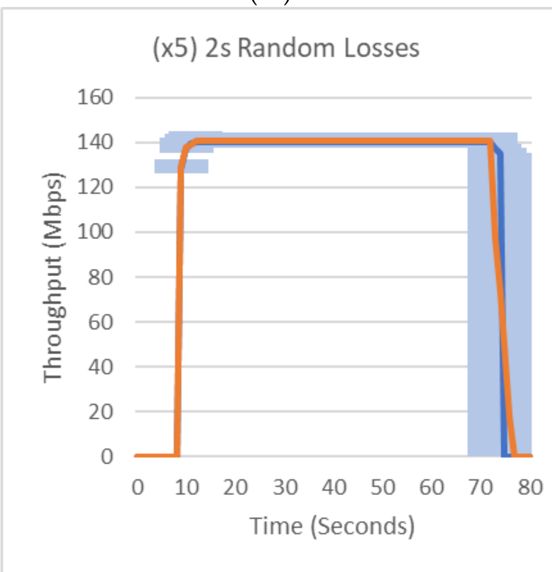
(b1) (b2)



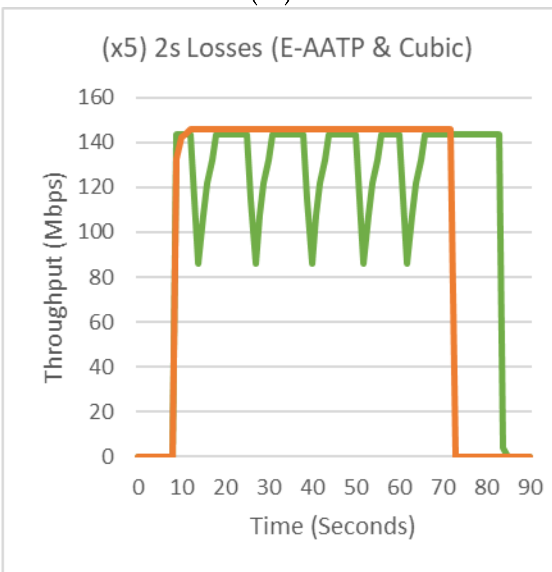
(c1)



(c2)



(d1)



(d2)

Figure 45. Enhanced-AATP performance with random losses. Enhanced-AATP Throughput (orange), its median with quartiles (blue) and TCP Cubic Throughput (green). (a1) No random loss—Averaged Enhanced-AATP, (a2) No random loss—Enhanced-AATP and TCP Cubic, (b1) 10 random loss episodes of 0.5 s—Averaged Enhanced-AATP, (b2) 10 ran-dom loss episodes of 0.5 s—Enhanced-AATP and TCP-Cubic, (c1) 10 random loss episodes of 1 s—Averaged En-hanced-AATP, (c2) 10 random loss episodes of 1 s—Enhanced-AATP and TCP-Cubic, (d1) 5 random loss episodes of 2 s—Averaged Enhanced-AATP and (d2) 5 random loss episodes of 2 s—Enhanced-AATP and TCP-Cubic

Packet queues are not formed because no bottleneck saturation occurs, so the Jr value is not increased. When a channel loss episode occurs (100% of losses), through the $LTD - smooth_{jr}$ comparison, the protocol identifies it and keeps the Throughput achieved before the losses, as shown in the graphs above. Figure 45 shows the behavior of the Enhanced-AATP protocol in different random loss situations.

- Figure 45a is the reference performance for the protocol because no losses occur. The Enhanced-AATP spends 54 s with a mean throughput of 145.36 Mbps. TCP Cubic spends 57 s with a mean throughput of 140.96 Mbps.
- In Figure 45b, 10 episodes of 0.5 s of random losses are introduced, being a total channel loss time of 5 s. In Figure 45(b1), the protocol keeps the throughput (145.38 Mbps) and spends approximately 5 more seconds than the reference. In Figure

45(b2), the Enhanced-AATP operation is shown together with the TCP protocol (TCP-Cubic), which modifies its throughput (135.03 Mbps) due to the losses, spending 11 s more.

- In Figure 45c, 10 episodes of 1 s of random losses are introduced, being a total channel loss time of 10 s. In Figure 45(c1), the protocol keeps the throughput (145.38 Mbps) and spends approximately 10 more seconds than the reference. In Figure 45(b2), the Enhanced-AATP operation is shown together with the TCP protocol (TCP-Cubic), which modifies its throughput (129.29 Mbps) due to the losses, spending 24 s more.
- In Figure 45d, 5 episodes of 2 s of random losses are introduced, being a total channel loss time of 10 s. In Figure 6(d1), the protocol keeps the throughput (145.35 Mbps) and spends approximately 10 more seconds than the reference. Figure 6(d2) shows the Enhanced-AATP operation together with the TCP protocol (TCP Cubic), which modifies its throughput (131.38 Mbps) due to the losses, spending 19 s more.

From Figure 45, the success detection rate for 100% channel losses (fading) is 1 because, compared with the TCP behavior shown, the Enhanced-AATP protocol keeps its throughput during a channel loss episode. If the detection was not successful (<1), the Enhanced-AATP's throughput would experience decreasing episodes. Moreover, the performance of the Enhanced-AATP (Mbps) and the average transmission period (seconds) for each random loss episode test are extracted in Table 15. In addition, TCP Cubic's performance (Mbps) and transmission period (seconds) are shown. Moreover, the time noted between parentheses in both Transmission period fields indicates the extra time dedicated by the protocol in reference to the case without random losses.

Table 15. Enhanced-AATP and TCP Cubic performance with different random loss episodes

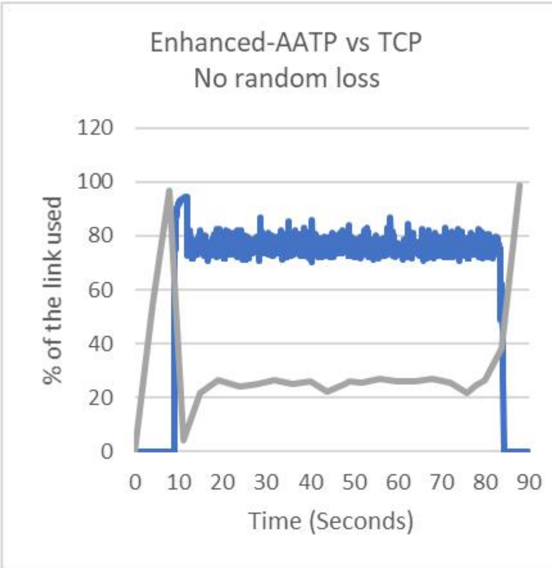
Loss Episode	**Enhanced-AATP (Mbps)**	**Transmission Period Enhanced-AATP (Seconds)**	**TCP Cubic (Mbps)**	**Transmission Period TCP Cubic (Seconds)**
No random losses	145.36	54	140.96	57
10 random loss episodes of 0.5 s	145.38	59 (+5 s)	135.03	68 (+11 s)
10 random loss episodes of 1 s	145.38	64 (+10 s)	129.29	81 (+24 s)
5 random loss episodes of 2 s	145.35	64 (+10 s)	131.38	76 (+19 s)

In the case of the Enhanced-AATP, the average transmission period is equal to the average transmission period without loss episodes plus the channel losses' duration, demonstrating the high performance (> 97%) operation of the protocol during distinct channel loss situations (Figure 45b–d). The Enhanced-AATP depicted together with TCP Cubic provides a view about how the fadings affect the performance of TCP protocols (in (Figure 45 (c2), more than a 10 s difference is noted between the Enhanced-AATP and TCP Cubic). Thanks to this experiment, the proper operation of the Loss Threshold Decision maker mechanism to identify the random losses of the channel is demonstrated.

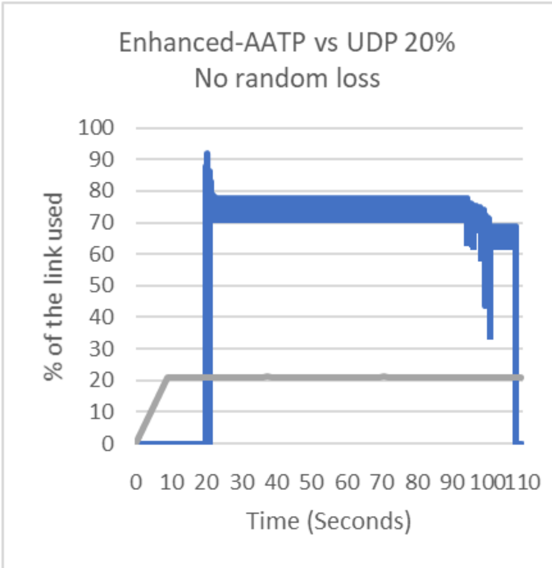
4.6.3 Loss Threshold Decision Maker (LTD)

In this experiment, the $LTD - smooth_{jr}$ comparison is tested to demonstrate the capacity of the Enhanced-AATP to differentiate the type of loss episode occurred. Distinct and varied loss episodes occur during the simulations run with best-effort TCP/UDP cross-traffic load is introduced. The control over the cross-traffic is limited because of simulator restrictions to manage the generic TCP (traffic trying to reach the maximum possible throughput, but with a Variable Bit Rate (VBR) traffic behavior profile due to its congestion control) and UDP flows (with a Constant Bit Rate (CBR) traffic behavior profile). The scenario is Figure 43a connected to Figure 43c.

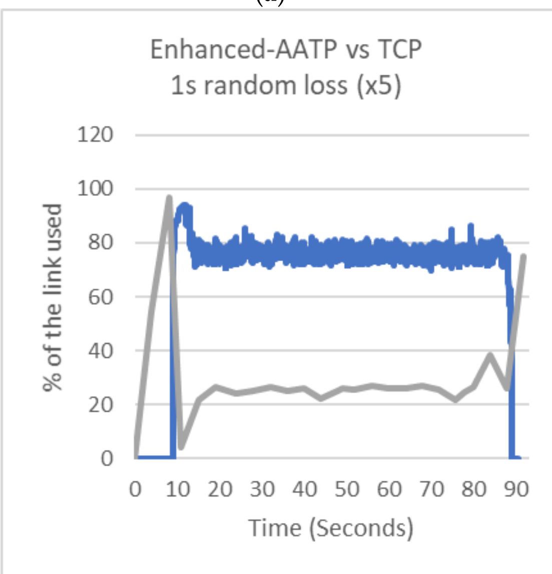
Figure 46 shows the performance of the Enhanced-AATP with random losses episodes and cross-traffic sending a file of 1 GB, showing the average percentage of the link used by the Enhanced-AATP (blue) and the average percentage of the link used by the cross-traffic (gray). The experiments simulated are: no random losses with TCP VBR cross-traffic (a), no random losses with 20% UDP CBR cross-traffic (b), 1-s random loss (×5) with a TCP VBR cross-traffic flow (c), 1-s random loss (×5) with a 20% UDP CBR cross-traffic flow (d), 2-s random loss (×5) with a TCP VBR cross-traffic flow (e), and 2-s random loss (×5) with a 20% UDP CBR cross-traffic flow (f).



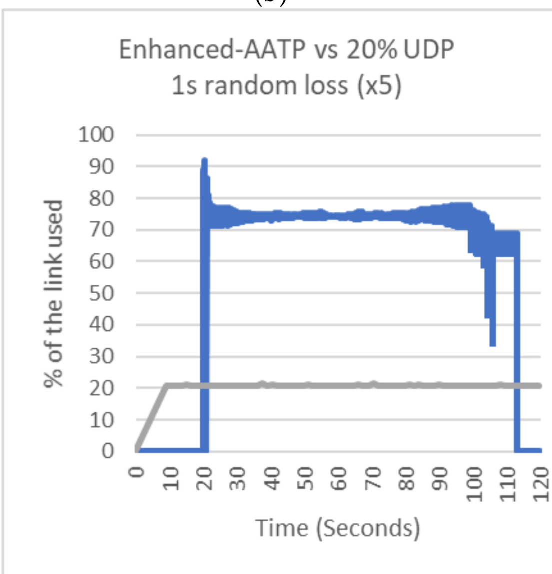
(a)



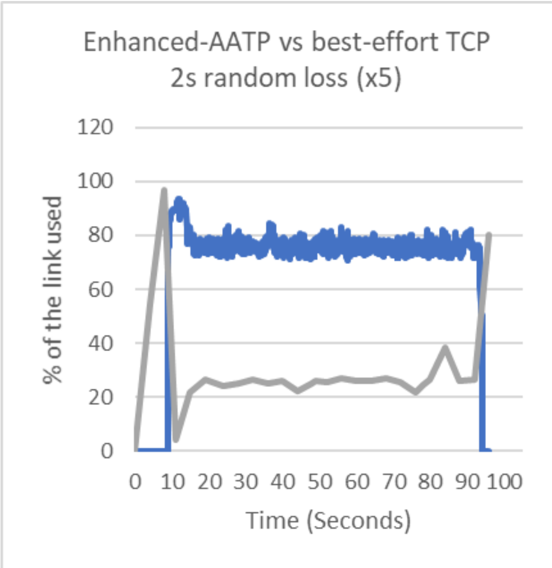
(b)



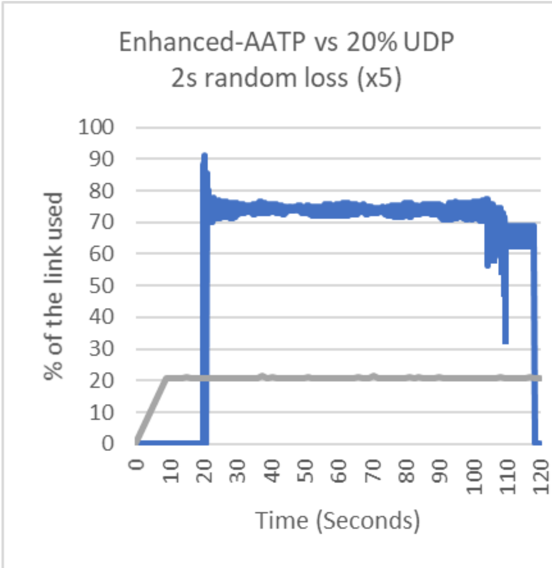
(c)



(d)



(**e**)



(**f**)

*Figure 46. Enhanced-AATP performance with TCP/UDP cross-traffic and random losses. Average percentage of the link used by the Enhanced-AATP (blue), Average percentage of the link used by the cross-traffic (gray). (**a**) No random loss episodes with TCP cross-traffic—11.65% of average losses, (**b**) No random loss episodes with 20% UDP cross-traffic—14.36% of average losses, (**c**) Five random loss episodes of 1 s with TCP cross-traffic—16.11% of average losses, (**d**) Five random loss episodes of 1 s with 20% UDP cross-traffic—18.48% of average losses, (**e**) Five random loss episodes of 2 s with TCP cross-traffic—20.14% of average losses, and (**f**) Five random loss episodes of 2 s with 20% UDP cross-traffic—22.29% of average losses.*

Figure 46 depicts the result of the Enhanced-AATP in distinct cross-traffic loads and random losses situations. The aggressive behavior of the VBR and CBR flows in Riverbed act without considering the status of the network.

- Figure 46a shows the result of the experiment when the Enhanced-AATP faces a TCP flow (trying to get the maximum bandwidth aggressively) without random losses. The TCP cross-traffic reaches around 24% of the residual bandwidth left by the Enhanced-AATP because of its aggressiveness, although TCP is trying to reach more. The improved protocol tries to take the maximum bandwidth possible, as the TCP flow tries to obtain the maximum bandwidth but in a less aggressive form, causing minor fluctuations of the Enhanced-AATP speed with a PLR of 11.65%. Considering the losses occurred because of the bandwidth conflict without random losses, in Figure 7c and Figure 7e, the random losses are introduced (100%), and the PLR increases up to 16.11% (+4.46%, ≈5 s of 100% losses) in (c) and 20.14% (+8.49%, ≈10 s of 100% losses) in (e). The increment corresponds to the percentage of time while the random losses are occurring.
- Figure 46b shows the result of the experiment when the Enhanced-AATP faces a 20% UDP flow, which does not reduce its speed but directly affects the performance. In this case, the UDP does not modify its throughput, even when losses occur, generating moderate fluctuations of the Enhance-AATP throughput and more congestion losses, causing a PLR of 14.36%. Considering the losses occurred because of the bandwidth conflict without random losses, in Figure 7d and Figure 7f, the random losses are introduced (100%) and the PLR increases up to 18.48% (+4.12%, ≈ 5 s of 100% losses) in (d) and 22.29% (+7.93%, ≈ 10 s of 100% losses) in (f). The increment corresponds to the percentage of time while the random losses are occurring.

- From Figure 46, the success detection rate for 100% congestion losses is 1 because, during the coexistence between Enhanced-AATP with cross-traffic flows, the Enhanced-AATP tries to get the maximum bandwidth, reducing the throughput from the other flows. Due to this bandwidth's conflict, a first level of convergence is reached (80%/20% distribution) and minor fluctuations occur due to the congestion produced by the two flows trying to obtain more bandwidth, which affects the network stability. In the case of a success detection rate lower than 1, the Enhanced-AATP's throughput would be maintained, and more losses would occur due to a higher congestion of the network.

At this point, given the proper operation of the Enhanced-AATP protocol differentiating the type of losses, it is necessary to check if the LTD Formula (14) is optimal to identify the type of loss occurred.

$$LTD = \frac{\#Inc_p}{\#Packets_{burst}} \tag{14}$$

In Figure 47, the LTD performance is evaluated by linking the transmission period (orange) and the lost packets (blue), modifying the LTD original value from ×0.9 to ×1.1 in steps of 0.01. As shown in the graph, if the $smooth_{jr}$ is compared with the 90% of the obtained LTD value, the transmission period is increased while the total number of lost packets decreases. This means that some random losses are considered as congestion losses. On the other hand, if the $smooth_{jr}$ is compared with the 110% of the obtained LTD value, the transmission period is reduced. However, the lost packets are incremented, meaning that some congestion losses are treated as random losses, generating more saturation and more packets loss.

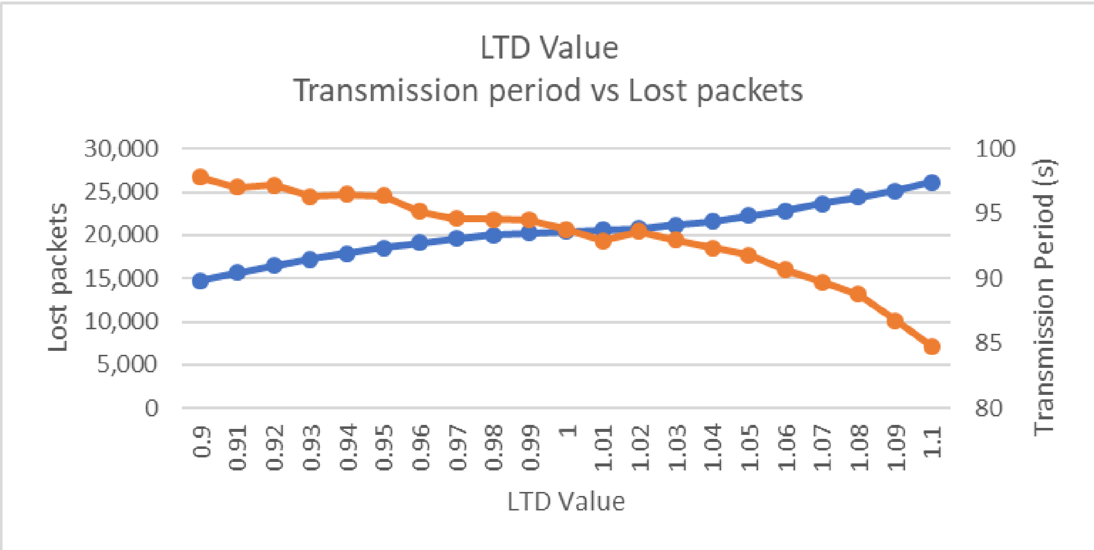


Figure 47. LTD value evaluation. Transmission period (orange) and Lost packets (blue)

The objective is to find the optimal working point of the LTD for the consequent status of the network. Thanks to Figure 47, the optimal point in order to reduce the losses generated without increasing the transmission period is shown. The trade-off point between the transmission period and lost packets is the LTD value obtained by relating directly the increased packets with the total burst. This result confirms the reasoning associated with the LTD design. After a congestion loss episode, the new packets included in the packet burst are the possible cause of the packet losses.

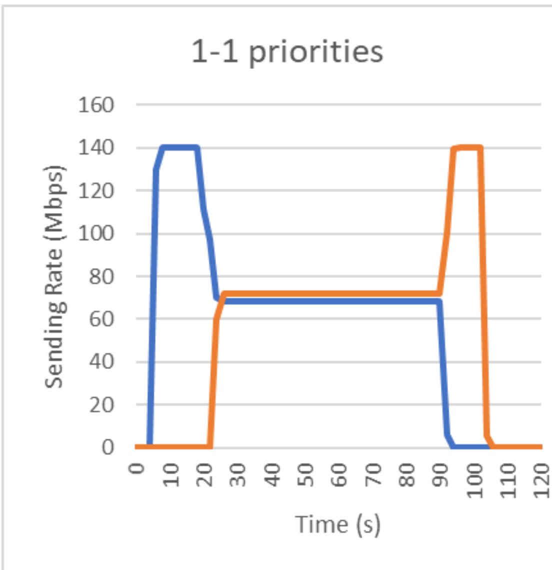
4.6.4 Fairness Mechanism

In this experiment, different priority levels are set to distinct Enhanced-AATP flows that share the destination endpoint. The scenario is Figure 43a connected to Figure 43b. The objective is to check the correct prioritized fair share of the network resources. The cases tested by priorities are: 1-1 (equal priority), 1-8 (maximum priority), and 2-4-6 (three flows).

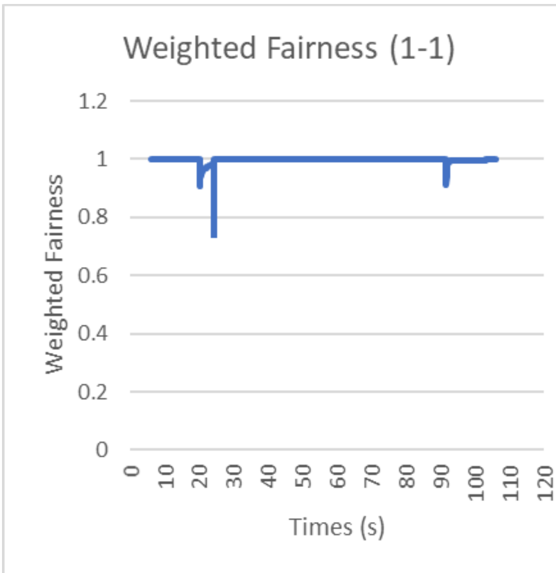
Figure 48 presents the results of the different cases.

- The first case, graphs Figure 48a and Figure 48b, proposes two flows with the same priority (1-1). The flows share the bandwidth (Flow 1 (blue) and Flow 2 (orange), around 50% use each), and the WF fluctuates only during the introduction of the second flow and at the end of the transmission, keeping the value of 1, which means a fair share of the resources.
- The second case, graphs Figure 48c and Figure 48d, aims to have two flows with a maximum difference priority (1-8). The flows share the bandwidth (Flow 1 (blue—11%) and Flow 2 (orange—89%)), and the WF is kept at 1, considering the prioritization established in its calculation.
- The last case, graphs Figure 48e and Figure 48f, aim to launch three flows with different priorities (2-4-6). The flows share the bandwidth (Flow 1 (blue—16%), Flow 2 (orange —33%), and Flow 3 (gray—50%)), and its WF has different fluctuations at the beginning before the flows converge to its assigned speed, always converging to 1, thus generating the fair share of resources.

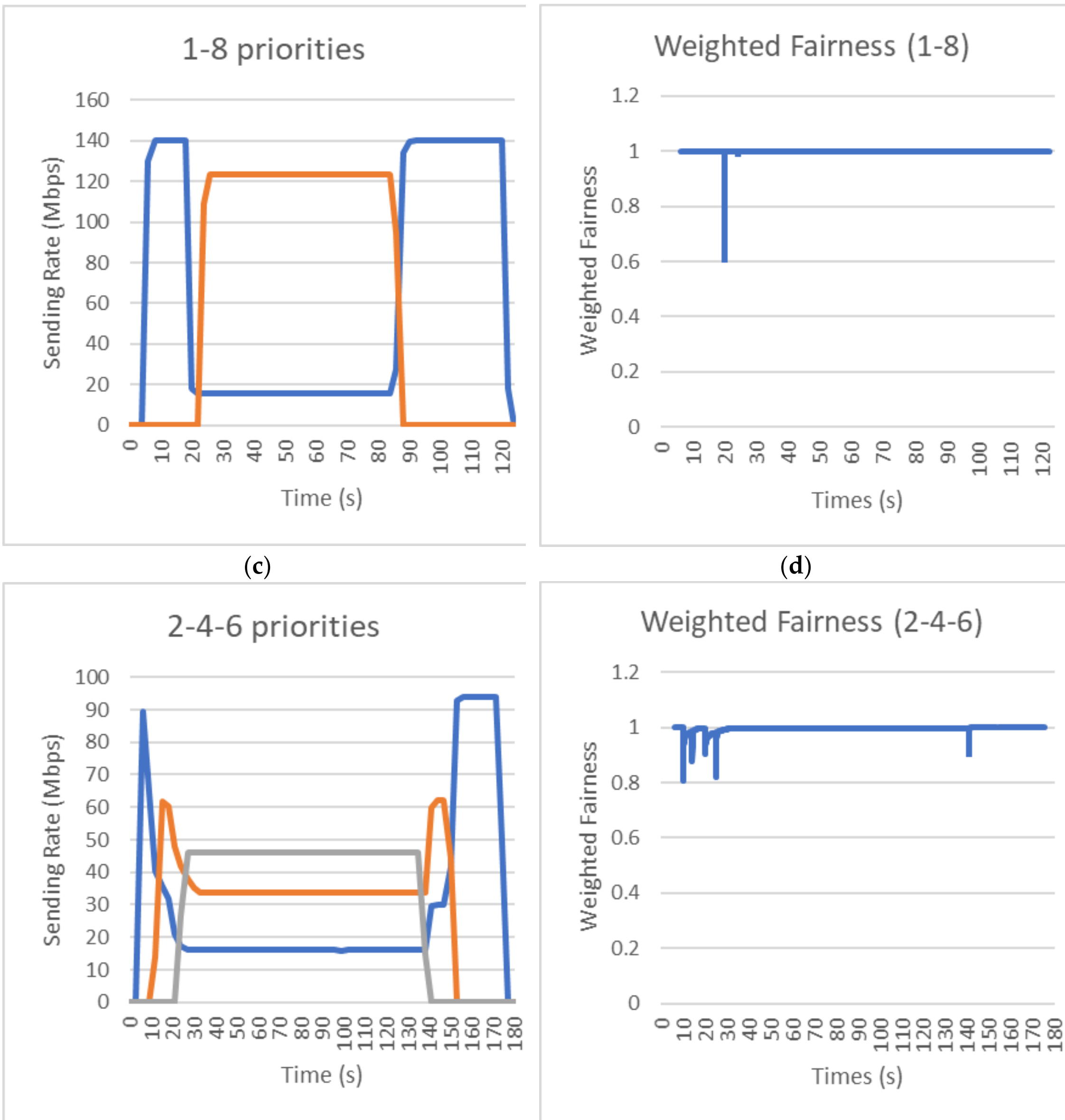
The fairness mechanism introduced regulates the flows without large fluctuations in the system thanks to the modification of the Sending Rate formula (19-20). The weighted fairness measures successfully ($WF = 1$) the correct fair share of the resources considering the priorities of the flows.



(a)



(b)



(c) (d) (e) (f)

Figure 48. Fairness mechanism with priorities. Case 1-1: Sending Rate of Flow 1 (blue) and Flow 2 (orange) (a) and its Weighted Fairness 1-1 (blue) (b). Case 1-8: Sending Rate of Flow 1 (blue) and Flow 2 (orange) (c) and its Weighted Fairness 1-8 (blue) (d). Case 2-4-6: Sending Rate of Flow 1 (blue), Flow 2 (orange) and Flow 3 (gray) (e) and its Weighted Fairness 2-4-6 (blue) (f).

4.6.5 Enhanced-AATP Performance Comparison

The objective of this last experiment is to compare the Enhanced-AATP with other modern transport protocols. Concretely, the settled protocols TCP Cubic, BBR, Copa, Indigo, and Verus.

Pantheon of Congestion Control [41] is an evaluation platform for academic research on congestion control, so therefore, it is considered a scientific reference for transport protocol performance test. Furthermore, Pantheon directly assisted the publication of four other new algorithms [31][35][50][51]. Moreover, this platform is the source of the compared protocols' code.

It is decided to emulate the most representative LFN scenarios from the last tests provided by the Pantheon platform over the Riverbed Modeler following its test methodology.

The chosen LFN scenarios (Figure 49) to be emulated are:

- L–I: GCE London to GCE Iowa (Bandwidth of 1 Gbps; latency of 45 ms)
- S–I: GCE Sidney to GCE Iowa (Bandwidth of 1 Gbps; latency of 85 ms)
- S–L: GCE Sidney to GCE London (Bandwidth of 1 Gbps; latency of 130 ms)

Figure 49. CGE Iowa-CGE London-CGE Sidney Riverbed scenarios following the structure

Once the test environment is defined and emulated, the tests are deployed following Pantheon's methodology. This methodology consists of launching the same test five times over the three scenarios. Each test lasts for 30 s, running three flows using the same protocol with 10-s interval between two flows. The performance metrics results consider the three flows and average the results of the five runs. The performance metrics to be evaluated are the Average of the throughput achieved in percentage (15), the Delay Ratio (16), and the Packet Loss Ratio (PLR).

$$Mean\ Throughput\ (\%) = \frac{Average\ throughput\ (Mbps)}{Bandwidth\ of\ the\ link\ (Mbps)} \times 100 \quad (15)$$

In the case of the delay, the Delay Ratio is used, which is the average one-delay achieved related with the minimum one-way delay in order to check the introduced delay in the network by each protocol.

$$95th\ percentile\ one-way\ Delay\ Ratio = \frac{95th\ percentile\ average\ one-way\ delay\ (ms)}{Latency\ of\ the\ link\ (ms)} \quad (16)$$

For the Packet Loss Ratio (%), the lost packets sent are related to the total packets sent. This metric reflects the effects of the load produced by the three coexisting protocol flows that are trying to reach the maximum bandwidth.

$$Packet\ Loss\ Ratio\ (\%) = \frac{Lost\ packets\ sent}{Total\ packets\ sent} \times 100 \quad (17)$$

The first metric for the performance comparison is the throughput (Figure 50). From this graph, it can be extracted that the Enhanced-AATP achieves a mean throughput of the 80% of the bandwidth, providing better performance than most of the protocols. Similar behavior can be checked with TCP-Cubic, but performance decreases as the delay increases. BBR reaches better results, but these results are over the maximum bandwidth, which means that the protocol might be destabilizing the network.

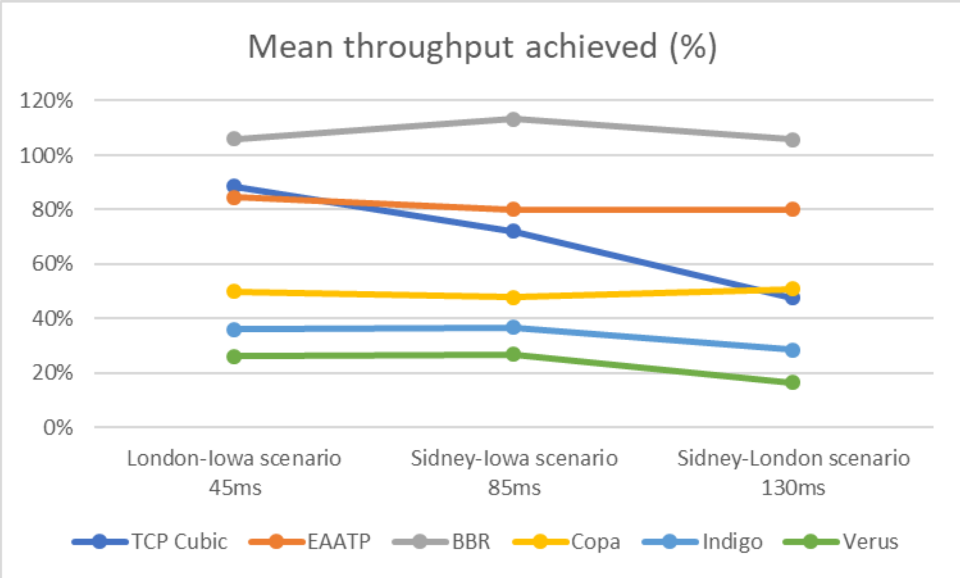


Figure 50. Mean throughput achieved (%) comparison

In order to check how the throughput performance affects the network, the following figure (Figure 51) shows the Delay Ratio (average delay achieved compared with the minimum delay). In the case of the Enhanced-AATP, the delay introduced by the protocol is around 25% (1.25), which means that the network is stable. It can be seen that BBR destabilizes the network because its one-way delay multiplies per 4 the latency of the network in the lower delay scenario. Similar behavior can be seen with TCP Cubic, which doubles the one-way delay of the network (2.00) in the lower delay scenario.

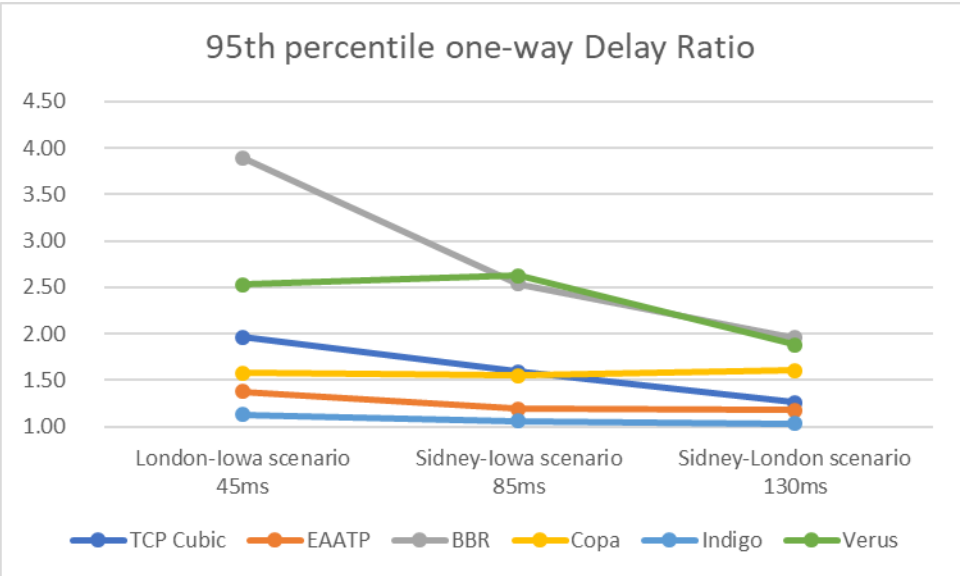


Figure 51. 95th percentile one-way Delay Ratio comparison

The Packet Loss Ratio is checked in Figure 52 in order to confirm the effects of the protocols' behavior regarding the throughput and the delay. The losses introduced by the Enhanced-AATP are low (0.02%), as it happens with the most of the protocols. It is confirmed that BBR achieves better throughput to the detriment of the introduced losses (from 3% to 7%).

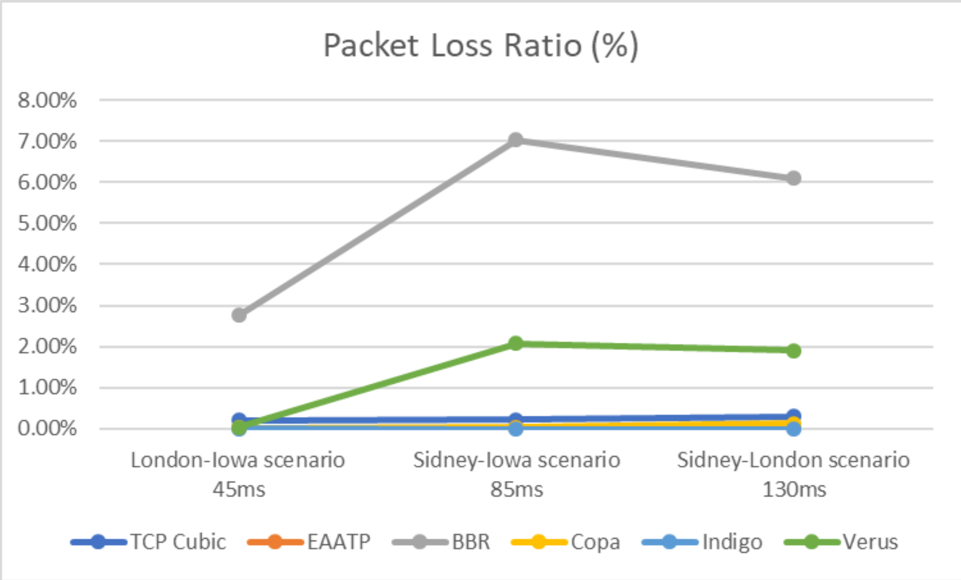


Figure 52. Packet Loss Ratio (%) comparison

Finally, with the information provided by the last three figures, the following graph (Figure 53) shows the protocols' performance for each scenario, relating the 95th percentile one-way Delay Ratio and the Average Throughput achieved. Moreover, the Packet Loss Ratio is noted. This relativized view of the data enables us to contrast the protocols' performance joining the three scenarios' results. The objective is to provide a final performance comparison of the Enhanced-AATP with these protocols: TCP Cubic, BBR, Copa, Indigo, and Verus.

The goal is to achieve the maximum throughput without affecting the delay neither causing losses. The Behavior Target (red circle) is the ideal protocol that achieves maximum throughput levels (100%) without affecting the congestion of the network (minimum one-way delay) nor generating losses during the data transfer. For the best performance, the protocols have to tend to the aforementioned behavior. Among the studied protocols, as the orange circle highlights, the Enhanced-AATP protocol achieves a high average throughput (80%) without destabilizing the network by slightly increasing (25%) the latency neither causing significant losses (0.02%).

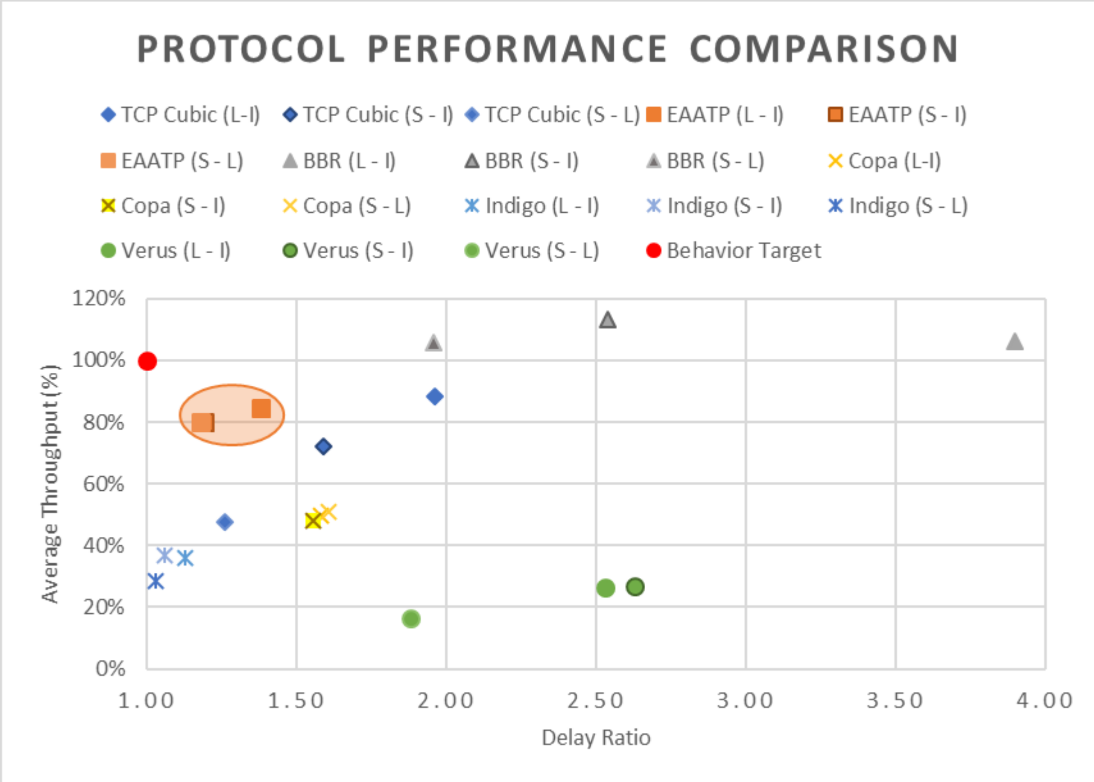


Figure 53. Protocol Performance Comparison (Throughput–Delay Ratio) over the three scenarios. Packet Loss Ratio (PLR) is noted. TCP Cubic: 0.24%; Enhanced-AATP: 0.02%; BBR: 5.30%; Copa: 0.06%; Indigo: 0.00%; Verus: 1.33%; Behavior Tar-get: 0.00%

Comparing the Enhanced-AATP with low delay protocols such as Indigo, the Enhanced-AATP obtains a greater throughput (Average Throughput: Indigo (35%)—Enhanced-AATP (82%)) causing a slight increase of the delay (Delay Ratio: Indigo (1.1)—Enhanced-AATP (1.4)) without provoking significant losses (PLR: Indigo (0.00%)—Enhanced-AATP (0.02%)).

Moreover, comparing the Enhanced-AATP with high bandwidth protocols as BBR, the Enhanced-AATP does not reach that levels of throughput (Average Throughput: BBR (110%)—Enhanced-AATP (82%)) but has a stable behavior without strongly increasing the latency (Delay Ratio: BBR (2.8)—Enhanced-AATP (1.4)) and causing losses (PLR: BBR (5.30%)—Enhanced-AATP (0.02%)).

It can be concluded that the Enhanced-AATP protocol achieves the goal. The protocol maintains its throughput close to the limit without destabilizing the network thanks to the Bandwidth Estimation process, the LTD mechanism, and its operation states, which modify the Sending Rate depending on the network situation (Table 13). In addition, the Weighted Fairness mechanism provides a fairly controlled share of the network resources among the flows without causing significant losses due to the dispute of the bandwidth.

4.7 Conclusions

In this paper, we propose the Enhanced-AATP transport protocol as an improvement of the Aggressive and Adaptative Transport Protocol (AATP), which aims to modify operations and add new functionalities to achieve improved performance over fairly shared heterogeneous Long Fat Networks. One of these functionalities ensures the differentiation of the type of loss episode (congestion or channel), which then proposes a corresponding operation to solve the different types of loss. Moreover, a prioritized fair share of the network resources when multiple AATP flows are connected to the same node is achieved thanks to the new Weighted Fairness mechanism.

After analyzing the different proposals of distinct transport protocols, their metrics and mechanisms for wireless networks, the smooth Jitter Ratio ($smooth_{jr}$) is the reference metric chosen to distinguish the type of losses. The $smooth_{jr}$ relates the effect of the queued packets at the bottleneck and the delay among packets at the destination, also considering past values of the Jitter Ratio. This metric is not affected by the high delay introduced in the LFNs.

Having selected the Jitter Ratio metric, the Loss Threshold Decision maker (*LTD*) is designed. It is defined as the added number of packets in the burst over the total packet sent in the burst. By comparing it with the smooth Jitter Ratio ($smooth_{jr}$) of the received packets, the result of this comparison enables the protocol to discern between losses caused by network congestion or channel fault.

If the $smooth_{jr}$ is greater or equal to LTD, a congestion loss occurs; if the $smooth_{jr}$ is lower than the LTD, it is assumed that a channel failure caused the loss. As a result of this loss detection mechanism, the throughput is not reduced during a random loss episode, as it occurs during a congestion loss episode, thus reducing the loss recovery time and increasing the efficiency of the protocol.

The performance of the Enhanced-AATP and its operation over wireless connections is shown, as well as its capability to detect a random loss produced by the channel. Similarly, the capacity of the protocol to decide the type of loss occurred is exhibited over different scenarios. Finally, the optimal value of the LTD is demonstrated. All the experiments are deployed over the SteelCentral Riverbed Modeler simulator.

As a result of studying different indicators for a controlled fair share of the network resources of a node, the Jain Fairness Index (JFI) is chosen due to its characteristics and compliance with the requirements demanded. After adapting the JFI to consider the prioritization of the flows, the Weighted Fairness (*WF*) index is included in the operation of the Enhanced-AATP protocol. If the WF is equal to 1, it means that there is a fair share of resources; if not, it means that some unfair treatment is happening to one or more flows. Therefore, the protocol operation is adjusted to include a modifier related to the result of the WF to manage the flows for a fair system. Different simulations are run with different priorities and flows to demonstrate its performance. The *WF* suffers fluctuations during the beginning or end of a new flow.

It can be concluded that the Enhanced-AATP can effectively differentiate the types of losses occurred during a communication, adapting its operation to the situation, and assuring a fair sharing of the resources of the node over HLFNs.

Finally, the Enhanced-AATP's performance is compared with other transport protocols' performance. It should be highlighted that the protocol reaches a higher throughput than low delay protocols, slightly increasing the delay but keeping a similar low level of losses. Moreover, compared with high bandwidth protocols, the Enhanced-AATP reaches lower throughput levels (>80%) but does not destabilize the network, nor does it highly increase the latency (+25%) or cause significant losses (0.02%) as may occur with other protocols. This high performance is the result of including the proposed Loss Threshold Decision maker (in order to identify the type of losses occurred) and the Weighted Fairness mechanisms (fairly share of the server network resources) in the improved AATP operation, which modifies its behavior and, concretely, its Sending Rate depending on the network situation.

Our future work aims to introduce a way to detect the loss and recovery of the channel by way of preventing unnecessary packet transfers in order to save energy, and a method to create a distributed fairness system, as opposed to one that is controlled by the node where different Enhanced-AATP flows coexist. Finally, an exhaustive analysis of the relationship of the γ and β parameters of the Transcendence Factor (A) can be done to study its optimal performance and convergence.

5. Results

The results from each publication of these compendium [52]–[54] are presented and discussed in this chapter. The Research Questions (**Q**) answered and the Objectives (**O**) achieved are explained in each section.

The main results achieved within the publications of this compendium are: (1) An innovative NGN conceptualization for the sustainable comfort monitorization in Smart Campuses by integrating multidisciplinary technologies, ellaborated in [52]. (2) The design, deployment, test and analysis of a new transport layer protocol which operation is focused on improving transport layer protocol performance over Long Fat Networks by calculating the maximum bandwidth and adapting its throughput to the network circumstances, presented in [53]. (3) The enhancement of the aforementioned protocol to upgrade its operation and performance in Heterogeneous Long Fat Networks by distinguishing the type of losses occurred during the data transfer, detailed in [54].

5.1 A Smart Campus' Digital Twin for Sustainable Comfort Monitoring

After researching on specific technologies to solve particular NGN issues, this publication is the representative from all the knowledge acquired during my PhD path [48]- [56].

All the work detailed previously helped to accomplish the objective **O1** (*Identify the Next Generation Networks' problematics through the study of the NGNs' application fields and their characteristics*). Thanks to this, I was able to answer to the **RQ1** (*Which Next Generation Network application fields are experiencing bulk data transfer problematics over Heterogeneous Long Fat Networks?*) and find which application field experience problematics during bulk data transfers over HLFNs.

The Smart City application field is one of the biggest scenarios in the NGNs. It encompasses different sectors, defines distinct services and includes the digital transformation of traditional sectors as is the Cloud Data Sharing, Industry 4.0 or the eHealth. Moreover, it also includes brand-new NGN conceptualization as is the Smart Campus.

The Smart Campus proposes another dimension of challenges, more focused on a small group of inhabitants with specific necessities (students, teachers, administrative staff, …). Among these challenges, the most relevant are the Smart Learning, the Smart Sustainability or the Smart Living.

In [52] proposes a proposal for conception of the sustainable comfort monitorization of the Smart Campus and its implications. Our innovative Smart Campus proposal is the definition of the Campus through the efficient use of resources, thereby reducing operational costs and making life more comfortable. Concretely, the authors propose a digital twin modeling procedure that merges well-known approaches used in Smart Campus to integrate a set of advanced intelligent features by using an Internet of Things network and cloud computing to transform university spaces into information sources for intelligent decision-making processes (**O1**).

Our proposed Smart Campus goes further than only applying technology, it is about promoting the multicultural and interdisciplinary collaboration. The combination of different profiles boosts innovative solutions for a broad range of challenges in the Smart Campus paradigm. In this case, the task force, mainly composed by architects and engineers, is focused on the sustainability of the model by also considering the comfort of the actors that live in.

The investigation of the authors aims at integrating the Building Information Modeling, also known as BIM, and the IoT-based wireless sensor networks (WSN) for the monitorization of the environment and the occupants' comfort in the variety of Smart Campus' spaces meant for teaching, research, management and other services.

Three different domains of the Smart Campus are covered by the authors' proposal. On the one side, related to the climate change and sustainability, the authors propose a Green Campus by controlling the energy activity through distinct sensors. On the other side, the authors also considered the conception of the Healthy campus by tracking the comfort of the campus activity. In order to balance the two aforementioned domains, the real-time facility management proposed must help to achieve the equilibrium between energy consumption and the comfortable life in the campus.

In order to provide prioritized domains in the proof-of-concept deployed, the authors first consider the comfort of the inhabitants of the Campus by measuring and controlling the Indoor Environmental Quality (IEQ) parameters, mainly composed by visual, acoustical and air quality comfort. Secondly, thanks to the IoT middleware introduced (Dynamo BIM visual programming) in the real-time digitalized campus facility deployed (software environment of Autodesk Revit 2020), it is possible to monitor the different environmental and personal parameters through the dashboard, being also possible to adjust the energy consumption and efficiency considering people's situation.

The proof-of-concept of the comfort-aware digital twin proposed by the authors is the first step of a long run. As it is stated, there are some points to be improved and introduced in the Smart Campus concept design and deployment. It must be highlighted the importance of the introduction and combination of disruptive technologies in the Smart Campus Digital Twin, also considering the Governance polices and priorities of the institution. Moreover, the involvement of the different actors and the flexibilization of the organization due to new society situations and requirements is another important working point.

5.2 Adaptive and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks

This publication of the compendium starts to answer to the **RQ2** (*Can transport layer protocols take advantage from the network metrics in order to achieve optimal performance over a Heterogeneous Long Fat Networks?*) by achieving the objective **O2** (*Improve Transport Layer protocol performance over Long Fat Networks*).

This publication [53] aims at detailing the designed, implemented and tested transport layer protocol for bulk data transfers over Long Fat Networks (LFNs) in the context of Cloud Content Sharing Use Case (**O2**). This transport layer protocol is the Adaptative and Aggressive Transport Layer Protocol (AATP).

First of all, I detail the Cloud Content Sharing Use Case and its main requirements. Due to its replicability conception, it is necessary to share high amounts of data between Cloud Regions. The interconnecting backbones between Regions have high bandwidth links but, as the Cloud server farms are separated from far distances, the delay is high. Due to its high Bandwidth-Delay Product (BDP), this causes problems with legacy transport layer protocols.

After analyzing distinct fast long-distance solutions, we present the design and performance of the Adaptative and Aggressive Transport Protocol (AATP) for the optimization of bulk data transfers in a LFN Cloud Content Sharing Use Case. Given the requirements from the real use case, this protocol is meant to be efficient, adaptable and friendly aggressive. The main characteristics highlighted from the AATP are the bandwidth estimation process, a mechanism to calculate the maximum bandwidth capacity of the communication, and the protocol's ability to adapt its operation depending on the network circumstances, as it can be a packet loss episode. Moreover, this protocol is meant to be aggressive towards other protocols to provide quality of service.

After implementing it in a network simulator and testbed on field, the authors proposed distinct tests to demonstrate the protocol characteristics. In terms of efficiency, the AATP's performance is around 95% over the different LFN scenarios deployed thanks to the bandwidth estimation and sending rate operation. Due its adaptability, the protocol is able to rapidly recover the 80% of the maximum capacity estimated after a loss episode and increase it gradually to reach again the maximum speed. Finally, given its aggressiveness, it is demonstrated that the protocol leaves residual bandwidth (<20%) to TCP flows. It is highlighted during the specification and tests the possibility of adapt distinct design points to modify its adaptability or aggressiveness, depending on the service requirements.

Moreover, from these tests, two main drawbacks are identified. First, the uncontrolled AATP's aggressiveness when two or more flows are sharing one node resources causes a high number of losses due to its bandwidth dispute. Second, the protocol's operation over wireless networks, which underperforms under lossy circumstances due to its incapacity to differentiate the type of losses occurred.

5.3 Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks

After achieving **O2**, this third publication focuses on finally answering to **RQ2** and, also, to **RQ3** (*Can transport layer protocols adapt its operation over wireless sections by distinguishing congestion and channel losses?)* by achieving the objectives **O3** (*Propose the wireless adaptation of the base solution to improve its performance over Heterogeneous Long Fat Networks*) and **O4** (*Progress towards protocol enhancement*).

The publication [54] proposes the evolution of the AATP protocol (Enhanced-AATP) in order to optimize its performance over Heterogeneous Long Fat Networks by considering the nature of the wireless media sections and the inconveniences introduced by these sections (**O3**). Moreover, given the bandwidth dispute between AATP's flows, we introduce a fairness mechanism in the protocol's operation for the fairly share of the end node resources (**O4**).

Firstly, due to the wired-wireless sections composition of the Heterogeneous Long Fat Networks, the authors study the main inconveniences of introducing wireless media in the last mile of the Cloud Data Sharing Use Case. Given the bandwidth degradation, network inefficiencies and interruption nature of the media, we have considered distinct wireless oriented Transport Protocols to check which networks metrics they have considered.

Thanks to this study, we have classified different mechanisms and network metrics (Network Status, Round-Trip Time, Intermediate Queue Length, Jitter, ACK action, ECN and Machine Learning) for the decision-making process to distinguish between the type of losses. Given the AATP protocol operation and the Use Case, the reference metric that we have considered is the Jitter Ratio. We have chosen the Jitter Ratio because it relates the effect of the queued packets at the bottleneck and the delay among packets at the destination, without being affected by the delay of the network. Concretely, we have selected the smoothed Jitter Ratio that considers past Jitter Ratio values.

Having selected the smooth Jitter Ratio metric, we have designed the Loss Threshold Decision maker (LTD). It is defined as the added number of packets in the burst over the total packet sent in the burst. By comparing the LTD with the smooth Jitter Ratio of the received packets, the result of this comparison enables the protocol to discern between losses caused by network congestion or channel fault and, consequently, to adapt its operation.

At the same time, to solve the AATP's flows bandwidth dispute, we have studied different indicators for a controlled fair share of the end node's network resources. We have selected the Jain Fairness Index (JFI) due to its characteristics and compliance with the requirements demanded. After adapting the JFI to consider the prioritization of the flows, we have included the Weighted Fairness (WF) mechanism in the operation of the Enhanced-AATP protocol. The Enhanced-AATP's operation is adjusted given the output of the WF.

After fully adapting the AATP protocol with the proposed mechanisms, the Enhanced-AATP is updated in the Network Simulator implementation. We have designed different tests in order to show the performance of the Enhanced-AATP under different circumstances.

First, we exhibit the protocol's performance operation over wireless, which is around the 80%, and its capability to detect random wireless loss episodes. For the random wireless loss episode tests, we have run the same tests with the Enhanced-AATP and TCP Cubic, a representative TCP protocol. The results showed the Enhanced-ATTP keeps its throughput thanks to being able to notice that the loss is not caused because of a congestion in the network, meanwhile the TCP protocol reduces its sending rate due to the loss channel which is translated in more time spend to send the same amount of data (TCP Cubic doubles the increased time compared to the Enhanced-AATP).

Second, in order to demonstrate the protocol's capacity to differentiate the type of losses occurred, different tests were run under distinct circumstances. By combining cross-traffic causing congestion and programmed wireless random losses, both type of losses occurs. It can be seen that the time spent in the data transfer increases only by the time that the network is down due to channel loss episodes. Also, we have demonstrated the optimal LTD value, a balance between packet losses and time spent during transfer, by slightly modifying its value within a range and checking how this affects to the decision-making process. Different tests were proposed with different Enhanced-AATP's flows. By this way, the proper Weighted Fairness' operation is shown under with different flows and priorities. The bandwidth is fairly shared considering the priorities stablished without destabilizing the network.

Finally, the authors compare the Enhanced-AATP protocol with other relevant transport protocols in different LFN scenarios. The metrics considered are the Mean Throughput, the one-way Delay Ratio and Packet Loss Ratio. Also, we have defined the Behavior Target, an ideal reference protocol that achieves the maximum throughput levels (100%) without affecting to the status of the network (no packet losses due to congestion (0%), no increasement of the one-way delay (0%)). For the best performance, the protocols should to tend to behave like the Behavior Target. The Enhanced-AATP protocol achieves a high average throughput (80%) without destabilizing the network by slightly increasing the delay (25%) neither causing significant losses (0,02%).

From these tests, different research directions arise. The first point is about studying a way to detect the loss and recovery of the channel while preventing sending packets to save energy. Also, added to the fairly share of a node, a distributed fairness system for coexistent Enhanced-AATP flows without having the same end node must be considered. And, finally, the authors consider an exhaustive analysis of the design points to study its optimal performance under different circumstances.

6. Final discussion and conclusions

My main motivation when I joined GRITS Research Group in 2013, before starting my PhD in 2016, was understanding the Next Generation Networks that were meant to be one of the main pillars of the society in the digitalization era.

Through my participation in the different research projects, I have learnt about the characteristics from distinct application fields and their digital transformation, but also its requirements, trends and barriers. Internal and external aspects must be considered when the digitalization process is under development. The key is the importance of the technology as a driver of this evolution.

The advancements in brand-new technologies solve problems that had no solution years ago but it also opens the door to new scenarios. That is why it is important to identify the opportunities and obstacles in the different application fields in order to propose innovative solutions with new technology or through its multidisciplinary integration. Through my first years working on the digital transformation of different sectors, new challenges were identified. That is how my PhD started, trying to give response to them.

Thanks to be involved in projects from different application fields during this first part of my career, through the study and research, I noticed a problematic with bulk data transfers between geographically separated high-speed networks. As the technology for data transfer was reaching higher capacity and the network composition was evolving, it was necessary to propose a new communication protocol that optimally perform over NGN considering the requirements from new services to be deployed and the amount of data to be transferred.

As stated before, legacy transport layer protocols underperform over Long Fat Networks given its high bandwidth and high delay (high BDP) due to out-of-date protocols' conception. Moreover, the LFN's composition is evolving by including wireless sections, expanding its conception to Heterogeneous Long Fat Networks, which directly affect to the protocols' understanding of the network because they were meant to be deployed over wired networks. Furthermore, it is necessary to contextualize the role of the technology and its effects in the NGNs paradigm.

To face it up, it was hypothesized that

the introduction of mechanisms that analyze network metrics and efficiently exploit network's capacity meliorates the performance of Transport Layer protocols over Heterogeneous Long Fat Networks during bulk data transfers.

Three main Research Questions were proposed to be answered to accomplish and demonstrate the hypothesis.

[RQ1] Which Next Generation Network application fields are experiencing bulk data transfer problematics over Heterogeneous Long Fat Networks?

[RQ2] Can transport layer protocols take advantage from the network metrics in order to achieve optimal performance over a Heterogeneous Long Fat Networks?

[RQ3] Can transport layer protocols adapt its operation over wireless sections by distinguishing congestion and channel losses?

Related to these Research Questions, four Objectives were set to be achieved to answer them.

[O1] Identify the Next Generation Networks' problematics through the study of the NGNs' application fields and their characteristics.

[O2] Improve Transport Layer protocol performance over Long Fat Networks.

[O3] Propose the wireless adaptation of the base solution to improve its performance over Heterogeneous Long Fat Networks.

[O4] Progress towards protocol enhancement.

With all the premises set, I established a transversal objective **O1** (Identify the Next Generation Networks' problematics through the study of the NGNs' application fields and their characteristics), which have been present during the whole thesis. As my main personal goal is keep learning about Next Generation Networks, even if I was also focused on identifying which application fields were experiencing data transfer problematics over HLFNs to propose a solution from a practical point of view, I always wanted to be involved in the innovation of different NGN sectors. This provided us the possibility of opening our mind about combining different technologies to propose new solutions.

From all these experiences [48]- [56], it can be said that innovation in NGN not only consists on the integration and deployment of disruptive and new technologies, it is also necessary to consider the needs from the environment and the users that live in. That is why we can confirm that it is possible to propose innovative paradigms in NGNs through the integration of multidisciplinary disruptive technologies but we have to add that it is necessary to consider other facts very related to the digital transformation as is the costumer or users, the processes involved and the organization itself, not only the product or service.

The most representative work, as we are based in a multidisciplinary University campus where different stakeholders share the same environment with different uses, is the Smart Campus scenario and its challenges. After conceptualizing it, several challenges were identified (Smart Living, Smart Security, Smart Sustainability, etc.). In order to put focus, we have investigated the integration of Building Information Modeling tools with Internet of Things (IoT) based wireless sensor networks in the fields of environmental monitoring and emotion detection to provide insights into the level of comfort.

The integration between BIM and IoT provided many benefits. Real-time access to information and process automation from the IoT sensors deployed in the BIM environment. Also, the comfort level monitoring is accomplished using BIM. Data analytics techniques are added in the construction industry for statistical analysis, allowing multiple disciplines (architecture and ICT engineering) to collaborate together in the same model where data are processed and visualized in a unique model.

The preliminary research presented in [52] allowed us to establish a basis for the Smart Campus' comfort digital twin experimentation. In terms of NGN paradigm, we have focused on the fields of: Green campus, in line with the issue of climate change, which includes the intelligent energy consumption and the implementation of sensor technology for accurate reporting. And Healthy campus, to monitor and promote the level of comfort by tracking and recording the status of the campus activity and real-time facility management, which includes the facilities, infrastructures and people (staff, students and visitors).

Moreover, through the accomplishment of the **O1**, I was able to answer the **RQ1** (Which Next Generation Network application fields are experiencing bulk data transfer problematics over Heterogeneous Long Fat Networks?) and find which sector is experiencing these performance problems in their use cases. From the aforementioned experiences in different application fields, it can be said that one of the most outstanding application field with these HLFNs problematics is the Cloud Data Sharing use case between regions. The main reasons are the evolution of these deployments and its complexity in terms of network architecture and service requirements.

First of all, given the complexity introduced by wireless sections, it was decided to focus on traditional Long Fat Networks. The main drawback of LFNs for legacy transport layer protocols is the high Bandwidth-Delay Product (BDP) and the protocol's poor ability to achieve high performance by filling the pipe. By this way, we designed an efficient and adaptable Transport Layer protocol in order to solve the Cloud Data Sharing low performance during bulk data transfers. The key performance features are the mechanism to measure the maximum bandwidth at the beginning and during the data transfer and the mechanism to adapt the sending rate of the protocol to the network circumstances (losses, bandwidth degradation, incoming flows, …). Moreover, given the friendliness of transport layer protocols, this designed protocol was meant to be friendly aggressive to other coexistent flows, letting only the residual bandwidth (in our case, due to design decisions, it was < 20% of the bandwidth). The Adaptative and Aggressive Transport Protocol (AATP) was born [53].

After its design, the AATP was implemented over the network simulator and, also, in a testbed on field. Distinct tests were run in order to demonstrate its main characteristics. The efficiency of the protocol is around the 95% and its adaptability is achieved by rapidly recovering the 80% of its maximum sending rate, outperforming other protocols (TCP variants) under the same network circumstances. Finally, the aggressiveness is demonstrated by leaving only the 20% of the bandwidth to the other flows. By this way, **O2** (Improve Transport Layer protocol performance over Long Fat Networks) was achieved.

Thanks to this work [53], we were able to start answering to **RQ2** (Can transport layer protocols take advantage from the network metrics in order to achieve optimal performance over a Heterogeneous Long Fat Networks?). Yes, transport layer protocols can take advantage from the network metrics by measuring the maximum bandwidth and noticing network status alteration. With this information, the AATP protocol can modify its behavior to optimally perform over Long Fat Networks. Given the AATP's performance, it is not possible to say that the **RQ2** is totally answered. The AATP's operation must be adapted to optimally perform over Heterogeneous LFNs, not only wired LFNs. Moreover, from the analysis of the AATP's test results, it is highlighted that it is necessary to adapt the behavior of the protocol in order to be able to coexist with other AATP flows because a high number of losses occur due to the uncontrolled aggressiveness.

This enabled me to achieve **O3** and **O4** to finally answer to the **RQ2** and **RQ3**. After the design, implementation and test of the AATP protocol, it was necessary to adjust its operation over heterogeneous networks and, also, modify its aggressiveness towards other AATP protocols.

The main problem from heterogeneous wired-wireless networks is the cause of packet losses. In wired networks, when a loss happens, it is usually because of a congestion in a bottleneck. When it comes to wireless sections, the cause can be a congestion or a channel loss. Current transport layer protocols reduce its throughput because they assume that the losses are caused due to a congestion event, even when it is a channel loss due to the nature of the media. This directly impacts to the protocol's performance.

It was necessary to be able to distinguish between the type of losses. By this way, if the protocol is able to identify a channel loss, after recovering the connection, the protocol can keep its performance without modifying its operation. Set on this basis, we have designed a new mechanism based on the Jitter Ratio (Loss Threshold Decision maker) for the packet loss identification. Depending on this comparison, the Enhanced AATP adapts its operation. This mechanism was introduced in the AATP's design, implemented in the network simulator and new tests were run. The objective was checking the capacity of the protocol to identify channel loss events and, also, if it was able to distinguish between type of losses.

Within these tests, The Enhanced AATP successfully identifies the type of losses, while other TCP protocol (as is the most representative, TCP Cubic) fails to do it almost doubling the delay introduced by random losses. The success detection rate is 100% and the protocol adapts its operation regarding to the lossy event. In addition, the optimal LTD maker value is demonstrated. Thereby, the **O3** (Propose the wireless adaptation of the base solution to improve its performance over Heterogeneous Long Fat Networks) was achieved. This work was presented in [54].

It was also necessary to check and amend the aggressiveness of the AATP protocol. During the review of the AATP protocol, a new mechanism was studied and designed for the fairly share of end node's resources.

The Weighted Fairness mechanism was meant to control the aggressiveness of the AATP flows when they are sharing the same node's resources. By considering the priority from each flow, the end node distributes its bandwidth among the flows. This is done by adapting their sending rate to the node circumstances, not by limiting their maximum bandwidth, which could cause network instabilities. Different tests demonstrated the proper bandwidth distribution between distinct prioritized flows. This mechanism was also presented in [54].

Due to the protocol adaptation, the Enhanced AATP protocol has been optimized for prior uncontrolled network circumstances, achieving the **O4** (Progress towards protocol enhancement).

These new achievements let us to answer to answer **RQ3** and, finally, **RQ2**. As the **RQ3** (Can transport layer protocols adapt its operation over wireless sections by distinguishing congestion and channel losses?) was strictly related the wireless issue, it will be answered first. We have studied and evaluated different parameters to consider from the network. Through these metrics, it is possible to modify the transport layer protocol operation but under specific network circumstances. Specifically, the Jitter Ratio metric allows the Enhanced AATP to clearly distinguish the causes of losses by monitoring the reception of the packets. As the Jitter Ratio value is kept, it means that there is no queue active in the end-to-end communication. If a channel loss occurs due to the nature of the media, the Jitter Ratio value will remain stable, pointing that the cause is not the number of packets in the pipe. If the Jitter Ratio starts to rise, it will mean that the congestion is starting and, if some losses happen, the cause will be the congestion. The answer is Yes, the Enhanced AATP protocol adapts its operation distinguishing between the type of losses.

In addition, the improvement of the protocol, very related to the Weighted Fairness mechanism introduced in the protocol adaptation, helped us to strengthen its reliability and increase its performance.

The Enhanced AATP's outcomes allowed us to directly answer to the **RQ2** (Can transport layer protocols take advantage from the network metrics in order to achieve optimal performance over a Heterogeneous Long Fat Networks?). Relying on the network metrics, specifically, the Bandwidth Estimation, Sending Rate operation, Weighted Fairness and Loss-Threshold decision maker introduced mechanisms, the protocol is able to improve its performance over HLFNs. We fixed a Behavior Target protocol with the following characteristics to compare it with the Enhanced AATP. Its maximum throughput (100%), the one-way delay introduced equal to 0% and no packet losses. As it is an ideal protocol, the objective was having it as a ideal reference for the Enhanced-AATP. The result was that the Enhanced AATP achieved a maximum throughput of 80%, slightly introducing one-way delay (25%) and causing very low losses (0,02%). With these final outcomes, also knowing that the Enhanced AAP doesn't cause instabilities in the network with these performance values, we can answer a final Yes for the **RQ2**. The Enhanced-AATP optimally performs over Heterogeneous Long Fat networks by considering the network metrics.

Finally, we can say that the hypothesis is confirmed. The introduction of mechanisms that analyze network metrics and efficiently exploit network's capacity meliorates the performance of Transport Layer protocols over Heterogeneous Long Fat Networks during bulk data transfers. All of these thanks to the design and development of the AATP protocol, and its enhancement, which is composed by mechanisms that measure the maximum bandwidth of the network and, also, adapt its operation to the network circumstances, even in wireless networks or coexisting with other flows.

Next Generation Networks have been the path I have followed my entire career, undertaking different roles and proposing solutions from different perspectives. The development of new technology for a specific use case; the enhancement of existent technology to improve its performance and adapting its operation to new circumstances; the introduction of distinct technologies in new deployments and the integration of multidisciplinary solutions to propose new NGN paradigms are the steps that I have completed through my journey, always with the support of my research group colleagues.

7. Further work

Through this journey we have identified different research directions related to each chapter. Three main future lines can be depicted. The first is related to the NGNs and its evolution. Another one more related to the technology itself and its improvement. And finally, one more related to the technology developed (Enhanced AATP) and its application in other fields.

Chapter 2. The proposed Smart Campus proposed paradigm and its conceptualization must be expanded and tested. The integration of the Digital Twin and the complex adaptive systems from the facility management also must be developed, also considering the distinctive features and services that can be deployed. The intelligence of the deployed model is based on static rules and relies on recommendations for the occupants and the facility manager. Despite noticeable progress in our university campus, the concepts and principles of the smartness level are not clear. This can be attributed to the obvious novelty of the concept and numerous types of smart systems, technologies, and devices available to students, learners, faculty, and academic institutions. Ongoing projects, as is the DigitalTwin, will contribute to work on this line.

Moreover, related to the NGNs evolution, it is always necessary to understand the new needs and contribute to it considering the new technology developed and the social context.

Chapter 3 & 4. From our base protocol and its extension, some working points are identified. One sustainable mechanism to be introduced in the AATP operation is a way to detect the loss and recovery of the channel by way of preventing unnecessary packet transfers in order to save energy. An enhanced feature, the distributed fairness system, could provide us a better fairness between Enhanced AATP flows that not share the same end node.

An exhaustive analysis of the relationship of the γ and β parameters of the Transcendence Factor (A) can be done to study its optimal performance and convergence.

Related to deploying the Enhanced AATP in different NGN use cases, which design was mainly focused on Heterogeneous Long Fat Networks, it can be interesting to deploy it in other use cases with other network characteristics and behavior, in order to check its performance and, if necessary, study its adaptation. From one of our contributions [49], we know that one of the main challenges in Antarctica is its lack of conventional telecommunication systems, which hardens the deployment of heterogeneous sensor networks. To overcome these difficulties, it is proposed the use of Near Vertical Incidence Skywave (NVIS) High Frequency (HF) radio links to provide innovative Antarctic communications. This signal is reflected by the ionosphere, providing a long backhaul link of 250 km radius coverage area but, at the same time, its reliability is very dependent on the ionosphere state, and during the night, the performance is drastically reduced. Each sensor network should have collected high amount of sensed values from each station during the night. We expect that, due to the large quantity of data to be sent, network congestion could occur. At this point, it is important to consider the trustworthiness of the network, as the information is critical to be collected. For these reasons, the use of the Enhanced AATP could improve the performance during the data transfer, positively affecting the trustworthiness of the network during the data collection.

As a final reflection, the human capacity to imagine, think and build new realities is one of the most powerful tools that we have. It is our mission to boost it to foster a better sustainable world.

“I am devoting myself to research because I want to improve the society in which we live, by contributing to the well-being of people with new technological advances in the world of telecommunications”.

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Appendix A. Projects

INTEGRIS

Acronym

INTEGRIS

Title

INTelligent Electrical Grid Sensor communications

Duration

02/2010 – 12/2012

Type

FP7 - ICT

Summary

INTEGRIS project proposes the development of a novel and flexible ICT infrastructure based on a hybrid Power Line Communication-wireless integrated communications system able to completely and efficiently fulfill the communications requirements foreseen for the Smart Electricity Networks of the future.

https://cordis.europa.eu/project/id/247938

Background

Smart Grid

Companies

- Enel – Endesa
- iLight
- Tesmec Service SRL
- Indra Sistemas SA
- Current Technologies International GMBH
- Maxlinear Hispania SL
- Schneider Electric Industries
- a2a
- TTY-SAATIO

VSNoIPv6

Acronym
VSNoIPv6

Title
VSN over IPv6

Duration
04/2013 – 12/2013

Type
Technological Transfer

Summary
Study of the different Use Case from the media company.

Analysis their current solutions for media data transfers.

Solutions for the deployment of their application over IPv6 networks.

Background
Media

Companies
- Video Steam Networks (VSN) Innovation & Media Solutions

SMCT Málaga

Acronym
SMCT Málaga

Title
Smart City Málaga

Duration
2009 - 2013

Type
Centro para el Desarrollo Tecnológico e Industrial (CDTI)

Summary
Smartcity Málaga was a project devised with the aim of complying with the guidelines set by Europe regarding energy, which promote efficiency, the use of renewable energies and advanced electrical networks with storage capacity. From distributed generation to telecommunications, to remote management to grid automation, Smartcity Málaga combines all technologies of the smart grids in a real, live environment: it is there where the main difference resides between Smartcity Málaga Living Lab and the other initiatives studying smart cities.

https://malagasmart.malaga.eu/es/habitat-sostenible-y-seguro/energia/smartcity-malaga/

Background
Smart City

Smart Grid

Companies
- Endesa

SHECloud

Acronym

SHECloud

Title

Smart Hybrid Enterprise Cloud

Duration

01/2014 – 06/2016

Type

“Acción Estratégica de Economía y Sociedad Digital (AEESD)” from Spanish Ministery of Industry, Energy and Tourism

Summary

Through the analysis of the state-of-the-art hybrid cloud solutions (a combination public and private cloud strategies to offer the best features of both types), SHECloud pretended to create an intelligent orchestrator for the interoperability of public and private clouds, automatizing the migration of workloads (virtual machines and other resources) among clouds.

Background

Cloud

Companies

- ABIQUO
- Claranet
- MediaCloud

MBTAP

Acronym
MBTAP

Title
Media Bus Transfer Protocol

Duration
06/2014 – 12/2015

Type
"Acción Estratégica de Economía y Sociedad Digital" (AEESD) from Spanish Ministery of Industry, Energy and Tourism

Summary
Study possible solutions for their current protocol by providing new mechanisms to improve its performance of media networks.

Background
Media

Companies
- Video Steam Networks (VSN) Innovation & Media Solutions

FINESCE

Acronym

FINESCE

Title

Future INtErnet for Smart Utility ServiCEs

Duration

2013 - 2015

Type

2nd Phase of Future Public Private Partnership (FI-PPP) funded by the European Union with FP7

Summary

FINESCE contributed to the development of an open IT-infrastructure to be used to develop and offer new app-based solutions in all fields of the Future Internet related to the energy sector. The project will organize and run a series of field trials at trial sites in 7 European countries.

http://www.finesce.eu/

Background

Smart Grid

Companies

It was coordinated by Ericsson, and the consortium was built by 29 energy and ICT companies, R&D centers and universities from 13 European countries representing the big Smart Grid players as well as SMEs and young know-how.

OMBTAP

Acronym

OMBTAP

Title

Optimization MBTAP

Duration

04/2016 – 02/2017

Type

"Acción Estratégica de Economía y Sociedad Digital" (AEESD) from Spanish Ministery of Industry, Energy and Tourism

Summary

Optimization of the proposed solution in the MBTAP project for wider Use Cases.

Background

Media

Companies

- Video Steam Networks (VSN) Innovation & Media Solutions

BUSAN

Acronym

BUSAN

Title

Busan Smart City - Sasang District Regeneration

Duration

07/2017 – 09/2017

Type

Contract

Summary

The project is focused on consulting in the Smart Cities area for the urban rehabilitation of a neighbourhood in the city of Busan, the Sasang district. This district is a purely industrial and outdated district and it is wanted to reform it taking as example the urban reform made in 22@Barcelona.

The objective is study the use case of the Sasang District in order to propose different innovative changes to improve the technological infrastructure district and the associated services.

https://www.salleurl.edu/en/delegation-koreas-busan-sasang-industrial-complex-visits-la-salle-technova-technology-transfer

Background

Smart City

Companies

- Busan Municipality and Dohwa Engineering, South Korea

SPRINT 4.0

Acronym

SPRINT 4.0

Title

Strategic Partnership for Industry 4.0

Duration

09/2017 – 08/2020

Type

Erasmus+

Summary

The purpose of the project is to provide students with the skills and competences they will need to work on companies adopting Industry 4.0 principles, to foster their employability and professional development. Entrepreneurial skills and an entrepreneurial mind-set are necessary for successfully working under this new paradigm. To adapt a company to the Industry 4.0 means to rethink the traditional business model. Therefore, entre/intrapreneurship methods and tools need to be part of a technology-based training.

https://www.sprint40.eu/

Background

Smart City

Industry 4.0

Companies

- BIBA
- CELSA Group
- Fondazione Giacomo Brodolini
- Intooition
- OHS Engineering GmbH
- Selettra
- TOI

SmartCampus

Acronym

SmartCampus

Title

Secured and Distributed Smart Campus

Duration

2018 - 2019

Type

Ramon Llull University – Call for projects

Summary

The purpose of the project was to deploy a proof of concept of SmartCampus (Internet of Everything around a university campus). Specifically, design a proof of concept to (1) store heterogeneous data in one (or several) clouds using the SIoT paradigm, (2) provide a single gateway for the different services of a Smart Campus (for example, predictive analytics, access control) can access the data collected, and (3) provide a holistic and centralized view of the events being monitored on a campus.

Background

Smart City

Smart Campus

Companies

- Ramon Llull University

ATHIKA

Acronym

ATHIKA

Title

Advanced Training in Health Innovation Knowledge Alliance

Duration

01/2019 – 12/2021

Type

Erasmus+

Summary

ATHIKA will build a set of advanced training programs involving academia, health public administrations, SMEs, start-ups and health business consultants. The variety of profiles of the project partners will provide an overall perspective of the sector and will enable to identify its most urgent challenges. They will guide and coach students during the development of novel technical and ethical-compliance solutions to implement ICT solutions in the health sector. The training activities include four workshops and a final symposium to showcase the project results and exchange knowledge between partners, students and health sector stakeholders all across Europe.

https://athika.eu/

Background

Smart City

eHealth

Companies

- Fundació TICSalut
- Mcrit, S. L
- Pharmatics Limited
- Tartu Ulikool
- Technopolis Group Eesti Ou
- Technosens Evolution
- University of the West Scotland
- Viesoji Istaiga Kauno Mokslo Ir Technologiju Parkas

DigitalTwin

Acronym

DigitalTwin

Title

GEMELO DIGITAL — Gestión de Smart Buildings para la era post COVID-19

Duration

2021

Type

"Iniciatives de Reforç de la Competitivitat (IRC)" from ACCIÓ - Agència per la Competitivitat de l'Empresa

Summary

The objective of this project is to build a virtual model of a pilot building, connecting it to the physical building and thus creating its digital twin. In this way, it will be possible to improve its management and optimize its use based on simulations in different areas or scenarios. The possibility of gathering and processing all the information generated by the Smart building in a digital environment will bring a great number of benefits.

Background

Smart City

Smart Campus

Companies

- CT Solutions Group
- MSI Studio
- Prosume Energy
- TECNALIA Research & Innovation
- Noumena
- Siemens
- Innova IT
- Loxone España

Appendix B. Published articles included in this thesis

sustainability

MDPI

Article

A Smart Campus' Digital Twin for Sustainable Comfort Monitoring

Agustín Zaballos *, Alan Briones, Alba Massa, Pol Centelles and Víctor Caballero

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check for updates

Abstract: Interdisciplinary cross-cultural and cross-organizational research offers great opportunities for innovative breakthroughs in the field of smart cities, yet it also presents organizational and knowledge development hurdles. Smart cities must be large towns able to sustain the needs of their citizens while promoting environmental sustainability. Smart cities foment the widespread use of novel information and communication technologies (ICTs); however, experimenting with these technologies in such a large geographical area is unfeasible. Consequently, smart campuses (SCs), which are universities where technological devices and applications create new experiences or services and facilitate operational efficiency, allow experimentation on a smaller scale, the concept of SCs as a testbed for a smart city is gaining momentum in the research community. Nevertheless, while universities acknowledge the academic role of a smart and sustainable approach to higher education, campus life and other student activities remain a mystery, which have never been universally solved. This paper proposes a SC concept to investigate the integration of building information modeling tools with Internet of Things- (IoT)-based wireless sensor networks in the fields of environmental monitoring and emotion detection to provide insights into the level of comfort. Additionally, it explores the ability of universities to contribute to local sustainability projects by sharing knowledge and experience across a multi-disciplinary team. Preliminary results highlight the significance of monitoring workspaces because productivity has been proven to be directly influenced by environment parameters. The comfort-monitoring infrastructure could also be reused to monitor physical parameters from educational premises to increase energy efficiency.

Keywords: sustainable ecosystem; environmental monitoring; IEQ calculation; BIM

1. Introduction

1.1. Research Motivation and Scope

Smart cities must be large towns able to sustain their citizens' incremental needs while promoting environmental sustainability. With the emergence of new information and communication technologies (ICTs), such as the Internet of Things (IoT) and big data, smart cities are closer to this realization. However, the deployment of such an amount of technology in a wide geographical area requires experimentation and testing. Consequently, our research proposes to create smart campuses (SCs) to experiment with the deployment of these ICT technologies [1,2]. The aim is to support the efficient management of a "small" smart city. In the context of an SC, we consider the needs of students and campus staff while improving environmental sustainability.

This way, we narrow the scope of the present paper by focusing on two properties: students' comfort and energy efficiency. We aim to integrate the ICTs to monitor and manage both of them;

therefore, IoT devices are responsible for detecting comfort levels and energy efficiency on the campus and take consequent corrective action. We propose to conceptualize groups of smart devices that could be used to achieve a determined goal by acting as physical-world proxies for agents. For instance, an agent is responsible for improving energy efficiency and comfort in a given classroom, and it senses and actuates on the physical world (e.g., classrooms) through IoT sensors and actuators.

According to Eurostat and the European Commission report in Education and Training Monitor 2019, more than 31% of the European population is currently enrolled in educational programs. This percentage only includes physical-based learning. However, in recent years remote learning and distance education have grown significantly [3]. Hence, more than 138 million European people spend a considerable amount of their time in educational facilities (schools, universities, colleges, etc.). Most of these facilities were constructed a long time ago to rapidly address the educational needs of growing local populations due to the societal changes in which young adults began to complete a full education plan: primary school, high school, and university/vocational training. At that time, educational institutions were large infrastructures to allocate all students, faculty members, and staff. However, little or no attention was paid to the overall comfort of these environments—understood as a measure that balances the wellbeing of all users, the efficiency of the processes involved, and the pro-environmental footprint of their facilities.

Recent studies have suggested that comfort in educational environments is a critical parameter for the success of learning and the evolution of society [4]. Comfort is usually related to individual and isolated parameters such as air quality, temperature, or noise [5]. Measuring these parameters can be tackled seamlessly with unobtrusive equipment as an enabler to obtaining reasonable—yet incomplete—partial conclusions [6]. Indeed, much effort has been made to improve ICT-based solutions in the direction of more accurate and more complete systems (e.g., including more local variables) [7]. However, these recurrent solutions typically fail at quantifying the side effects of measuring comfort involving external parameters to the educational environment that still have a great impact on its associated issues (e.g., overall sustainability, energy efficiency, learning and teaching performance, etc.). For instance, they are unable to address dilemmas such as whether it would be worth increasing the energy consumption to keep the optimal thermal conditions in order to ensure an improvement in the students' academic output or not.

In essence, current ICT-based proposals to monitor comfort either do not deal collectively with the vast amount of internal and external parameters to measure them, or only provide local (i.e., partial) qualitative views of comfort as they are more focused on keeping the technological paradigm of cost-effectiveness [5]. Hence, existing developments are incremental, concerning a conceptual and technological paradigm that remains unchanged. Understanding, monitoring, predicting, and optimizing comfort in educational environments requires a holistic and cross-layer view able to frame and quantify the dynamic and nonlinear relations of their involved users [8]. Indeed, addressing the comfort in educational facilities cannot be tackled in a linear way since several interdependent parts are continuously changing. Therefore, it is safe to say that comfort in educational environments has remained under-sampled for years mostly due to the complexity of objectively quantifying and acting on it.

Specifically, authors have examined, measured, and analyzed all the potential external (e.g., available open data, weather information, architectural issues, etc.) and internal (e.g., thermal or acoustic data) variables affecting such comfort to (1) quantify, monitor, predict and optimize comfort in physical and, eventually, virtual educational environments; (2) enhance overall sustainability and (3) overcome potential issues in the teaching-learning process. The proposed structural model of our SC will help to predict the impact of the distinct institutional policies on comfort and, as such, it will encourage drivers to address changes such as conducting active learning methodologies, adopting eco-friendly initiatives to reduce environmental footprint toward carbon neutrality, or incorporating renewable energies to save natural resources.

Overall, our research proposes a radical paradigm shift and the use of IoT technology in monitoring and optimizing comfort in university learning environments, where the frame for analysis and modeling of the comfort parameter holistically covers the internal and external meta-dimensions, as a whole, that characterize the socio-environmental interactions of three strategic stakeholders: teaching and learning community, facility management staff, and energy providers. If these dimensions, and their impact on comfort, were defined, quantified, and validated through innovative scientifically-grounded methods, this would drive the conception of a new technology able to transform the current generation of comfort analysis in physical and virtual educational environments. This achievement will endow them with a completely novel functionality to improve their sustainability while helping to understand, design, populate, monitor, and perceive comfortable learning environments.

1.2. The Importance of the University in the Promotion of Sustainability

Universities and colleges play a crucial role in the development of knowledge and innovation, especially in more environmentally benign technologies and goods to promote sustainable living [9]. They represent vital places to explore, test, develop, and communicate the necessary conditions for effective and sustainable change [10,11]. Many universities and colleges are similar to micro cities because of their population, size, and the many different types of activities happening on campus. According to the literature, a sustainable university is “a higher educational institution that addresses, involves and promotes, on a regional or a global level, the minimization of negative environmental, economic, societal, and health effects generated in the use of their resources in order to fulfill its functions of teaching, research, outreach and partnership, and stewardship in ways to help society make the transition to sustainable lifestyles” [12].

Although universities acknowledge their roles in our present culture, there is a part of university life that has been rendered a mystery and has never truly been solved universally among universities: sustainable development. Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [13]. Since sustainability is an issue of present-day and future societies, it is crucial that places of learning, such as universities, play a critical role in teaching sustainability to citizens who will be the future decision-makers. Sustainability practices begin at the university level by adapting environmentally sustainable policies and expanding to local, regional, national and international levels [14].

Since graduates of any discipline will need knowledge and skills related to sustainability, the challenges and possible solutions should be integrated within the main functions of a university: the development of an interdisciplinary curriculum, environmental literacy, sustainable academic research, sustainable physical operations of the campus, and collaboration amongst universities. The common ground of sustainable practices is the ethical and moral responsibility of universities to be leaders in promoting sustainability [15–17]. Campus sustainability has become an issue of global concern for university policymakers and planners as a result of the realization of the impacts the activities and operations of universities have on the environment. Generating more sustainable campus life, including actual innovative campus projects and administrative policies, creates opportunities for students within sustainability [18].

Due to their unique position, universities and colleges play a key role in educating the future generations of citizens who will have expertise in all fields of the labor market. This role includes both the promotion of environmental literacy among students and research in sustainability, as well as a contrived effort to decrease the university’s impact on the environment [19]. Although universities worldwide are constantly improving their vision and curricula to address future sustainability challenges, there is still much work to do. The goal of sustainability education is to give students knowledge and skills and help them find solutions to environmental, health-related, and economic challenges [20]. Another important element in the methodology used for teaching students about sustainability is the need to undertake hands-on projects to ensure the students’ understanding of the challenges and possible solutions. Self-sustainable campuses with many projects (e.g., composting, rooftop gardens and solar panels) teach students about sustainability and require the active work of the students. Students who participate in planning, building, and maintaining these projects will be more likely to develop lifelong sustainability habits.

1.3. The Statement for Our Smart Campus Comfort Challenge

The main goal of the Advanced Training in Health Innovation Knowledge Alliance (ATHIKA) [21] is to use knowledge transfer to duplicate, yet also locally customize, sustainability innovations undertaken by diverse institutions. The ATHIKA project will build a set of advanced training programs involving academia, public administrations, SMEs (Small and Medium Enterprises), start-ups, and health business consultants. The variety of profiles of the project partners will provide an overall perspective of the sector and will enable the identification of its most urgent challenges. They will guide and coach students and researchers during the development of novel technical and ethical-compliance solutions to implement ICT solutions in the health sector, especially the solutions related to the smart campus (SC) ATHIKA challenge. Authors envisage that the accurate monitoring, analysis, prediction, and management of comfort will lead to a reduction in the overall environmental footprint of educational environments while increasing the comfort of their users.

In this paper, we present the development and implementation of novel and advanced healthy SC by using comfort as a quality metric, based on ICT that relies on greater interaction between healthcare professionals, education communities, and technological experts. Available SC data are becoming massive, and needs to be handled in controlled environments, under proper ethical criteria. The goal is to establish a challenge-based learning program where teams of students from various disciplines and countries will compete to find solutions for our SC challenge. The devised solutions, or pretotypes, have been developed into prototypes, following a technology coaching (supported by universities) and the application-oriented coaching (conducted by the target company). This program will be used to reduce the learning and experience curve associated with targeting, developing, and implementing sustainability projects in university settings. The current paper introduces the research carried out in the smart campus challenge within the ATHIKA Erasmus+ project [21].

Reaching a comfortable and responsive SC implies focusing on the two interrelated concepts: "smartness", mainly related to addressing the problems cities face with the aid of information and communication technologies (ICT), and "healthy sustainability", emphasizing citizens' inclusion (students and faculty) and social wellbeing (social dimension), ecosystem protection (environmental dimension) and boosting of the local economy (economic dimension) [22].

Nowadays, new ICTs make the real-time monitoring of university campus conditions possible. A variety of sensors and intelligent devices deployed throughout the campus can monitor pollution, noise, natural or artificial risks as well as epidemics, and manage public spaces and facilities to reduce or avoid negative impacts on educational community health. Our SC challenge also aims to build a platform capable of assisting contemporary university campuses in transforming towards sustainable and comfortable campuses by exploiting data from both existing data sets and on-field sensors. The proposed approach is based on an interdisciplinary digital twin modeling that can be integrated into existing decision support systems by providing quantitative hints and suggestions on architecting and ICT engineering sustainable policies. Using novel trends in ICTs—such as cloud computing, big data, artificial intelligence and Internet of Things—to process, visualize and analyze real-time data is now feasible to accurately monitor citizens and their interactions with the physical infrastructures, and thus, identify, learn, and act to improve the future public health conditions.

In fact, ATHIKA aims to (1) explore innovative approaches to contribute to the sustainable campus transformation, employing technologically advanced pedagogy in a multi-disciplinary way through ICT engineering and architecture frameworks, (2) propose innovative good practices for managing a university campus, involving data-driven sustainable products and service outcomes in order to support environmental policymaking and (3) use novel edge computing architectures for advanced submetering and distributed hybrid intelligence algorithms [23]. Nevertheless, in this paper, the authors introduce a quantitative and measurable definition of comfort, together with the first-ever accurate and unbiased measurement of the concept. It includes the development of computational models and low-cost infrastructures for automated, resilient, and reliable data acquisition, storage, processing, and visualization of comfort. The innovative and scientifically grounded technologies of our proposal have been validated in our real-world university campus.

1.4. Framework-Based Methodology

Smart cities are usually associated with complex systems [24]. Complex systems are defined as systems formed by heterogeneous elements that interact with each other and their environment [25–27]. The diversity of these elements, the non-linearity of relationships between them and the multiple influences of the environment determine their complexity [28]. Indeed, the level of complexity of smart cities and their ability to achieve urban sustainability has called for debate [29]. Additionally, adding smartness to the city leads to an increase in complexity—and more complexity requires more energy [30,31]. Therefore, in light of the debate surrounding the sustainability of smart cities and with the acknowledgment that smart campuses are similar to small smart cities [1,2]—thus, potentially able to shed light on the debate—the methodological framework used in this work considers the smart campus as a complex system.

Under the umbrella of complexity theory comes the framework of complex adaptive systems (CAS) [25]. CAS refers to systems that involve "a large number of components, often called agents, which interact and adapt or learn" [32]. General top-level properties and features such as self-similarity, complexity, emergence and, self-organization induce CAS to be considered as an appropriate framework for the methodological sequence of the presented research project proposal on comfort in educational environments: agents (i.e., teaching and learning community, facility managers, and energy providers) and the system (i.e., physical and virtual educational environments) are adaptive, and the system is a complex self-similar collectivity of interacting, adaptive agents.

In juxtaposition with the vision of smart campuses as CAS, some authors model the IoT—an enabler technology for SCs—as a complex system too [30,33–36]. To exemplify our SC modeling approach, we consider the increase in students' comfort and energy efficiency. We allocate each space (e.g., classroom) with an agent with two goals. The first, concerning students' comfort, the second, aiming at energy efficiency. The agent is responsible for sensing different properties of both students and classrooms through IoT sensors, gathering contextual information, and acting according to the desired level of comfort and energy efficiency through IoT devices. Therefore, we allocate several agents in the campus.

Agents in a multi-agent system (MAS) cooperate to maximize their goal [37]. For example, given a determinate number of students in a classroom, the agent sets a level of comfort for the classroom. At the same time, the agent sets a determinate energy efficiency goal. Then, the agent needs to carry out actions to achieve a reasonable level of students' comfort and energy efficiency. Additionally, the environment in which the agent operates might be modified by other agents and external factors. Modification by other agents might be due to their operation in other spaces (e.g., spaces on the same floor or building), and modification by external factors might be due to weather conditions, for example.

With regard to the characterization of the hierarchical structure of the system comprehended by IoT devices and agents (in our framework, guardians), we add a higher-level module providing a decision support system: the wise module. Therefore, IoT devices, the guardian module, and the wise module have a hierarchical relationship in the digital twin as well. IoT devices are deployed in a zone or section of an SC building, and the guardian perceives and acts on the physical world using those devices; therefore, the relationship between the guardian and the IoT devices is one-to-many. In turn, the wise module is connected to the guardians in a one-to-many relationship and contains the support decision system to coordinate the guardians, so they operate towards a common goal: students' comfort and energy efficiency.

Essentially, at a lower scale, an IoT-enabled device is a system of software and hardware components; at an upper scale, in consideration of the model we propose, devices (sensors and actuators) cooperate to enable an agent to sense and actuate on the physical world (*guardian*), zooming out, agents in a MAS form a system (*wise* module), and beyond these scales, more systems of systems arise.

In addition, regarding the interaction between agents in a CAS and their implementation using ICTs, we now set our focus on the relationship between agents. The authors in [38] compare network and complexity theories and define CAS as "a pattern of relationships among adaptive, self-organizing and interdependent elements (agents)". As stated, our technological framework is under the umbrella of IoT technologies among other novel ICTs. To frame the relationships between agents—and the organizing dynamics of their relationships—we use the Social Internet of Things (SIoT) paradigm.

The SIoT [39] promotes a scalable and flexible network structure between things. It enables things to be part of a social network to search for required services or things. The search is influenced by the trust assigned, subjectively or objectively, to each thing. In an SC, sensors and actuators might be placed at relevant locations such as classrooms. Then, according to the proposed SIoT relationships, sensors and actuators in a classroom create social relationships between each other, either by their closeness in space (called co-location relationships) or by their need to cooperate and work together to achieve a certain goal (called co-work relationships). Moreover, in the presence of an agent per classroom (the guardian), they create a hierarchical relationship; the agent on top, sensors, and actuators (things) at the bottom.

Some properties of our study (e.g., air quality, humidity, and temperature) might share a greater space than a classroom. For example, the temperature in a classroom dissipates and affects other classrooms in the same building. Consequently, when considering the spaces and locations in a building, agents need to cooperate to achieve balance and to improve students' comfort and energy efficiency, agents in different classrooms and spaces cooperate and create SIoT relationships between them by using the *wise* module. Furthermore, agents need to perceive the state of the physical world to validate that their acts work towards the desired behaviors in the digital twin model. In a large deployment, communication between all agents would create communication overhead. To reduce this overhead, the state of the world should be perceived within the agents' neighborhood [33].

Concluding, the SC is considered a small smart city in the scope of our research. SCs, similar to smart cities, are CAS but on a smaller scale, where heterogeneous elements adapt, interact, and create a pattern of relationships. The main elements in our SC model are IoT devices, guardians and the wise module, which have been modeled in the digital twin environment. The guardians and the wise module create relationships, interact, and adapt, whereas IoT devices (which may have limited resources) create relationships and interact. Additionally, we frame the potential relationships under the IoT paradigm called SIoT. The SIoT aims to provide a scalable and flexible network of things to facilitate their search and discovery, both processes influenced by security-related trust mechanisms. Those interactions are depicted in Figure 1.

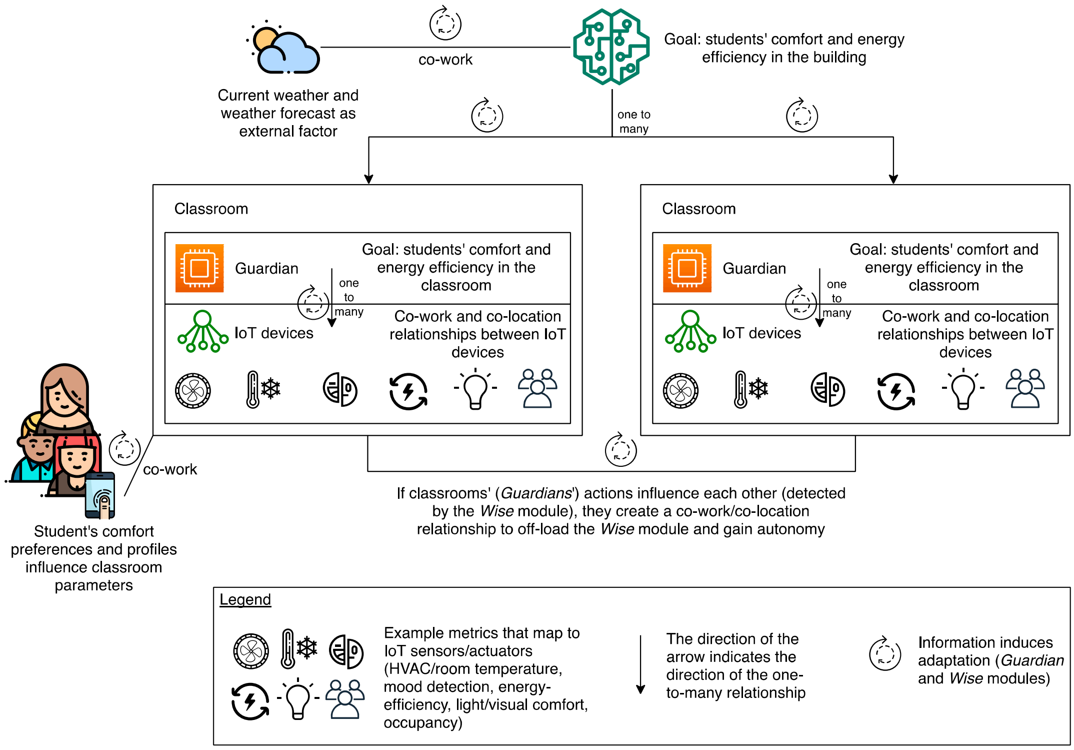

Figure 1. Complex adaptive system and Social Internet of Things (SIoT) relationships in the smart campus digital twin.

1.5. IoT Platforms

In the literature, there are only a few papers that present descriptions of current SC proposals [8,40]. Nevertheless, authors in [41–43] have carried out extensive research on previous SC designs and have encountered several examples. There are SCs based on the development of an open data platform or based on cloud computing, service-oriented architecture, and IoT platforms.

As stated before, the main principle of communication inside an IoT system implies that each collector node must "speak" the same language. In IoT, this is a big issue since there is a deluge of devices, each with its own language that does not follow the standards [44]. However, this compatibility problem is solved through a middleware [37,45,46] (i.e., a software that provides interoperability between incompatible devices and applications). In the literature, IoT middleware solutions are sometimes referred to as IoT platforms or IoT middleware platforms because generally, the middleware is a platform. However, as it is proven in this project, other middleware tools exist, such as building information modeling (BIM) or computational simulation software, which can act as a middleware [47–49].

Various IoT platforms can be generally categorized into four categories known as (1) public traded IoT cloud platforms, (2) open source IoT cloud platforms, (3) developer friendly IoT cloud platforms, and (4) end to end connectivity IoT cloud platforms [50]. Table 1 describes various platforms in each of these categories that could be used in deployments of smart cities and IoT environments [21,50].

Table 1. Comparisons among some of the most used Internet of Things (IoT) platforms.

IoT Middleware	Type	Access Model	Data Format Supported	Programming Language Supported	Protocols	Pricing	Technologies Used
AWS IoT Platform	1	PaaS, IaaS	JSON	Java, C, NodeJS, Javascript, Python, SDK for Arduino, iOS, Android	HTTP, MQTT, Websockets	Pay when executing your own written functions	All Amazon services
Microsoft Azure IoT Hub	1	IaaS	JSON	.NET, UWP, Java, C, NodeJS, Ruby, Android, iOS	HTTP, AMQP, MQTT	Pay according to the number of devices and messages per day	Azure Cosmos DB, Azure Tables, SQL database
IBM Watson IoT Platform	1	PaaS, IaaS	JSON, CSV	C#, C, Python, Java, NodeJS	MQTT	Pay according to the number of devices and messages per day	Cloudant NoSQL DB
Google IoT Platform	4	PaaS, IaaS	JSON	Go, Java, NET, Node.js, php, Python, Ruby	MQTT, HTTP	Priced per MByte	Google's services
Kaa IoT Platform	4	IaaS	JSON	Java, C, C++	MQTT, CoAP, XMPP, TCP, HTTP	Free	NoSQL, MangoDB, Real time analytics and visualizatoin with Kaa
ThingSpeak	2	PaaS	JSON, XML	Matlab	MQTT API and REST	Free	Matlab, dashboard and Matlab analytics, MySQL
Carriots	3	PaaS	XML, JSON	Java	MQTT	Paid services	NoSQL Big- Database
Temboo	3	PaaS	Excel, CSV, XML, JSON	C, Java, Python, iOS, Android, javascript	HTTP, MQTT, CoAP	Free access for first 100 devices after that paid per device	Microsoft Power BI, Google BigQuery
Thinger.io	2	PaaS	JSON		HTTP, MQTT		MongoDB
Sentilo	3	PaaS	JSON	C, Java	HTTP	Free	Redis, Apache, PubSub, MongoDB, ElasticSearch

2. A Proposal for Smart Campus' Metrics to Obtain a Digital Twin Model

The term smart campus (SC) has been used to refer to digital online platforms that manage university content and the set of techniques aimed to increase university student smartness and knowledge transmission ease [51]. Several research questions have to be addressed in order to model the SC concept. In [52], a systematic literature review is performed to explain the problem by analyzing more than 300 tracked publications: (1) what are the SC features? (2) What kinds of technologies support the implementation? (3) Is there any standard model? (4) What are the main applications? (5) What are the SC contributions? The main conclusion of the research community is that the research in the smart campus area is still growing, and there is no standard used for the development of the smart campus concept and implementation. In essence, an SC is generally considered as the integration of cloud computing and the IoT, which pursues intelligent management, teaching, research, and other activities of universities [8,52,53]. As stated in [8,52], the main challenges of a sustainable SC are (1) the promotion of intelligent energy management by inner facility management, (2) the existence of a digital twin model that facilitates simulations and knowledge extraction for intelligent decision-making and (3) obtaining real-time data to render campus map information ergonomically, to generate event response and warning services, etc.

The parameters that influence the SC's environment are interconnected, so a specific component of comfort can make a space not comfortable in academic terms [54]. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Technical Committee Terminology [55], the indoor environmental quality (IEQ) is the perceived indoor experience of the building's indoor environment that includes aspects of design, analysis, and operation of energy-efficient, healthy, and comfortable buildings. Fields of specialization include architecture, heating, ventilation, and air conditioning (HVAC) design, thermal comfort, indoor air quality, lighting, acoustics, and control systems.

Thus, the term that comprises the evaluative numerical summary of IEQ performance data is known as the IEQ model [56]. To provide an outline picture of how well a workspace is performing, IEQ models require the aggregation of data by using objective physical measurements (e.g., air temperature, humidity, measurement of noise level, dioxide concentration, luminance, etc.), subjective occupant perceptions (e.g., how satisfied are you with the temperature in your workstation? Does the air quality in your workspace enhance or interfere with your ability to get your job done? etc.) collected with manual surveys or both objective and subjective data [5,17]. The measurement of subjective IEQ indexes is widely achieved by methods such as the Building Use Studies Ltd. (BUS) [57] and through the Center for the Built Environment (CBE) survey [58]. Nevertheless, surveys do not always capture IEQ issues that may have energy implications (e.g., over-lighting or economizer operation) and have incomplete diagnostic capability, and they also have a difficulty finding a general interpretation criterion of results [59].

This paper will focus on several objective measurement methods that have been developed and justified in the literature, since our goal is to quantify the comfort level experienced at the campus facilities by collecting environmental data in order to maintain the updated digital twin. The criterion followed to review the studies previously completed has been the same as the proposed by David Heinzerling et al. [56], without forgetting our introduced restrictions related to energy efficiency.

2.1. Comfort Modeling

As stated in [55], the indoor environmental quality models combine multiple IEQ parameters, comprised of acoustic comfort (AC), indoor air quality (IAQ), visual comfort (VC), thermal comfort (TC), and represent the relation between occupant satisfaction and objective measurements by way of a single number. Nevertheless, not all physical environments of indoor comfort are equally important to the occupants. In [56], authors have defined the weighting scheme regarding the four types of comfort that comprise the IEQ model. The existing literature on indoor environmental quality (IEQ) evaluation models is explored from previous literature studies [60–64]. Then, a new weighting and classification scheme is proposed.

The criteria followed in this paper to select an existing IEQ weighting and model schema are not only settled on the weighting schema closest to the one defined by experts in the field, but are also based on observations (surveying), creating a generic formula for each of the four comfort metrics. As a result of applying the above foundation, the proposed schema that our research has followed [63–65] is the one weighted in Figure 2 and quantified in Table 2.

Table 2. Proposed indoor environmental quality (IEQ) schema.

Metric	Regression Constants	Calculation
AC	$K_0 = 4.74$	$\phi_0 = 1 - \left(\frac{1}{1+e^{(9.54-0.134 \cdot dBA)}}\right)$
IAQ	$K_1 = 4.88$	$\phi_1 = 1 - \frac{1}{2}\left(\frac{1}{1+e^{(3.118-0.00215 \cdot CO_2)}} - \frac{1}{1+e^{(3.23-0.00117 \cdot CO_2)}}\right)$
VC	$K_2 = 3.70$	$\phi_2 = 1 - \left(\frac{1}{1+e^{(-1.017+0.00558 \cdot lx)}}\right)$
TC	$K_3 = 6.09$	$\phi_3 = 1 - \left(\frac{\text{PPD}}{100}\right)$
IEQ	$K_{IEQ} = -15.02$	$1 - \left(\frac{1}{1+e^{(K_{IEQ}+\Sigma_{i=0}^{3} k_i \phi_i)}}\right)$

Figure 2. IEQ metric weighting chart.

Table 3 shows our proposal for physical environmental parameters to be measured and the sensors that could be used, specifying the comfort metric.

Table 3. Possible metrics of environmental monitoring and their associated sensors.

Metric	Parameter	Unit	Measurement Method	Tool or Resource
TC	Operant Temperature	°C	Temperature-humidity sensor	DHT22
TC	Relative Humidity	%	Temperature-humidity sensor	DHT22
TC	Occupant metabolic rate	Met	Pulsometer	MAX30102
TC	Mean Radiant temperature	°C	Globe thermometer	Blackglobe-L
TC	Air temperature	°C	Temperature-humidity sensor	DHT11

Table 3. *Cont.*

Metric	Parameter	Unit	Measurement Method	Tool or Resource
TC	Exterior air temperature	°C	Temperature-humidity sensor	DHT22
TC	Exterior air humidity	°C	Temperature-humidity sensor	DHT22
TC	Surface of element (wall, radiators, windows)	m^2	Thermographic camera module	Adafruit AMG8833 8×8 Thermal Camera Sensor for Arduino
TC	Person Clothing resistance	clo	Survey/infrared thermography camera	ThermaCAM s45/FLIR TG165-X
IAQ	Air velocity	m/s	CFD simulation	Ansys CFX 18.2/Visual-CFD/SolidWorks and AutodeskInventor CFD add-ons
IAQ	Specific flow of air introduced	m^3/h	CFD simulation	Ansys CFX 18.2/Visual-CFD/SolidWorks and Autodesk Inventor CFD add-ons
IAQ	Air change per hour	h-1	CFD simulation	Ansys CFX 18.2/Visual-CFD/SolidWorks and Autodesk Inventor CFD add-ons
-	Room volume	m^3	-	-
-	Number of occupants	-	Camera/PIR motion sensors	Sony IMX219 fish eye module for Raspberry/ElectroPeak HC-SR501 PIR sensor
IAQ	TVOC	mg/m^3	TVOC and eCO_2 gas sensor	Adafruit SGP30
IAQ	CO	ppm	Carbon monoxide sensor	MQ-7
IAQ	CO_2	ppm	Analog CO_2 gas sensor	DFRobot/MG-811
IAQ	Dust	$\mu g/m^3$	Grove—Dust sensor	PPD42NS
IAQ	multi-Gas (NH_3, NO_x, alcohol, Benzene, smoke)	ppm	Multi-gas sensor detector	MQ-135
IAQ	Odors	ouE/m^2	Electronic nose	zNose 4300 or 7100 model
AC	Reverberation time	s	Sound analyzer	Dual-channel Brüel & Kjaer BK 2260 real-time sound analyze
AC	Speech transmission index	-	Acoustic simulations	Odeon 9.0 software
AC	Level difference index	dB	Acoustic simulations	Odeon 9.0 software
AC	Impact sound pressure level	dB	Acoustic simulations	Odeon 9.0 software

Table 3. *Cont.*

Metric	Parameter	Unit	Measurement Method	Tool or Resource
AC	Clarity	dB	Sound sensor	Sparkfun sound sensor
AC	Sound insulation	dB	Dual-channel sound analyzer and an omnidirectional loudspeaker	Dual-channel Brüel & Kjaer BK 2260 real-time sound analyze
VC	Maintained luminance	lux	Lux meter	BH1750/PCE-170
VC	Discomfort glare	-	Image luminance measuring device/luminance meter	OP75/TES 137
VC	Daylight	cd/m^2	CAD simulations	Simulink software
VC	Dry bulb temperature	°C	Product specifications	-

2.1.1. Thermal Comfort (TC)

The human body tries to maintain a temperature of around 37 °C. The temperature is maintained through heat exchange between the human body and the environment through convection, radiation, and evaporation [66]. In a building, any sense of discomfort of the occupants motivates them to modify comfort parameters (e.g., those of the HVAC system or opening/closing windows) to obtain the desired comfort, usually obtaining non-optimal levels regarding energy efficiency [54]. A thermal comfort model based on the thermal balance of the human body was developed by Fanger [67] for living spaces in 1970 (see Figure 3). In this model, Fanger calculated the predicted mean vote (PMV) index (seven-point scale) by relating the net heat in the human body and the surrounding thermal equilibrium, using six different parameters consisting of four environmental factors (indoor air temperature, mean radiant temperature, air velocity, and humidity) and two personal factors (activity or metabolic rate and clothing resistance) [66,68].

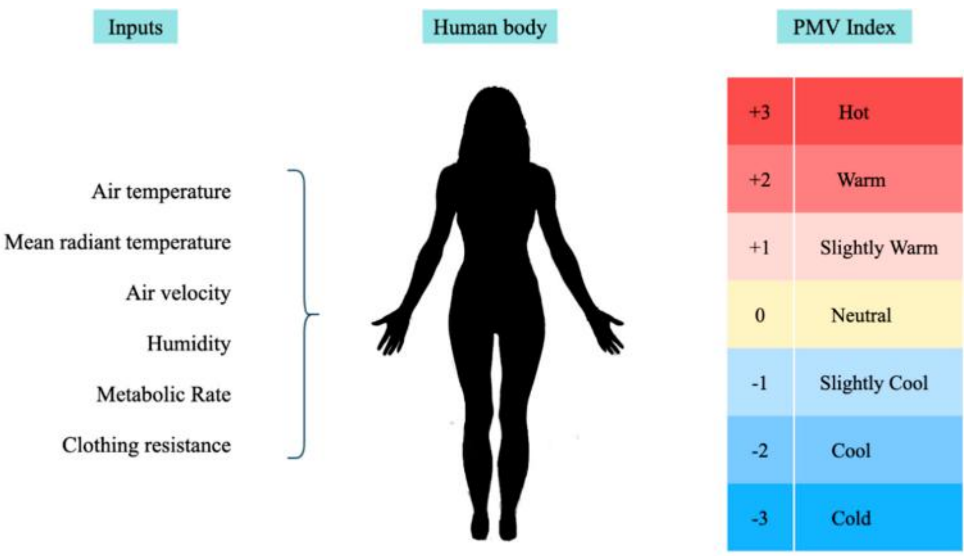

Figure 3. Predicted mean vote (PMV) index parameters and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal sensation scale.

In terms of thermal preferences, various studies collected by Zheng Yang et al. [69] have shown that students easily accept slightly cool thermal conditions [70] but prefer slightly warm environments [71] (e.g., temperatures above 23.33 °C (74 °F) influence student performance in math and reading [72]).

2.1.2. Acoustic Comfort (AC)

In classrooms, knowledge is mainly transmitted through oral communication. The quality of this communication, and ultimately, of classroom education itself, is closely linked to the classroom's acoustic quality [73]. This acoustic quality can be characterized based on some parameters described in the International Organization for Standardization (ISO) 3382 standard [74], where methods include measuring the reverberation time [75], speech transmission index [76], sound insulation [73], and the noise levels inside and outside the classroom [77–79]. According to these authors, high noise levels in the classroom impair oral communication, causing students to become tired sooner more often. This premature fatigue tends to provoke a negative effect on their cognitive skills. In fact, the recommended noise level in [77] is 40 dB(A) for classroom purposes.

2.1.3. Visual Comfort (VC)

The main focus on visual comfort has traditionally been light levels, contrast, and discomfort glare. Upon these, there is agreement on many principles [80], defined by the International Commission on Illumination (CIE) [81,82], the European Committee for Standardization (CEN) [83], and also lighting guides for specific building properties, such as the Lighting Guide LG5 for educational buildings [84] or the recommended practice for office lighting [85] by the Illuminating Engineering Society of North America (ANSI/IES).

The light levels are determined by the maintained luminance, which is provided by artificial lighting, and the luminous flux (either artificial or natural), which describes the quantity of light measured at 0.75 m above the ground with a lux meter (see Table 4, where the discomfort glare rating is used).

Table 4. Recommended visual comfort parameters for some of the educational spaces [84].

Space or Area	Maintained Luminance	Discomfort Glare	Observations
Classrooms for morning classes	300 lx	19	Lighting should be controllable
Classrooms for evening classes and adults education	500 lx	19	-
Lecture hall	500 lx	19	Lighting should be controllable
Black board	500 lx	19	Prevent specula reflections
Practical rooms and laboratories	500 lx	19	-
Computer practice rooms	500 lx	19	-
Student common rooms and assembly halls	200 lx	22	-
Preparation rooms and workshops	500 lx	22	-
Technical drawing rooms	750 lx	19	-

2.1.4. Indoor Air Quality (IAQ)

According to [55], indoor air quality is defined as the attributes of the respirable air inside a building (indoor climate), including gaseous composition, humidity, temperature, and contaminants (Table 5). Having poor indoor air quality (IAQ) is related to sick-building-syndrome (SBS), which can be tied to a lack of adequate outdoor air ventilation, improper exhaust, ventilation of odors, chemicals or fumes, or poor indoor air quality. Other sources of sick buildings may be linked to contaminants produced by outgassing of some types of building materials, volatile organic compounds (VOC), bacteria molds, etc. This syndrome does not conform to a particular illness and is difficult to trace to a specific source.

Table 5. Recommended indoor air quality comfort parameters [80,86].

Indoor Contamination	Allowable Air Concentration Levels
Carbon monoxide (CO)	<9 ppm
Carbon dioxide (CO_2)	<800 ppm
Airborne mold and mildew	<20 µg/m^3 above outside air
Total VOC	<200 µg/m^3 above outside air

Air quality does not only affect the health status of the occupants, but it also affects the monitoring of odorous compounds in ambient air, which is an important task for environmental researchers because of the presence of some toxic volatile organic compounds (VOC) and carbonyl compounds in odorous compounds [87]. The VOC and carbonyl compounds present in malodors have adverse effects on the air quality in the surrounding areas of the sources as well as on the health of the people residing near the sources [88].

2.2. Energy Efficiency Monitoring

Energy efficiency is the objective of reducing the amount of energy required to provide products and services. There are many motivations to improve energy efficiency (e.g., financial cost savings and solutions to the problem of reducing greenhouse gas emissions). According to Leadership in Energy and Environmental Design standards (LEED standards [89]), the design of an energy-efficient building consists of implementing a whole-building system approach in the most efficient way to achieve an energy-efficient building. The whole-building approach treats the building as one energy system with separate but dependent parts. This means that, in order to fulfill our objective, we have to make our university campus an energy-efficient building capable of measuring and reducing its energy consumption by defining a whole-building's digital twin where IoT sensors and agents are in charge of the real-time data updating. The most relevant tactics for this objective are the following [89]:

- Design of an energy-efficient building: the implementation of a whole-building system approach to new construction is the most efficient way to achieve an energy-efficient building (see Figure 4).
- Weather usage: the design should take into consideration the building orientation. The way a structure is situated on a site and the placement of its windows, rooflines, and other architectural features is critical for efficiency. Weather data could be incorporated by outdoor sensor agents or by using a public Application Programming Interface (e.g., Meteostat's API offers historical and daily weather data from anywhere [90]).
- Ventilation: in a traditional building that uses natural ventilation or extract ventilation, 20 to 40 percent of energy consumed for heating is caused by ventilation.
- Lighting: the decision to install (1) IoT sensors such as timers and photocells that turn lights off when not in use and (2) dimmers, when used to lower light levels are good decisions to save money and energy. Light over ethernet or digital addressable lighting interfaces are smart solutions that make luminaries controllable. These methods are applied with light-emitting diode (LED) technology and allow a total control and monitoring of the whole building's luminaries [91,92].
- Heating: this concept is the largest energy expense in educational and commercial buildings. The incorporation of energy-efficient and real-time measures into a building's heating and cooling systems is essential to create an energy-efficient accurate model of the current behavior inside the digital model. In terms of heating, a programmable or smart thermostat is one of the best options to work hand in hand with the wise module. When you install a programmable thermostat, it is

easier to eliminate wasteful energy use from heating and cooling without upgrading the HVAC system or sacrificing any comfort [93].

- Monitoring: an energy modeling software is an effective way to bridge the physical and the virtual world. The digital twin could also integrate historical data from past usage to factor into its digital model. Thus, data must be transmitted seamlessly, allowing the virtual entity to exist simultaneously with the physical entity [94,95].

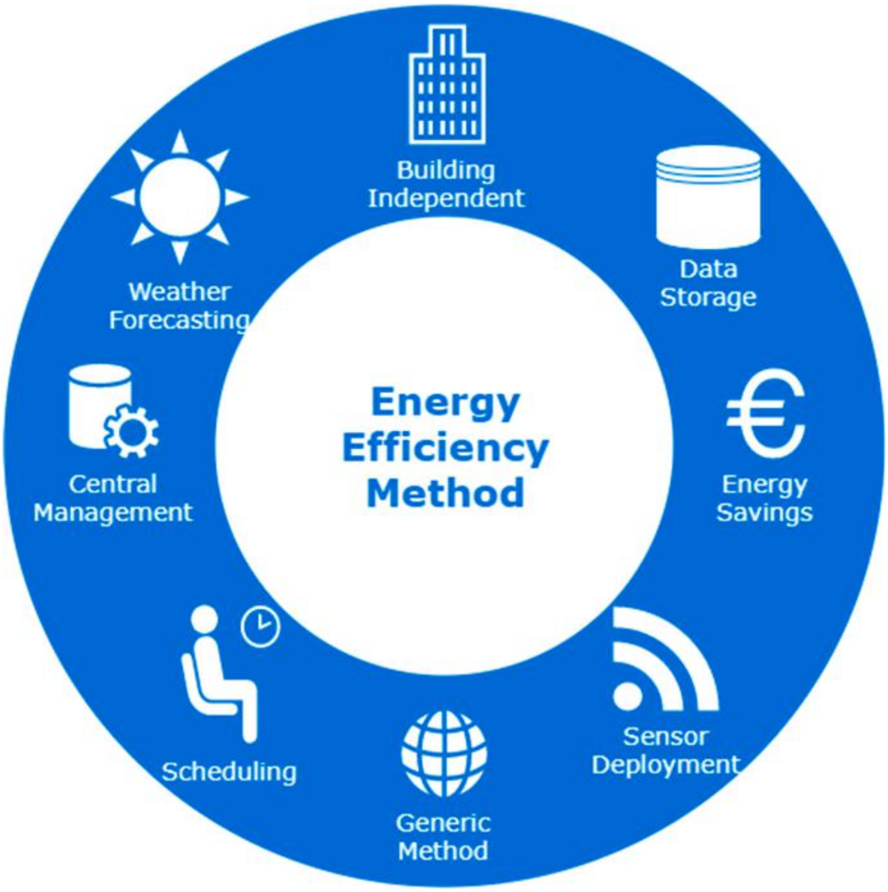

Figure 4. Subtopics for an energy efficient zone.

In an SC, the integration of systems can be used to reduce operating costs through experimentation with a digital twin model. This would result from applying most of the engineering and architectural characteristics mentioned before. If we divide the whole campus into zones, the smart system can easily control each room's energy consumption [96]. We assume that the data sensed by IoT agents for the SC's comfort must be useful enough for a system that aims to find energy efficiency as well, which can use them to generate efficiency improvements. However, these benefits should not be imposed on the comfort of the occupants of the building. Our proposal aims for efficient energy usage by using the data measured by sensors deployed inside the building for the TC, AC, VC, and IAQ assessment (Section 2.1), and other accessible data such as room schedules and weather forecasting (Figure 5).

In the SC that we propose, a zone defines a limited space within the building. The zone, which is usually a room or a section of the building, is described by a list of parameters such as capacity, occupancy schedules, daylight availability, current and historical occupancy, and comfort metrics (e.g., temperature and humidity). The guardian, a digital agent, is responsible for a unique zone (in a one-to-one relationship). It has the autonomy and responsibility to control the IoT devices and maximize the comfort and energy efficiency of the zone. Once the guardian gathers the data from the

IoT sensors, it processes the data and stores them in the storage subsystem. Moreover, the guardians relay this information to a digital entity that aggregates them (and is on top of the hierarchy), the wise module. The wise module contains the support decision system that manages the entire building and guides each guardian, with the overarching goal of providing optimal comfort and energy efficiency (Figure 6). Thus, the wise module is the main actor for the inferred level of the smartness of the campus [97].

Figure 5. Sensed parameters for efficient energy and comfort assessment.

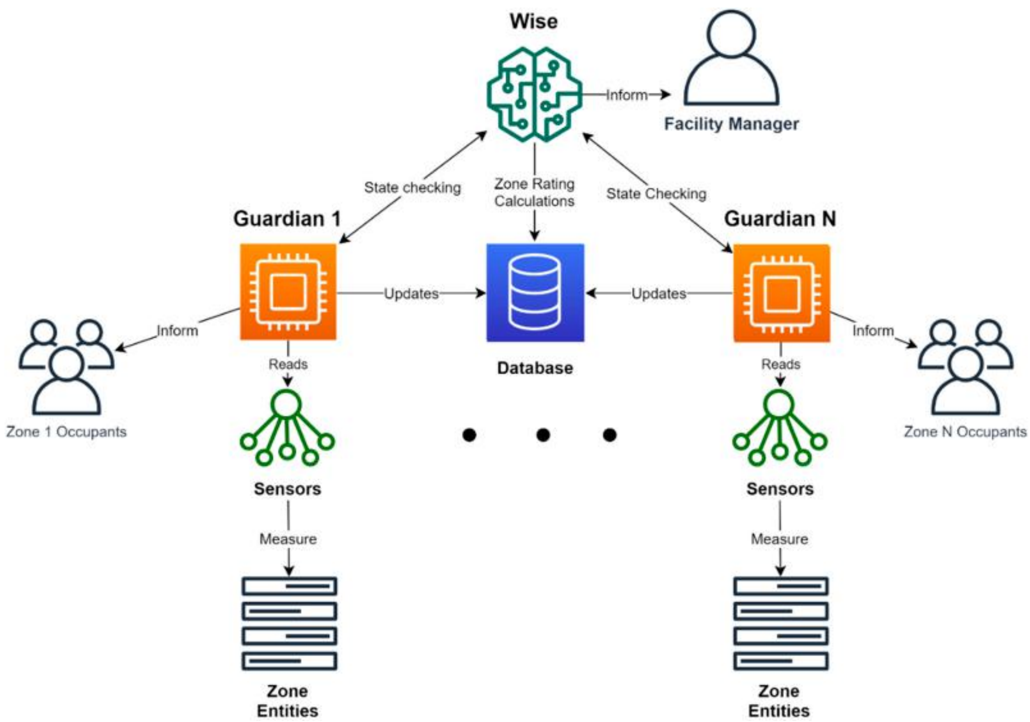

Figure 6. The decision support system for the facility manager by using the digital twin information.

3. The Digital Twin Deployment

3.1. The Building Premises Modeling

The Internet of Things Institute of Catalonia (facilities of LaSalle-URL (University Ramon Llull at Barcelona)) is the first interdisciplinary European R&D laboratory in which everything related to the interaction of people with the social and technological changes of their environment will be worked on, with a focus on the Internet of Things (digital interconnection of everyday objects with the internet). In fact, it is a space for the development of innovation initiatives and start-ups, in which business technological challenges coexist, in search of differentiating answers, with start-ups propelling new value propositions, with demonstrations of talent (researchers, professors, university students, experts, and consultants, among others) of a diverse nature and with connection to other technological parks.

The IoT institute has been co-financed since 2020 by the European Regional Development Fund (ERDF) under the framework of singular institutional projects in R&D infrastructures in the generation of excellent research, the attraction of talent, and the development of knowledge transfer activities. The laboratory is based on design, prototyping, and scaling the products and services of tomorrow for society and the business world, as well as taking students and professors toward the new realities and needs of future societies. The 2000 m^2 space (situated below the international students' residence) will be dedicated to research, innovation, and the promotion of talent and entrepreneurship (Figures 7 and 8).

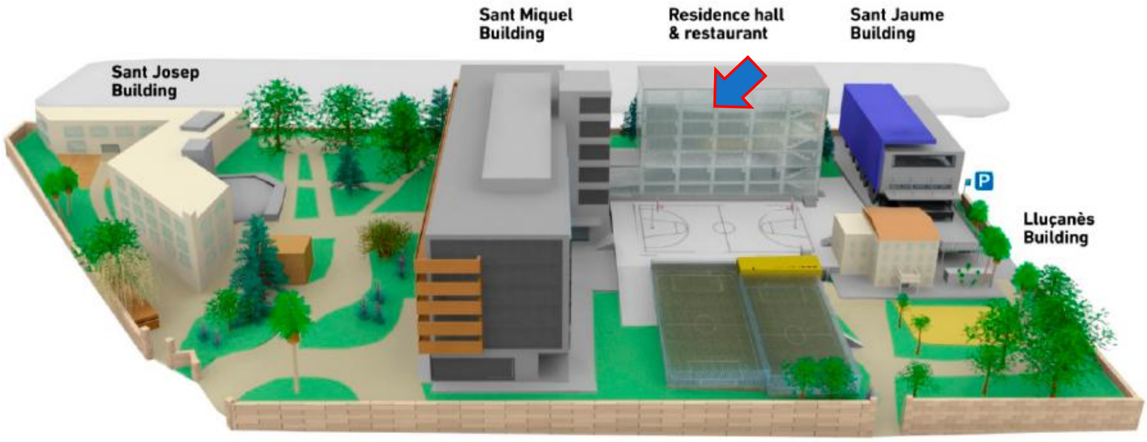

Figure 7. La Salle-University Ramon Llull (URL) (Barcelona).

Figure 8. IoT institute premises; digital twin model for automatic monitoring.

The laboratory has four different areas (Figure 9):

Figure 9. IoT institute at La Salle-URL: (**A**)—architectural plan, (**B**)—maker Space, (**C**)—agora, (**D**)—city lab.

- A common social meeting point where people can debate, show, and even try out any idea that has been conceived during the innovation process. Ideas can later be tried out in the design and testing processes.
- Creativity room: spaces designated to fomenting creativity and information exchanges and where challenges are born into a creative and imaginative environment. These spaces can be used for structured activities, but also to facilitate an idea flow, which can be used to set off new innovation and research processes.

- Maker space: workspace designed to provide tools to develop projects for the group of researchers from the areas of architecture, management and engineering, together with designers, students, inventors, and entrepreneurs.
- City lab: space for the assembly and testing of technologies that have been developed. This is the showroom where the final products of projects are displayed, which promotes learning through overcoming challenges and is now being used all over our campus. This new laboratory will enable students to go further than case-studies, using new research and transfer techniques, with systemized processes to face tomorrow's challenges.

This paper is focused on the case-study location modeling regarding the co-creation rooms in the medium center of the laboratory. By grouping together the aforementioned information, a global vision of the system can be obtained as follows: on the one hand, IoT agents that measure the environmental monitoring are used to calculate the IEQ index, whereas the information regarding the emotions of the occupants provided by the middleware intelligence is used for a double-check of the objectively perceived comfort. Furthermore, the middleware layer is responsible for archiving the data in a database and communicating with the visualization platform to make a predictive analysis about the monitored space's comfortability, by rendering the data into a virtual classroom model and taking into account the energy monitoring (see Figure 10).

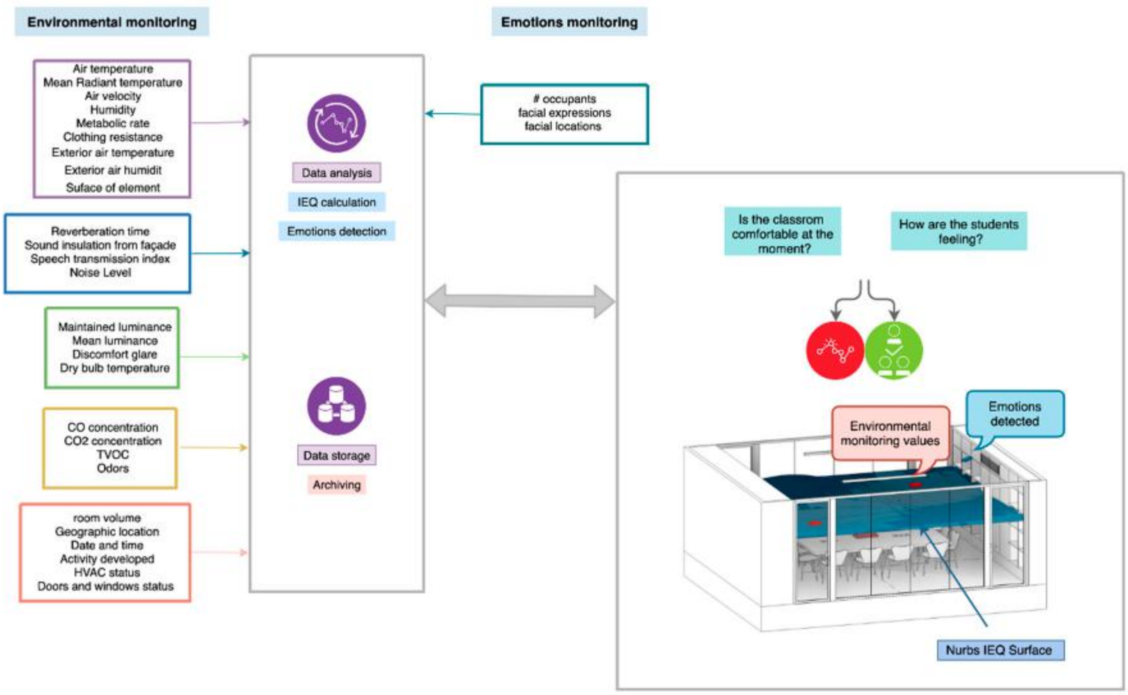

Figure 10. Conceptual system flow.

We have to consider that comfort is directly related to the monitored space and the environment parameters, as analyzed in the previous sections. This relation between space and parameters is where the usual IoT platforms would limit the project, most IoT platforms only consider the readings produced by IoT devices, but they do not relate those readings with the location of production (revisit Table 1). Conversely, if building information modeling (BIM) is used [98], the collected data can be linked with the building environment parameters and characteristics (such as other indoor and outdoor characteristics) and with data from external sources, adding value to the collected data.

BIM is one of the emerging developments in architecture, engineering and construction (AEC) industries [98], and there are three main concepts regarding BIM that we cover in the project:

- BIM or building information modeling is a process, not an application, to create and manage information on a construction project across the project's lifecycle. It refers to a virtual model that contains a data-rich, object-oriented, intelligent and parametric digital representation of facilities [99], coinciding with the main benefits over conventional 3D computer-aided design (CAD) [100]. Thus, BIM enables those who interact with the building to predict performance appearance and cost, resulting in a greater whole life value for the asset.
- Revit is a modeling software to simulate, visualize, and collaborate in order to capitalize on the advantages of the interconnected data within a BIM model [98]. When one piece of datum changes in one view, it is updated in all other views automatically by Revit because each view is displaying the same data.
- Dynamo Revit is a graphical programming interface that enables the customization of the building information workflow [98]. Dynamo is an open-source visual programming platform for designers and has been installed as part of Revit since 2020, and hence it allows designers to set up automated computing processes or platforms in order to correlate processed data to structural and geometric models.

Lately, the challenge of bringing environmental monitoring of energy efficiency in buildings to BIM modeling has been discussed and designed by many researchers [47–49,100,101]. Consequently, the integration of IoT into BIM can be considered a fusion between physical things and virtual models—the information acquired from objects in the environment joined with information that resides in digital models of buildings. Once this fusion of information is achieved, many fields, such as facility management, assets management, environmental monitoring, energy efficiency, and the maintenance or visualization of components, among other applications, will experience potential benefits (see Figure 11).

Figure 11. *Cont.*

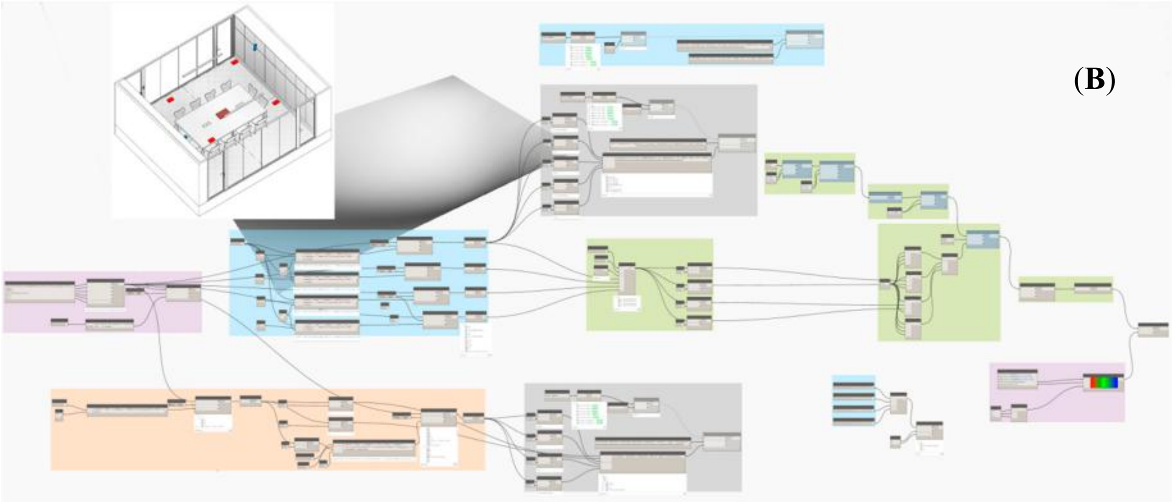

Figure 11. General overview of the digital twin developed in Dynamo Revit ((**A**)—spaces, (**B**)—sensed data and acquisition methods).

3.2. High-Level Design For The Sensing Level

The proposed monitoring system is divided into four main sections. They are necessary to model the behavior of the campus digital twin and make suitable recommendations to the management of the facility. This will allow us to infer the level of smartness [97] by taking into account the energy efficiency issues (see Figure 12):

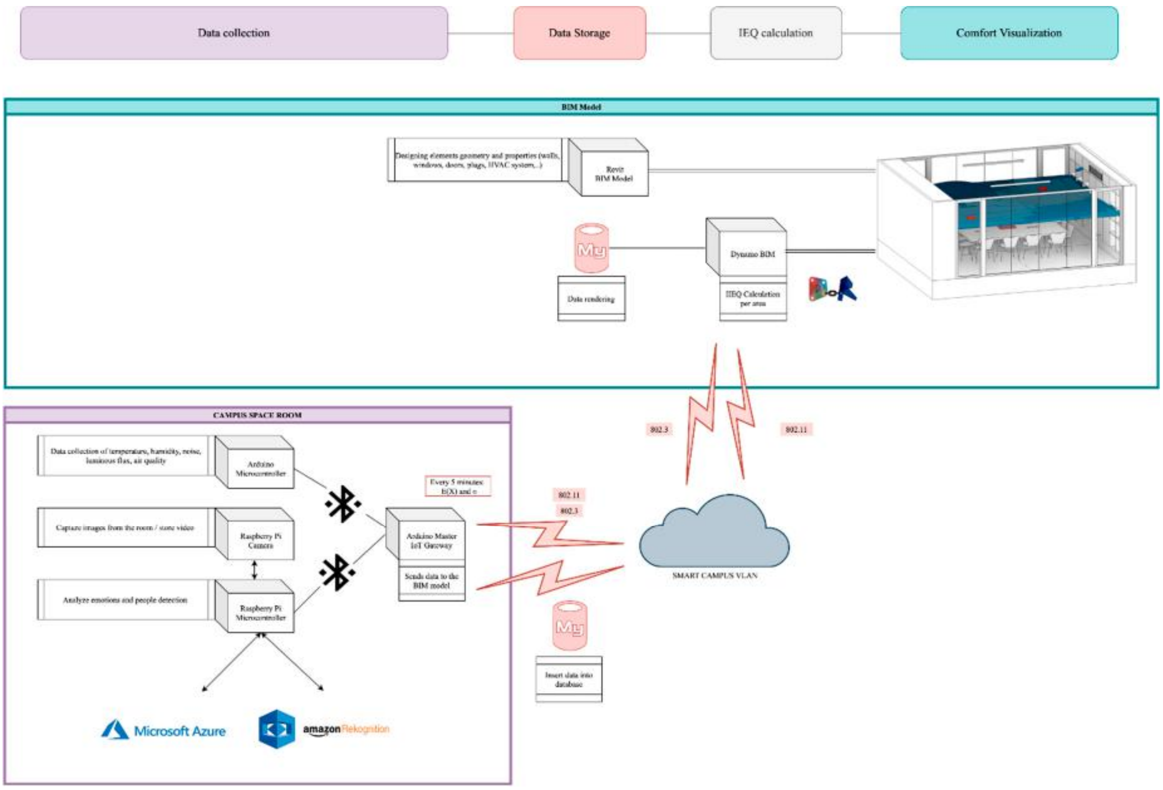

Figure 12. System high-level design.

3.2.1. Data Collection

The environmental monitoring data are measured with sensors embedded in Arduino UNO microcontroller boards with a sampling frequency of 30 s for each node (revisit Table 3). The data collected in the nodes from every sensor are sent to an Arduino MEGA 2560 board, which corresponds to the master node (Figure 13). The latter is in charge of collecting the nodes data and calculate the mean (E(X)) and the standard deviation (σ(X)) of each metric. Once 10 metrics are collected (5 min), the master node then sends an HTTP POST (Hypertext Transfer Protocol) request to the database middleware by sending out the metrics E(X) and σ(X).

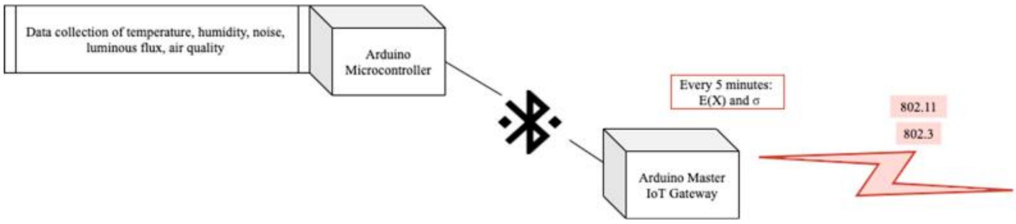

Figure 13. Environmental monitoring high-level design.

The occupants' emotions are validated by an intelligent emotion detection algorithm in charge of implementing a double check to detect IEQ inconsistencies with the modeled reality. The emotion detection system consists of capturing the faces of the occupants with a camera lens assembled in a Raspberry Pi 3b+ and subsequently sending the obtained frame to the "Microsoft Cognitive Services Face API" service for a simple emotion recognition response or continuous video recording to "Amazon AWS Rekognition" for a full pattern analysis at the end of the session. The results, containing the detected emotion for each recognized occupant, are sent to the master node, which in turn will aggregate the data with the environmental data and dispatch them to the implemented middleware (Figure 14).

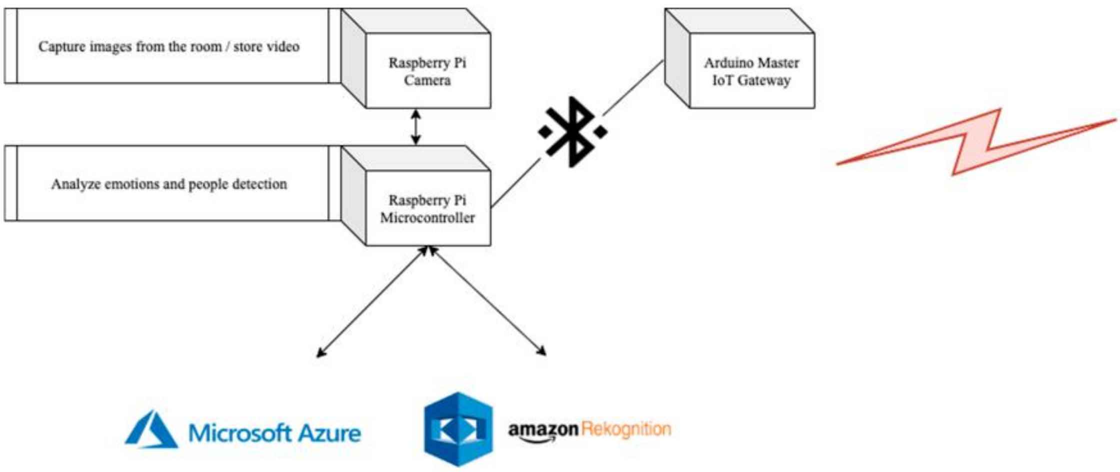

Figure 14. Occupants' emotions high-level design.

3.2.2. Data Storage

The designed middleware encompasses customized Hypertext Preprocessor files (PHP) that permit inserting new data records into a MySQL relational database in order to store the structured environmental monitoring and emotion recognition data (Figure 15).

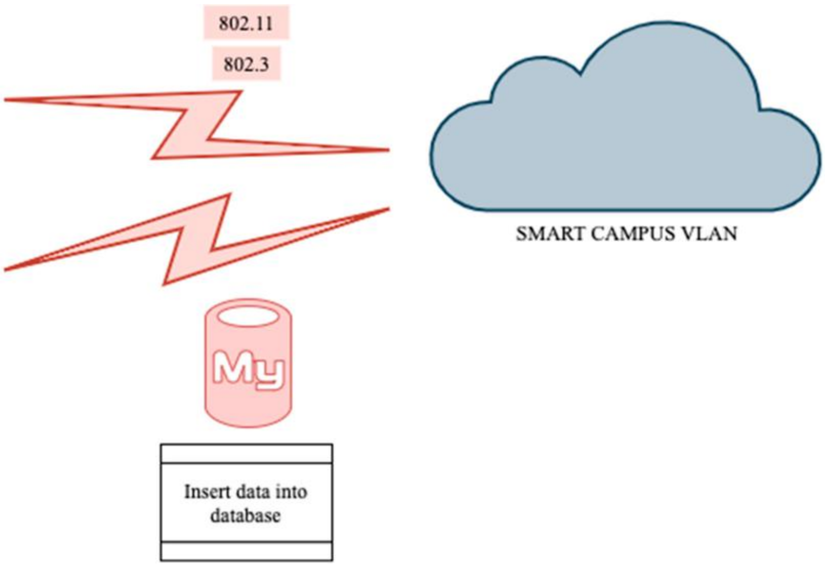

Figure 15. Data storage high-level design.

If you look at Figures 11 and 12 more closely, you will notice that the update of the real-time sensed data is performed from the IoT deployed physical infrastructure to the Revit model through the Dynamo interface. Thus, the digital twin of the smart campus is updated by accessing real-time stored data in the cloud (see Figure 16).

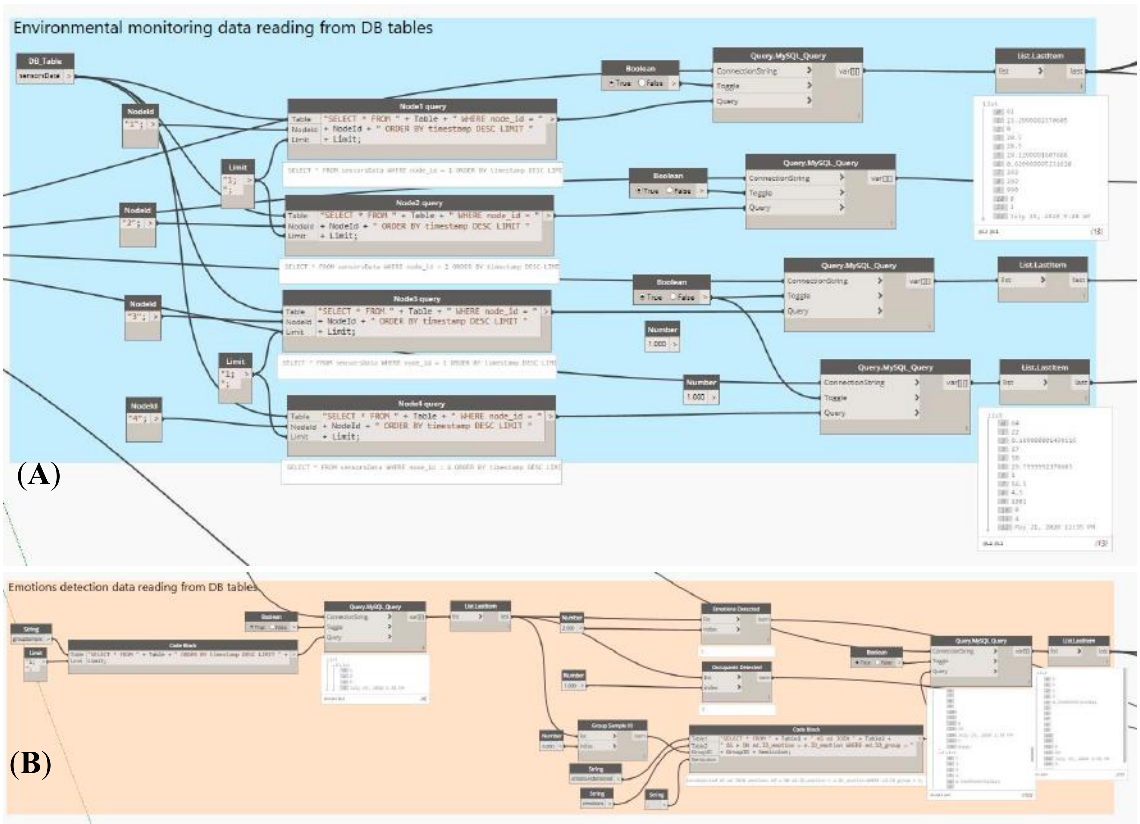

Figure 16. Dynamo flow representing (**A**) the current environmental data collection and rendering from each node stored in the database and (**B**) the current emotion data collection and rendering from each camera stored in the database.

3.2.3. IEQ and Energy-Efficient Calculations

The guardians for each zone provide sensed information to the wise module, which aggregates the information for the final visualization application (i.e., the IoT middleware). Our middleware is based on the visual programming software Dynamo Revit, usually embedded in BIM systems. The wise module reads the database in real-time and calculates the IEQ index using a Python script (Figure 17). Furthermore, an interpolation is made by the guardian between all the resulting indexes of each node of the monitored zone and is subsequently rendered on a color scale.

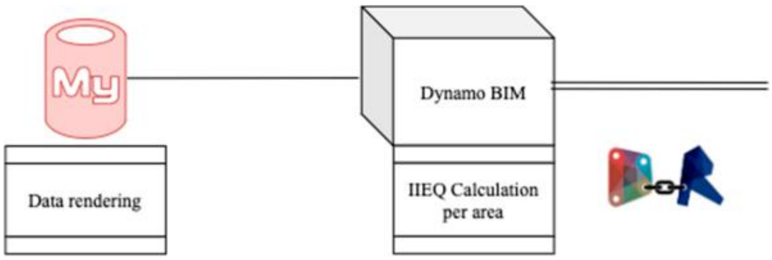

Figure 17. Data rendering and IEQ calculation high-level design.

With the geometric room parameters defined in our BIM model, sensed information is collected from the database. It is then submitted into a Python-script object (Figure 18), which calculates the IEQ index based on the ASHRAE standard and figures out the proposed weighted model stated in this paper for the real-time IEQ value.

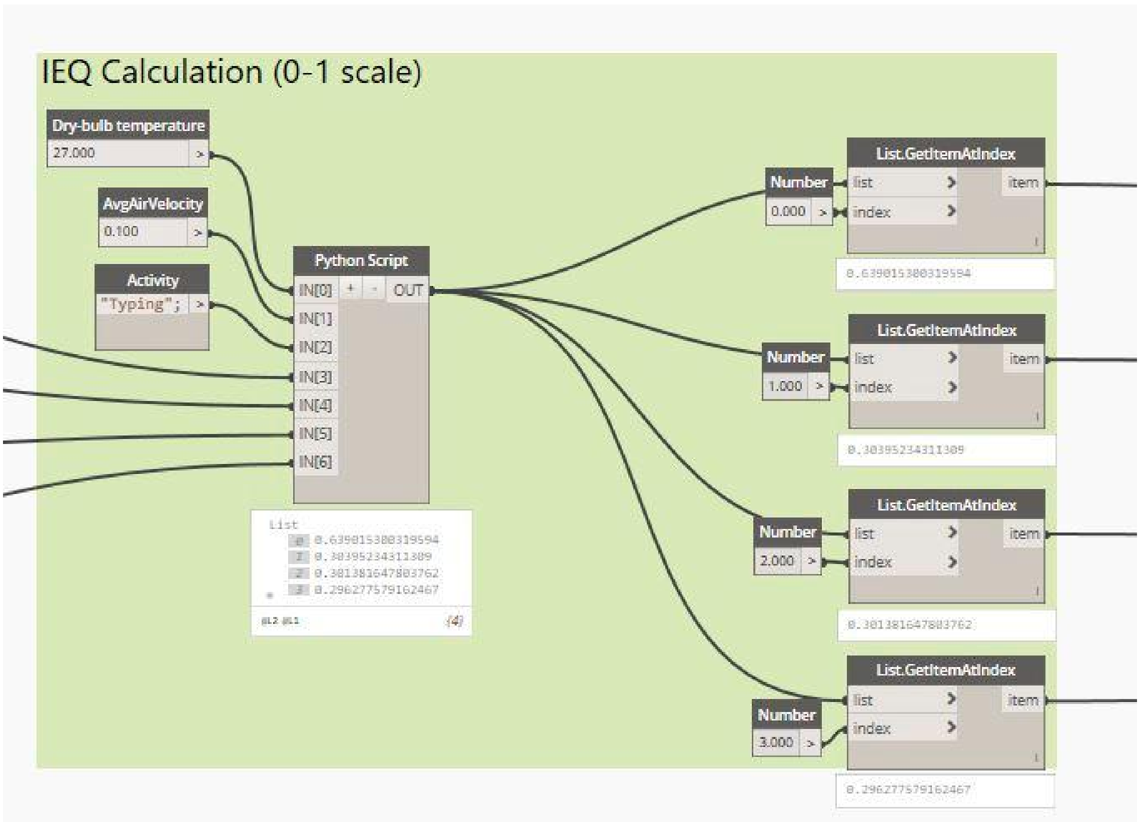

Figure 18. Dynamo flow representing the IEQ calculation.

As stated before, a zone identifies a section of a building. This zone is defined by a list of parameters such as zone ID, maximum capacity, occupancy schedules, daylight availability, occupancy and temperature samples, artificial light contribution, and a digital twin zone rating. The zone rating is a quantitative parameter that tries to rate the energy efficiency of the zone in order to compare it with others and therefore establish recommendations for the facility manager. In order to formulate recommendations, the sets of data mentioned previously will be used to build a light efficiency rating (LER) and a temperature efficiency rating (TER).

For example, a LER is used for the recommended light level interval that defines the amount of light needed inside the zone. This value is constantly calculated by the zone guardian, and the state can be one out of the three following states: (1) over, (2) under, or (3) inside the recommended light level interval (Figure 19). For this reason, the guardian calculates the occupancy rate (occupants divided by maximum occupancy) and provides the actual number of occupants of the zone (Figure 20). Moreover, each sensed sample is classified considering the occupation case. For example, the machine learning algorithm should avoid comparing samples obtained on weekdays with samples obtained on weekends or holidays. If the zone is in use, the system will first measure if the current light level is inside the recommended interval in order to recommend occupants turn on/off the light, and the facility manager will be informed about the situation as well. For heating and cooling, a recommended interval has also been specified. In this case, the wise module also considers weather forecast, occupation, and temperature samples to recommend actuation of heating and cooling systems.

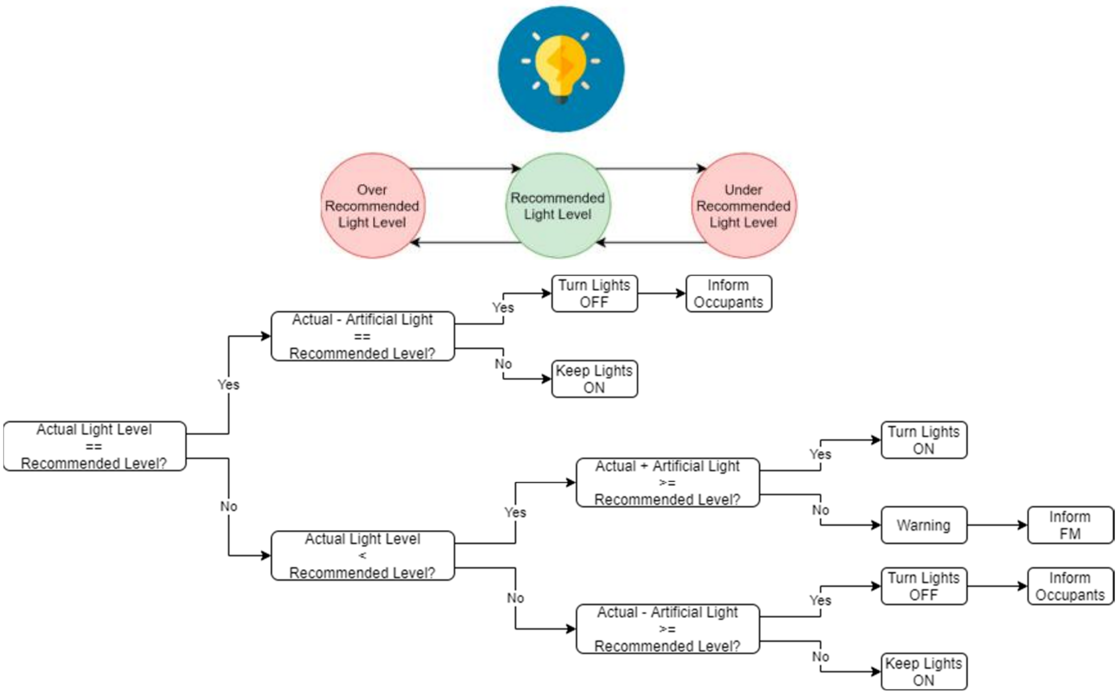

Figure 19. Finite state machine for light recommendations.

Figure 20. Occupancy monitoring.

3.2.4. Comfort Visualization

Lastly, the resulting data (raw data, IEQ indexes, and recommendations) are represented in a virtualized model of the campus area in the Revit for BIM software. The model also represents the sensors and cameras and their location and allows the user to navigate the virtual model, enabling the mesh of points that represent the level of comfort calculated since Revit and Dynamo are directly integrated, and changes are updated in real-time (Figure 21).

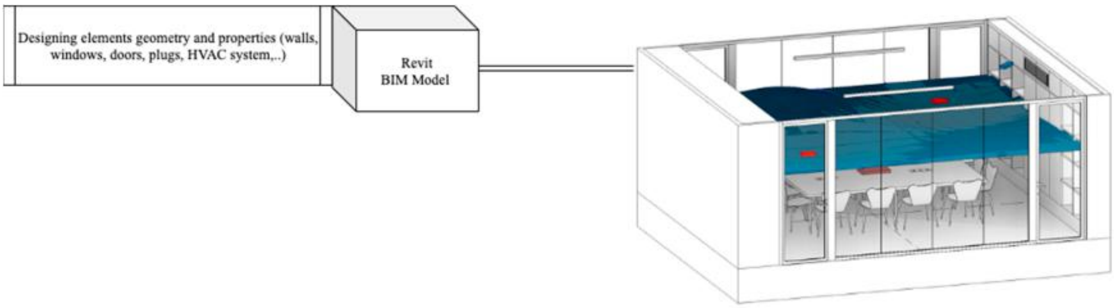

Figure 21. Comfort visualization high-level design.

4. Discussion and Conclusions

The collaboration between the ICT engineering and architecture faculties in sustainability education and research will help students and future citizens to both understand and be a part of the solution to contemporary real-life sustainability challenges. This study explored the structures, processes, and activities related to the SC concept, which promotes sustainability from a multicultural and interdisciplinary perspective. Today, nineteen Lasallian universities are involved in a global initiative to promote sustainability through research projects focused on campus transitions via sustainability development projects. The joint efforts provide a broad range of experts and knowledge that will create innovative solutions to complex sustainability challenges, as well as creative opportunities with the hope of helping the planet through concrete and real actions, which should be the backbone on which all degrees base their teaching, research, and learning programs.

The key findings to date relate to (1) multi-disciplinary and multi-actor cooperation, where students (architects and ICT engineers), as well as researchers and teachers, are all sustainable development learners (encouraging engagement and active contribution to societal processes); (2) crossing the boundaries between education and the world of work through joint activities and common languages; (3) connecting generations, such as students, lifelong learners, and schoolchildren, by reaching out to work more closely with primary and secondary schools in developing competences in sustainability learning and (4) improving sustainability knowledge, not merely curriculum-based, but learning from practice, learning in the ecosystem (and also about the ecosystem), and making this learning accessible throughout the ecosystem.

This paper proposes an SC concept to investigate the integration of building information modeling (BIM) with IoT-based wireless sensor networks (WSN) in the fields of environmental monitoring and emotion detection systems in order to provide insights into the occupants' level of comfort. Preliminary results highlight the significance of monitoring workspaces given that it has been proven that productivity is directly influenced by environmental parameters, including thermal, visual, acoustic, and air quality comfort (our proposed primary quality goal), which could be reused to collect, store, and visualize physical parameters of educational premises for energy efficiency (our proposed secondary restrictive goal). In this way, the preliminary research presented in this paper will allow the establishment of a basis for the SC's comfort digital twin experimentation.

The designed experimentation is implemented within the software environment of Autodesk Revit 2020, which integrates the Dynamo BIM visual programming interface in order to act as an IoT middleware, by reading data stored in a remote database, processing the data, calculating the IEQ indexes and rendering the obtained comfort levels into a virtual classroom model. It has been observed that the integration between BIM and IoT provides many benefits, including: (1) real-time access to information and process automation; (2) comfort level monitoring is fully accomplished using BIM tools, the transformation of BIM data to a relational database is the basis for linking this information; (3) big data techniques are added in the construction industry for statistical analysis (machine learning, intelligent monitoring, augmented reality, virtual reality and performance in spaces) and (4) it has allowed multiple disciplines (architecture and ICT engineering) to collaborate together in the same model where data are processed and visualized in a unique model.

Nevertheless, although we have modeled, designed, and implemented the comfort-aware digital twin of the Internet of Things institute facilities to evaluate energy efficiency as well, the smartness concept of the campus has yet to be exhaustively tested. The intelligence of the deployed model, as stated before, is based on static rules and relies on recommendations for the occupants and the facility manager. Despite noticeable progress in our university campus, the concepts and principles of the smartness level are not fully clarified yet. This can be attributed to the obvious novelty of the concept and numerous types of smart systems, technologies, and devices available to students, learners, faculty, and academic institutions.

As stated in [8], these kinds of projects usually emphasize the fact that many aspects of contemporary education need new flexible organizational structures, which can be referred to as smart. In this paper, the sensing and the fundamental inferred issues of the smartness level are addressed for a comfort-aware and energy-efficient SC, where:

- Sensing level is defined as the ability to automatically identify and become aware of a phenomenon and its impact (positive or negative) by using sensors.
- The inferred level is defined as the ability to make logical conclusions based on sensed data (e.g., activate HVAC, turn off lights, and recommend administrators to take certain pro-active countermeasures).
- Further work is required to consolidate in our digital twin campus the adaptation, learning, anticipation, and self-organization smartness levels [97].

In conclusion, we can summarize the objectives and contributions of our work in the following:

- This paper proposes a digital twin modeling procedure that merges well-known approaches used in SC to integrate a set of advanced intelligent features: the use of technology for a digital SC by using an IoT network and cloud computing to transform university spaces into information sources for intelligent decision-making processes. SC will adopt the technological paradigm in order to support multiple tasks in multi-functional buildings (teaching, research, management, and services) and include different users (students, researchers, guests, etc.). Our proposal is to develop the SC through the efficient use of resources, thereby reducing operational costs and making life more comfortable.
- Our contributions tackle three intelligence domains that should be equipped with various capabilities [8,52]. (1) Green campus, in line with the issue of climate change, which includes the intelligent energy consumption and the implementation of sensor technology for accurate reporting. (2) Healthy campus, to monitor and promote the level of comfort by tracking and recording the status of the campus activity and (3) real-time facility management, which includes the facilities, infrastructures and people (staff, students and visitors).
- The proposed SC concept is not limited to supporting smart learning processes and can also support other aspects of campus life (the comfort of the academy community understood as a quality metric).
- In the developed model, all the smart campus devices, the energy consumption performance, and the comfort evaluation dashboard can be accessed by the stakeholders through the BIM platform. This middleware facilitates the interoperability and the co-working between engineering and architecture staff by promoting an interdisciplinary task force. We envisage that if sustainable

policies have to be defined, an interdisciplinary team could easily cope with the identification of patterns and the suitability assessment of the proposed improvements.

- The main goal of our ongoing research project is to develop SC concepts, digital twin, and complex adaptive systems, and identify the main distinctive characteristics, modules, and technologies of a multi-disciplinary SC. The aim is to improve sustainability beyond that of a traditional campus with heterogeneous learning activities.

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Abbreviations

The following abbreviations are used in this paper:

AC	acoustic comfort
AEC	architecture, engineering and construction
AMQP	advanced message queuing protocol
ATHIKA	Advanced Training in Health Innovation Knowledge Alliance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AWS	amazon web services
API	application programming interface
BIM	building information modeling
BUS	Building Use Studies Ltd.
CAD	computer-aided design
CBE	Center for the Built Environment
CEN	European Committee for Standardization
CIE	International Commission on Illumination
CoAP	constrained application protocol
CAS	complex adaptive systems
ERDF	European Regional Development Fund
HTTP	hypertext transfer protocol
HVAC	heating, ventilation, and air conditioning
IaaS	infrastructure as a service
IAQ	indoor air quality
ICTs	information and communication technologies
IEQ	indoor environmental quality
IES/ANSI	Illuminating Engineering Society of North America
IoT	Internet of Things
ISO	International Organization for Standardization
JSON	JavaScript object notation
LED	light-emitting diode

LEED	Leadership in Energy and Environmental Design
LER	light efficiency rating
MQTT	message queuing telemetry transport
MAS	multi-agent system
PaaS	platform as a service
PHP	hypertext preprocessor
PMV	predicted mean vote
SBS	sick building syndrome
SC	smart campus
SMEs	small and medium enterprises
SIoT	Social Internet of Things
TER	temperature efficiency rating
TC	thermal comfort
URL	University Ramon Llull
UWP	universal windows platform
VC	visual comfort
VOC	volatile organic compounds
WSN	wireless sensor networks

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Adaptive and aggressive transport protocol to provide QoS in cloud data exchange over Long Fat Networks

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ABSTRACT

This paper analyses the different transport protocols used in transfers over high capacity and high delay networks, commonly known as Long Fat Networks (LFNs). After analysing relevant solutions that provide reliable communications, this article presents the design and performance of the Adaptative and Aggressive Transport Protocol (AATP) for the optimisation of data transfers in a LFN Cloud Content Sharing Use Case. Cloud server farms are geographically separated and there is a need to exchange and replicate large amounts of data. By providing calculations of the status of the network and an estimation of the bandwidth of the link, the performance rate of this protocol is high. Moreover, it also includes an adaptative sending rate in the case of packet loss and, as a result of AATP aggressiveness, only the residual bandwidth is left to other protocol flows. To demonstrate AATP performance, different tests have been carried out over a Network Simulator and a Testbed on Field.

1. Introduction

The usage of Internet has changed since its conception. In recent years, networks have increasingly had to deal with heavy data transfers, which may consist of multimedia files or applications from Cloud services or information gathered from millions of Internet of Things (IoT) nodes [1].

Current society needs data anywhere, anytime and that can be adapted to the context of the end-users. Increased user demands, as well as the rise of Cloud platforms and Big Data, have created the need for a network [2] that can move large amounts of information from one point to another, both efficiently and reliably. In addition, the need for effective data management has increased in response to the millions of IoT devices producing data [3].

For these reasons, Quality of Service (QoS) is a key factor in effective communications in terms of bandwidth performance and reliability [4,5].

The wide range of content has evidenced the need to have networks with higher bandwidth for end-to-end connections, especially when great distances separate the networks.

Within the classification of high capacity links, there is a type of network known as the Long Fat Network (LFN) [6]. The main characteristic that defines this type of networks is its high Bandwidth (BW) and high values of Round Trip Time (RTT). A network is considered LFN if its Bandwidth-Delay Product (BDP) is greater than 12,500 bytes (10^5 bits). For example, a link of 1 Gbps and 1 ms of RTT, obtains a BDP of 10^6, being classified as LFN.

These characteristics of the LFNs lead to lower performance rates when using the Transmission Control Protocol (TCP), which is the most commonly used transport protocol in the network, and have led to the need to define an extension of the protocol [7].

Moreover, the friendliness of the protocol creates an equitable distribution between several flows which share a link, regardless of its priority (unless Quality of Service is applied, which is not controllable outside the local network).

For these reasons, Cloud companies are trying to find a protocol which allows them to achieve a high throughput between their networks in order to optimise data exchange and replication.

The purpose of this paper is to present the design and show the performance of the AATP (Adaptive and Aggressive Transport Protocol) for a Cloud Data Sharing Use Case. In order to demonstrate its effectiveness and behaviour, different tests have been carried out over a Network Simulator and a Testbed on Field.

The rest of this paper is structured as follows. In Section 2, the use case is presented. In Section 3, the related work is summarised. Section 4 introduces the protocol specification. Section 5 presents the QoS objectives to be achieved and the tests deployed, and shows the reliability and efficiency of the design when tested in a Network Simulator and on a Testbed. Section 6 analyses the results obtained from the proof-of-concept implementation. Finally, conclusions and future works are presented in Section 7.

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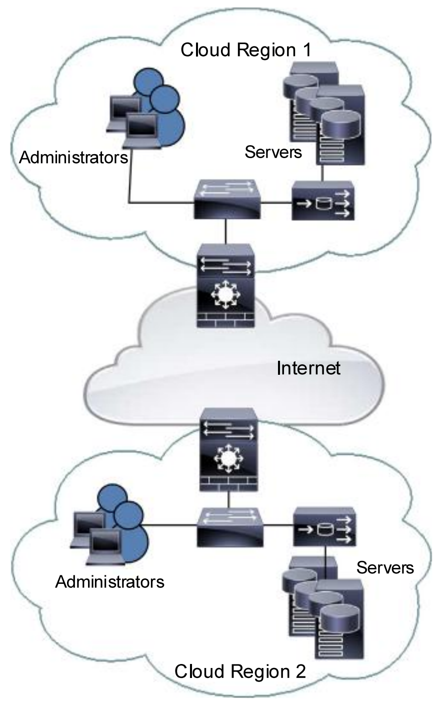

Fig. 1. Cloud data sharing network use case.

Table 1
Cloud data sharing network use case — network requirements.

Link	Bandwidth (Mbps)	Delay/RTT (ms)	Packet loss rate (%)
WAN	[20..2000]	[1..100]	[0..3]

2. Cloud data sharing use case

A specific Cloud company has set high-level data exchange requirements between their servers' farms deployed in Storage Area Networks (SANs) from remote branches in different regions. The main requirement of the company is a protocol that achieves the maximum link capacity, adapting its behaviour to the status of the network. Moreover, in order to leave the residual bandwidth for other non-critical flows, this protocol has to act aggressively on other protocols, given that it is not possible to apply Quality of Service in intermediate nodes.

In order to shape the protocol behaviour, a non-oriented connection protocol is needed to overcome the main TCP constraints. However, it is necessary to implement a flow control that can adapt its behaviour to the network status. Finally, some security features are requested, although they are not in the scope of this paper.

The use case network physical topology is shown in Fig. 1. This topology exhibits a data transfer of hundreds of GB from a server in Region 1 to another server in Region 2. An additional requirement of the company is the efficient transfer and replication of data. This traffic has to be prioritised in order to send the data as quickly as possible since there is no control beyond the gateway.

The typical company network values for wired connections are presented in Table 1. Wireless connections are out of the scope of this first specification.

In the following section, different protocols are analysed in order to extract the mechanisms to be adopted and integrated into the design of the AATP protocol.

3. State of the art

This state of the art will focus on the aforementioned characteristics related to the specific purpose of the proposed protocol in order to achieve more efficient and reliable transfers of large amounts of data from Cloud networks.

3.1. Congestion control

Congestion control aims to detect the network status before it collapses [8].

There are two main strategies to detect and mitigate network congestion [9]:

- Preventive, which is generally used in circuit-switched networks. Resources are reserved during connection set-up to prevent congestion during data transfer, limiting the number of users and monitoring the flow so that it does not exceed a predetermined limit.
- Reactive, typically used in connectionless packet-switched networks, in which no resource reservation is made prior to data transfer and techniques are used to resolve the congestion once it is detected.
  They could be classified into two classes:
  - Direct feedback: intermediate network nodes detect congestion risk and notify the sender and receiver of the end-points of the communication by tagging the packets or sending specific notifications.
  - Indirect feedback: end nodes detect the congestion, based on packet losses and delays (jitter) and notify the other end-nodes.

Although protocols that use direct feedback congestion could provide an improvement in high bandwidth-delay environments, the proposed cross-layer solution in real scenarios implies revolutionary changes to routers and end devices which would make them difficult to deploy on a large scale.

On the contrary, protocols that use indirect feedback congestion control are the most broadly used, with TCP being the most common, and the basis of many congestion controls.

3.2. TCP

TCP is currently the most widely used transport protocol [9]. Its main characteristics are reliability and information integrity. The receiver informs the sender of the receipt of the packet using acknowledgement packets (ACK). TCP adjusts transmission throughput employing an Additive Increasing Multiplicative Decreasing (AIMD). The main two mechanisms that control the throughput of the transmission are Slow Start (SS) and Congestion Avoidance (CA). This AIMD congestion control causes a sawtooth effect in the transmitted flow that renders it inefficient over error-prone links. However, some solutions have been presented to smooth this effect by splitting the transmission into multiple parallel connections.

Other legacy TCP variants [10], such as TCP Tahoe [6], have been released to improve TCP performance by implementing SS, CA and Fast Retransmit. In addition, TCP Reno [7] included Fast Recovery. Finally, New Reno [8] has tried to solve the main problems by estimating the optimal sending rate at the start of the transmission using the Packet Pair algorithm [9,10].

TCP SACK [11] implements all the mechanisms explained in previous variants, and it incorporates additional ones to adapt the congestion control to larger networks which are often error-prone and incur an elevated use of traffic. When a receiver detects that a packet is lost, it sends a duplicate ACK (DUACK) indicating that it has received the rest of the packets correctly. It allows the sender to know which segments should be retransmitted.

TCP Vegas [12] emphasises packet delay rather than packet loss, as a signal to determine the sending rate. Instead of looking for a change in the throughput slope, it compares the measured throughput rate with an expected throughput. The idea is to measure and control the amount of extra data this connection has in transit, that is to say, the data that would not have been sent if the bandwidth used by the connection exactly matched the available bandwidth of the network.

As a result, TCP Vegas is able to achieve between 40% and 70% better throughput than Reno, allowing transmission at an almost constant data rate. However, the aggressiveness of the protocol can cause inefficient use of the bandwidth.

3.3. Fast long-distance TCP variants

Other types of TCP are proposed, especially in two specific fields where the performance of standard TCP and explained variants is still poor, namely wireless and fast long-distance networks.

Given that the study of wireless networks is out of the scope of this paper, a brief summary of the most outstanding protocols focused on long-distance is presented.

FAST TCP

FAST-TCP [13] is a modification of TCP Vegas, conceived for networks with high latency. It works with the concept of not penalising the CWND and detects the delay of the communication.

Binary Increase Control TCP (BIC-TCP)

BIC-TCP [14] is a version of TCP that combines an additive growth of CWND when the congestion window is medium or high and a binary growth when the window is small. The protocol starts the transmission with an Additive Increase, increasing the window more slowly than with Slow Start. Next, the Binary Search mechanism is used, which updates the value of CWND to the midpoint between W_{max} (value of CWND where the last losses have occurred) and W_{min} (last value of CWND where no packets have been lost). Finally, the Max Probing mechanism is applied, which causes an exponential growth of the window. In addition, when losses are detected, the congestion window is reduced by a factor β. The main drawback of this protocol is that it takes a long time to reach a high throughput level, although when it does so, the bandwidth of the link is maximised and is highly stable.

CUBIC

CUBIC [14] is an improvement of BIC-TCP that stands out for its high stability in high-speed transfers.

This protocol replaces the BIC-TCP Binary Search for a cubic growth function, so when the value of CWND is much lower than W_{max}, the increase is higher. On the other hand, when the value of CWND is close to W_{max}, small increments are made, which attempt to overcome the value of W_{max}.

Regarding the reduction of the congestion window after losses, the Multiplicative Decrease of BIC-TCP with a factor $\beta = 0.2$ is maintained. Additionally, it incorporates a mechanism of Fast Recovery that BIC-TCP does not. The main drawback of CUBIC is the same as that of its predecessor — the time of convergence that is needed to reach a stable and high sending rate.

Bottleneck Bandwidth and Round-trip propagation time protocol (BBR)

BBR [15,16] is the evolution of CUBIC. This protocol bases its congestion control on the management of the maximum bandwidth and the minimum round-trip times. Taking into account these metrics and their values, BBR tries to maintain performance at its optimal level. Fig. 2 shows the behaviour of the RTT and the delivery rate of a transmission. The idea works on the point where the RTT is the minimum, which means that buffers are not saturated, and there is no queueing, at the same time that the delivery rate is sending at the maximum capacity of the link.

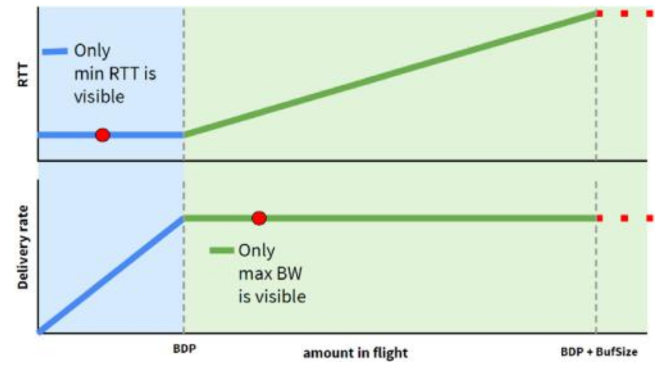

Fig. 2. BBR graph function (RTT & Delivery rate) [15,16].

3.4. UDP-based protocols

Besides the TCP variants mentioned, a set of UDP-based protocols attempt to provide efficient congestion control and reliability functions.

UDP-Based Data Transfer Protocol (UDT)

The UDT presents a better throughput [17,18] and some improvements beyond the state of the art of the standard UDP in terms of throughput utilisation, implementation flexibility and security. In addition, it presents some guidelines for its implementation, which take into consideration the operating system limitations that can hinder the development and operation of the standard UDT.

High-Performance and Flexible Protocol (HpFP)

Another protocol to highlight is HpFP [19]. HpFP sends asynchronous ACK messages for received packets every 200 ms, solving the problem of delay in LFNs. Data burst packets are sent independently from the ACK reception.

This protocol works by adapting its throughput to the available bandwidth and is friendly to the other flows. The authors do not detail the congestion control mechanism.

3.5. Other transport protocols — Stream Control Transmission Protocol (SCTP)

Finally, specific protocols have emerged in the last decade in an aim to make up for the inefficiencies of TCP and UDP.

The most commonly known is SCTP [20], which provides a series of additional mechanisms and functionalities that TCP does not offer. It significantly increases the obtained throughput and achieves a more optimal behaviour by adding new functionalities (security, multistream and multipath capacities, among others). For example, the protocol uses a 4-way handshake instead of the 3-way handshake of TCP, thus offering protection against denial of service attacks (DoS).

Many SCTP variants have appeared during the last years. Some of the most relevant are New-Reno SCTP [21], HSP-SCTP [20], CMT-SCTP [22], MPSCTP [23] and cmpSCTP [24].

4. AATP protocol design

This section presents the Adaptive and Aggressive Transport Protocol (AATP) design, which considers the Cloud Data Sharing Network Use Case requirements (Table 1). Concretely, this section is focused on explaining the workflow of the protocol by detailing the phases of the AATP and the selected mechanisms for each phase.

First, according to the requirements, this protocol is UDP-based but connection-oriented (in-band control). The idea is to avoid the synchronous locking of TCP and other associated problems analysed in the previous section.

In general, the AATP is inspired by UDT flow control and SCTP phases and messages.

The use case highlights the need for an aggressive protocol to reach the maximum capacity of the link. Furthermore, the AATP is conceived as an unfriendly protocol. It is created to leave residual bandwidth to the other protocols of the network due to the priority of the data to be sent so that the transmission of data is accomplished as quickly as possible.

AATP includes two differentiated phases after session establishment:

– Network Status Estimation
– Data Transfer

Regarding the aforementioned phases, this protocol is designed to add some additional security features, such as a 4-way handshake session establishment, encryption and authentication methods; and keepalive mechanisms, which are out of the scope of this paper.

4.1. Network Status Estimation

The Network Status Estimation process enables us to determine the potential bandwidth of the connection, which specifies the maximum bandwidth that will be available in that specific association. It is calculated at the beginning of the transmission and provides a rapid set-up of the sending rate, thus creating an immediate benefit in the throughput usage and optimising its convergence. In this phase, unlike other estimation mechanisms that focus on finding the residual (free) bandwidth of the link, it aims to estimate the total bandwidth of the communication (link capacity).

As shown in Fig. 3, this process consists of sending bursts in order to generate different representative samples at the time of calculating the total bandwidth. The blocks are arranged in groups of 2 to 20 packets, where the number of packets per burst is chosen according to the estimated speed of the link in the previous iteration. Therefore, the more packets are used, the lower the probability of error in the estimated bandwidth (avoiding potential deviation caused by packet losses or a high jitter during the estimation process).

The packets to be sent are data messages (DATA) that, depending on the communication situation, can be empty (initial BW estimation) or contain information on the transfer (periodical in-band estimation).

For the initial BW estimation, once the Source–Destination connection is completed, 10 bursts are sent. The Source sends the packets of each block (burst) consecutively. After that, the Destination sends a confirmation message (ACK) on receipt of the last packet of the block, which is flagged by the Source at the header.

For each burst, the reception times of the first and last packets are recorded, and the difference (Qb_i) is calculated. Once information on the size of the packets (b) in bits and the number of packets have been received (N), the bandwidth of the link (BW_i) for that burst can be calculated (Eq. (1a)). Once the Destination has received the ten bursts, ten values of the estimated bandwidth are obtained, using the arithmetic mean (Eq. (1b)) of these values as the definitive one ($BW_{estimated}$).

$$BW_i = \frac{b \cdot (N-1)}{Qb_i} \tag{1a}$$

$$BW_{estimated} = \frac{\sum_{i=1}^{10} BW_i}{10} \tag{1b}$$

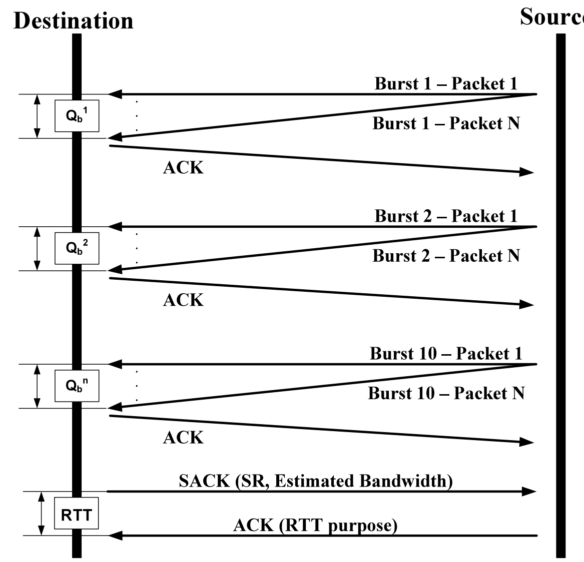

Fig. 3. AATP — Network Status Estimation process.

Finally, the Destination sends a message (SACK) indicating the Estimated Bandwidth ($BW_{estimated}$) in Mbps and the Sending Rate in packets per second, while the Source responds with a confirmation message (ACK). The Round-Trip Time (RTT) will be the difference between the sent SACK and the reception of the ACK at de Destination.

For the bandwidth calculation during the session, some data packets from information bursts can be used to calculate Eqs. (1c) & (1d).

$$BW_{LastBurst} = \frac{b \cdot (N-1)}{Qb_{LastBurst}} \tag{1c}$$

$$BW = 0,7 \cdot BW_{LastBurst} + 0,3 \cdot BW_{Historical} \tag{1d}$$

In Eq. (1d) a formula is proposed to stabilise the BW, where $BW_{Historical}$ is the mean of the last 100 samples of BW_i calculated.

4.2. Data transfer

This section describes the operation of exchanging messages between the Source (sender) and the Destination (receiver) once it starts the Data Transfer process.

At the beginning of the data transfer, the initial transmission speed (Sending Rate — SR) should be set, fixing it at a percentage of the maximum bandwidth ($BW_{estimated}$). Depending on the desired aggressiveness, a higher or lower value can be established.

The data is sent by bursts, separated by a period (T_{burst}) determined by the RTT or the minimum temporal resolution that can be offered by the operating system (OS) and the hardware (HW) on which the process operates. This time will be calculated by Eq. (2) in milliseconds or microseconds.

$$\mathrm{T_{burst}} = \max\left(OS/HW \text{ res.},\ \mathrm{RTT}\right) \tag{2}$$

Once we know the speed at which the packets are sent initially (in packets per second) and have determined the separation between bursts, the number of packets sent in each burst ($Packets_{\mathrm{burst}}$) is defined by Eq. (3).

$$\mathrm{Packets_{burst}} = \mathrm{SR} * \mathrm{T_{burst}} \tag{3}$$

Fig. 4 shows the process of sending the data. The receiver saves the information that it receives and simultaneously lists the lost

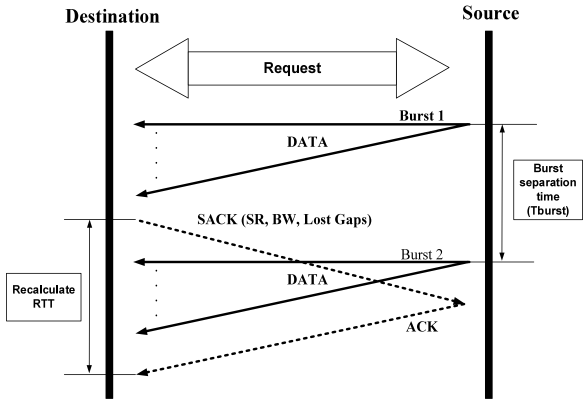

Fig. 4. AATP — Data Transfer process.

packets (sorted by gaps), which are requested in the confirmation message (SACK) of the received data. The SACK messages are sent asynchronously in relation to the bursts. Moreover, the SR and $BW_{estimated}$ are indicated in the message.

The receiver decreases or increases the SR value depending on whether or not any packets have been lost in the last burst (Eq. (4)). P_{size} is the size of the packet in bytes:

$$SR = \begin{cases} \dfrac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}, & LostPackets = FALSE \\ \dfrac{SR}{1 + 0.125 \cdot \frac{SR \cdot P_{size} \cdot 8}{BW}}, & LostPackets = TRUE \end{cases} \tag{4}$$

When losses are detected, the higher the use of the link, the greater the reduction in the SR.

The value of the Inc_p, packet increment (packets), is determined by (Eq. (5)):

$$Inc_p = 10^{\log(BW - (SR \cdot P_{size} \cdot 8)) - M} \tag{5}$$

This method of calculation causes a logarithmic growth of the SR. When the use of the link is low, the increase in the speed of transmission is greater, and vice versa.

The value M is a magnitude modifier (Eq. (6)) in order to apply a dynamic increase based on the efficiency of the link. It is more aggressive when efficiency is worse than 80% with the objective of achieving a high throughput without saturating the connection.

$$M = \begin{cases} 7, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} < 0.8 \\ \dfrac{SR \cdot P_{size} \cdot 8}{BW} \cdot 10 - 1, & \dfrac{SR \cdot P_{size} \cdot 8}{BW} \geq 0.8 \end{cases} \tag{6}$$

In the following section, in order to test the goodness of the designed protocol, a proof-of-concept implementation has been undertaken.

5. Performance tests

Based on the analysis and design described in the previous sections, the protocol is implemented, and performance tests are deployed in different scenarios in order to validate the objectives proposed during the design phase.

5.1. QoS objectives

The QoS objectives to be demonstrated from the results of the tests based on the use case are:

(O1) Efficiency

Maximum average bandwidth reached (Mbps) over different link speeds (>95% of the link capacity).

(O2) Adaptability

Modification of the Sending Rate to maximise the useful bandwidth used (Mbps) without causing congestion on the link (no losses objective during the recovery phase, immediate recovery after no losses in the last burst).

(O3) Friendly Aggressiveness

Aggressiveness against other TCP, UDP and AATP flows. The protocol contemplates the status of the network in order to let the other protocols use the residual bandwidth capacity of the link (>75%–80% of the bandwidth for AATP protocol, thus leaving the 20% of residual one to other flows).

5.2. Tests

Three different groups of tests are set to demonstrate the objectives related to the Cloud Content Sharing Use Case described before:

(T1) Single flow without losses and cross-traffic

Transmission of a single flow in order to demonstrate the efficiency of the communication at different speeds (O1).

(T2) Single flow with losses, without cross-traffic

Transmission of a single flow in order to demonstrate the efficiency of the communication at different loss levels and congestion (O2).

(T3) Single flow with cross-traffic

Transmission of a flow sharing link with other protocols, in order to demonstrate the Friendly Aggressiveness against these (O3):

a. TCP
b. UDP
c. AATP

In order to deploy these tests, two different phases were planned. First, an AATP implementation is done in a Network Simulator to analyse its behaviour and performance.

After analysing and verifying the results, an AATP prototype is deployed as a proof of concept in a Testbed on Field to check it over a real scenario.

Network Status estimation and *Data Transfer process* building blocks for the sender and the receiver have been coded in protoC (Simulator) and C (Testbed).

5.3. Phase 1 — network simulator

The Riverbed Modeler [25] is used to implement the protocol in a simulator. It is a programme that allows the design of scenarios of data networks of any size and type.

These processes are programmed as a finite state machine in C or C++ language, where each state is responsible for implementing a specific part of the functionality of each process.

The end-to-end BDP in all tests is 10^6 or greater to simulate an LFN and the base scenario that has been deployed.

The outcomes shown are the mean results of different executions, assuring a confidence interval of 99% with a maximum error deviation of ±1.5%. The results of the aforementioned tests performed are as follows:

5.3.1. Phase 1 – T1 – single flow without losses and cross-traffic — efficiency (O1)

Different links are set in order to test the estimated bandwidth and the throughput of the protocol.

(T1.1a) WAN SONET-3 (148.608 Mbps)

In a SONET-3 network, the mean estimated bandwidth is 145.93 Mbps (98.2%), and the mean throughput is 142.68 Mbps (95.99%).

Fig. 5. Random Loss – T2.1a – Simulator — Blue: Estimated Bandwidth; Green: Sending Rate; Red: Throughput accomplished. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(T1.1b) WAN SONET-12 (601.344 Mbps)

In a SONET-12 network, the mean estimated bandwidth is 573.03 Mbps (95.29%), and the throughput is 568.44 Mbps (94.53%).

(T1.1c) WAN SONET-48 (2.405 Gbps)

In a SONET-48 network, the mean estimated bandwidth is 2.34 Gbps (97.37%), and the mean throughput is 2.32 Gbps (96.6%).

The results of the test show an efficiency rate of around 95% of the bandwidth for different links.

5.3.2. Phase 1 – T2 – single flow with losses, without cross-traffic — adaptability (O2)

For this test, random losses are set in order to test the adaptability of the protocol in a lossy network.

To check the adaptability of the protocol in the simulator, a packet discarder is configured to generate random packet losses. The simulation software limits the configuration of the packet discarder.

(T2.1a) 3.5% random losses

A Packet Discarder is configured to generate 3.5% of random packet losses, which is the worst-case loss scenario of the use case requirements described in this paper.

Given that the objective is to show how the protocol adapts its behaviour to random loss episodes and not performance, these losses are considered sufficient. In Fig. 5, the result is shown. The blue line represents the estimated bandwidth, the green one represents the Sending Rate and the red line the throughput accomplished.

It is observed that the throughput starts at around 147 Mbps and when the losses begin, it oscillates between 126 and 128 Mbps (84.8–86.1%). Finally, when the losses disappear, the speed of the connection returns to 136.75 Mbps (92% usage). It is also possible to verify that the operation of the calculation of the Sending Rate is correct, with a logarithmic increase when losses are not detected and a linear reduction when detected.

5.3.3. Phase 1 – T3 – single flow with cross-traffic — friendly aggressiveness (O3)

Three comparisons are proposed in order to check the aggressive behaviour of AATP when it shares a link with other transport protocols. These protocols are TCP (friendly), UDP (aggressive–inflexible) and AATP (aggressive).

To generate additional traffic between the end nodes, the following flows are used:

Fig. 6. TCP flow – T3.1a – Simulator — Blue: AATP flow; Red: TCP flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. UDP flow – T3.1b – Simulator — Blue: AATP flow; Red: UDP flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- TCP Flow: Riverbed node running FTP traffic (3 GB of data).
- UDP Flow: Riverbed node running UDP traffic (30 Mbps).
- AATP flow: AATP instance to generate AATP traffic (No speed fixed).

Due to the limitations of the simulator, it is not possible to configure the characteristics of the TCP and UDP flows.

(T3.1a) TCP flow — SONET-3 (148.608 Mbps)

In this test, the link is shared between a TCP flow and an AATP flow (Fig. 6). The blue line is the AATP flow and the red one is the TCP flow.

In this case, AATP forces TCP to use the residual BW (20%). AATP maintains the BW established first with fluctuations (80%). After sending the AATP, FTP takes the full bandwidth.

(T3.1b) UDP flow — SONET-3 (148.608 Mbps)

For this test, a UDP flow of 30 Mbps is launched (Fig. 7). The blue line is the AATP flow and the red one is the UDP flow. Neither flow lets the other take the bandwidth because of its aggressiveness. This situation causes packet loss in both flows.

(T3.1c) AATP flow — SONET-3 (148.608 Mbps)

Finally, in this test, two AATP flows share a link. The result of this test (Fig. 8) shows that the first flow launched uses almost the entire bandwidth. Meanwhile, the other flow does not obtain more than 10% of the bandwidth. The blue line is the first AATP flow and the red one is the second AATP flow.

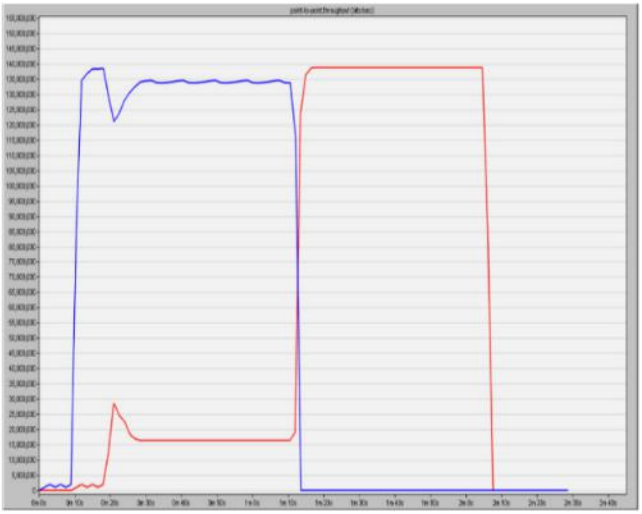

Fig. 8. AATP flow – T3.1c – Simulator — Blue: AATP flow 1; Red: AATP flow 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

After deploying the protocol in the Riverbed Simulator, a first analysis has been carried out to improve the implementation of the protocol before the final implementation of the proof of concept.

5.4. Phase 2 — testbed on field

With the objective of testing the protocol in a real environment as a proof of concept, a Testbed on Field is deployed. The Testbed consists of two extreme nodes (Source and Destination) which are interconnected through a central node that emulates the behaviour of a WAN network with LFN characteristics.

The physical connections between devices are made by twisted pairs CAT-5 at 100 Mbps Full Duplex and latencies of up to 100 ms. To simulate different network characteristics, the *WANem* software [26] is used in the central node.

During the entire test, a total of 1GB is sent and a BDP greater than 12,500 bytes (10^5 bits) is fixed. In the graph, the blue colour indicates the estimated bandwidth (Mbps), the green colour the throughput (Mbps) and the red colour the losses (%).

The results of the aforementioned tests performed are shown.

5.4.1. Phase 2 – T1 – single flow without losses and cross-traffic — efficiency (O1)

The maximum speed is set in order to check the efficiency.

(T1.2) 100 Mbps — 1 GB of data

In a 100 Mbps scenario, the estimated bandwidth is 97 Mbps (97%) and the throughput is around 96 Mbps (96%).

95% of link utilisation is exceeded. It should be noted that the actual sending speed of the protocol is, in most situations, below the estimated one. This is due to the step used when increasing the sending speed, the one defined by the size of the packages that are sent.

5.4.2. Phase 2 – T2 – single flow with losses, without cross-traffic — adaptability (O2)

Two main tests are set in the Testbed using WANem to check the behaviour of the protocol during a random loss scenario.

(T2.2a) From 0% to 5% random losses

First, the result of the throughput accomplished in a range from 0% to 5% random packet losses (Table 2).

Table 2
From 0% to 5% random losses – T2.2a – Testbed.

Random losses (%)	Average efficiency (%)
0	96
0.001	96
0.01	96
0.1	90
1	40
3	35
5	18

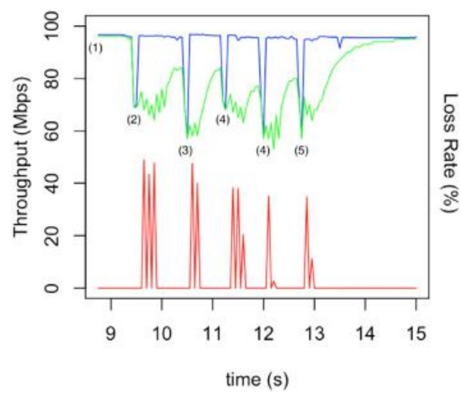

Fig. 9. Congested network – T2.2b – Testbed — Blue: Estimated Bandwidth; Green: Throughput; Red: Losses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The results with up to nearly 0.1% random losses show an efficiency of 90% for AATP. From this point to 3% losses, the efficiency decreases to 40%. After that, where losses are over 3%, the throughput of the protocol drops to 20% of the link capacity.

(T2.2b) Bandwidth occupation from 0% to 100%

A test divided into different stages is proposed. The objective is to show how AATP modifies its throughput depending on the network congestion by introducing contention traffic using an Iperf flow [27]. The sequence of execution of flows is described below:

(1) The test starts with an initial link occupation of 70%. The AATP flow starts shortly after.

(2) Interfering traffic is added, transmitting at 100% of link capacity.

(3) An interfering flow is introduced and progressively increased in steps from 20% to 100% occupancy.

(4) Increasingly, an interfering flow in steps of 20% occupancy to reach 100% and decrease to 0%.

(5) Interfering traffic from 100% to 0% occupancy is gradually decreased, in steps of 20%.

In Fig. 9, the results of (T2.2b) can be observed and the previously defined sections can be identified. The blue line represents the estimated bandwidth (Mbps), the green line the throughput (Mbps) and the red line the Loss Rate (%).

It is observed that the mechanisms react to both congestion and losses. Congestion causes a decrease in the Sending Rate, which occurs continuously to decongest the link and is reflected

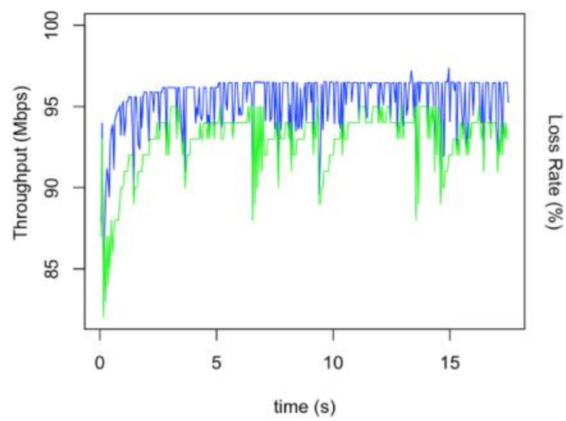

Fig. 10. AATP sharing with TCP flow – T3.2a – Testbed — Blue: Estimated Bandwidth; Green: Throughput. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

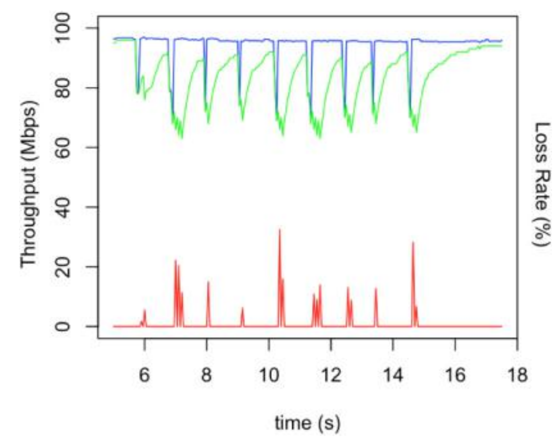

Fig. 11. AATP sharing with UDP flow – T3.2b – Testbed — Blue: Estimated Bandwidth; Green: Throughput; Red: Losses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

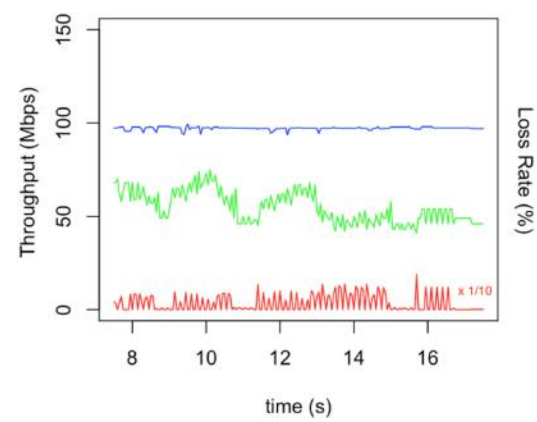

Fig. 12. AATP flow – T3.2c – Testbed — Blue: AATP flow 1 Bandwidth; Green: Throughput; Red: Losses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the throughput. Losses cause throughput decreases, which prevent the mechanism from recovering until the channel is ready. It is also capable of recovering the sending speed as soon as the channel allows it in less than half a second.

5.4.3. Phase 2 – T3 – single flow with cross-traffic — friendly aggressiveness (O3)

In order to check the friendly aggressiveness of the protocol, three sets of tests are proposed over the Testbed. The following flows are set to generate additional traffic between the end nodes:

- TCP flow: File Transport Protocol (FTP) to generate TCP traffic [28]. 1 GB of Data.
- UDP flow: Iperf [27] to generate UDP traffic. 1 GB of Data.
- AATP flow: AATP instance to generate AATP traffic. 1 GB of Data.

(T3.2a) TCP flow — 100 Mbps

This test shows how the protocol AATP shares the link with a non-aggressive protocol.

Fig. 10 evidences the throughput achieved by the designed protocol. AATP reaches around 93% of the link capacity, allowing TCP to only obtain the residual bandwidth of the link (7%), without generating losses.

(T3.2b) UDP flow — 100 Mbps

The UDP flow performed in this test is inflexible. The software used to simulate UDP (*Iperf*) does not decrease the sending rate even if losses are generated.

In this context of aggressiveness, this test shows the throughput achieved by AATP sharing a 100 Mbps link with a UDP flow (Fig. 11).

Under these circumstances, the congestion control is not capable of occupying the entire channel since the UDP flow is highly aggressive and inflexible. This situation generates considerable losses, meaning that the large number of retransmissions to be made results in a significant decrease in the real speed of data transmission. However, it does achieve an average throughput of 75 Mbps. This is because the UDP flow is invariable even when saturation losses of the link occur.

(T3.2c) AATP flow — 100 Mbps

In this final test, two AATP instances share the same link. Fig. 12 shows the behaviour of one of the two AATPs transmitting simultaneously in which we can observe a struggle for the total bandwidth of the channel (100 Mbps), where each one achieves a distribution of 50% but incurs losses.

Both flows compete for the available bandwidth without considering the presence of other flows, which generates congestion due to the aggressiveness of the protocol.

6. Tests output analysis

In this section, the output of the tests deployed in both phases (Network Simulator and Testbed) is analysed in order to meet the QoS objectives.

It is necessary to highlight that the implementation in both scenarios differs slightly depending on the programming language and the simulation (Riverbed Modeler) or emulation (WANem) options available of the software used.

The main reason for deploying the protocol in these two phases is to cover the maximum number of possible cases and situations in order to prove and demonstrate the real behaviour of the designed protocol.

6.1. Efficiency (O1) — analysis from tests 1

The objective of deploying this first set of tests is to check the Efficiency (O1) of the protocol to use all the bandwidth of the link capacity (>95%).

The AATP is designed with a Bandwidth Estimation mechanism. It is launched during the connection establishment, calculating the bandwidth of the communication. With this information, the initial Sending Rate is set directly to the maximum capacity, depending on the aggressiveness set in the protocol behaviour.

Table 3
Results from T1.

Test	Link capacity (Mbps)	Estimated BW (Mbps)	Throughput (Mbps)	Efficiency (%)
T1.1a	148.6	145.9	142.7	95.9%
T1.1b	601.3	573.0	568.4	94.5%
T1.1c	2405.4	2342.2	2323.5	96.6%
T1.2	100	97	96	96%

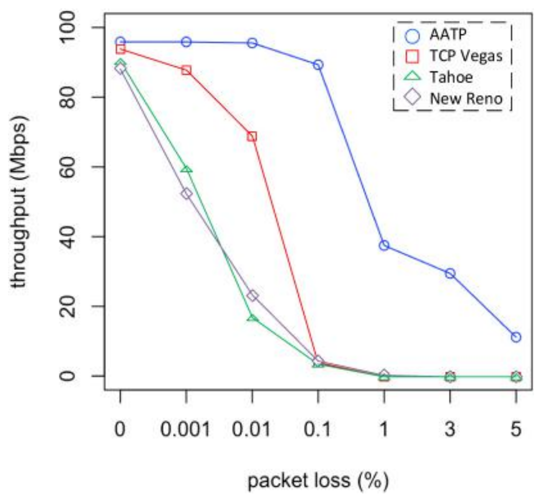

Fig. 13. Comparative between AATP, TCP Vegas, Tahoe, New Reno.

As shown in Table 3, the protocol uses around 95% of the link in all tests deployed over links without losses and cross-traffic, accomplishing the Objective 1 — Efficiency.

6.2. Adaptability (O2) — analysis from tests 2

This set of tests helps to demonstrate the adaptability (O2) of the protocol in lossy or congested networks. It is necessary to highlight that Packet Discarder (Simulator) and WANem (Testbed) have different implementations and behaviour in terms of random losses, which consequently affects the results.

The protocol is designed to react to network losses, without differentiating the cause. This reaction causes a reduction of the Sending Rate, which is proportional to its use of the link at that moment.

After detecting the end of the lossy event, the protocol aggressively increases its Sending Rate with the objective of reaching an efficiency rate of 80%. As a consequence, the Sending Rate is increased gradually, in order to avoid causing congestion.

With the results from T2.2a (Table 2), the AATP is compared with other protocols (TCP Vegas, Tahoe and New Reno) deployed over the same scenario. The comparison is shown in Fig. 13:

The results, of up to nearly 0.1% random losses, show an efficiency of 95% for AATP. This situation is considered inefficient for other protocols. From this point to 3% losses, the efficiency decreases to 40%. After that, where losses are over 3%, the throughput of the protocol drops to 20% of the link capacity.

Focusing on the adaptability of the protocol, a detailed study of the results (T2.2b — Fig. 9) shows how the reactivity to the losses

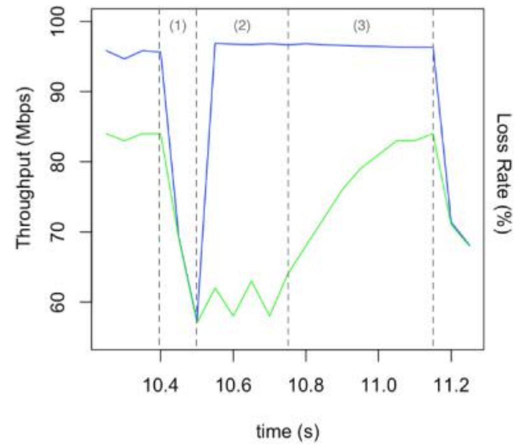

Fig. 14. Congested network – Recuperation process – T2.2b – Testbed – Blue: Estimated Bandwidth; Green: Throughput. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

can be decomposed into three phases (between seconds 10 and 12), observable in Fig. 14.

In the first place, the initial sending speed is decreased until the aggregate sending speed stops causing congestion (Fig. 14 — (1)).

The congestion control then detects that the available bandwidth is the maximum of the channel. At this point (second 10.5), it enters a second phase in which it experiences the losses generated by the previous congestion period (Fig. 14 — (2)), where the efficiency is around 60%.

Moreover, in that same phase, since the estimation of the link no longer detects congestion, the sending window is increased.

Finally, once the losses have been treated, the recovery process is started (Fig. 14 — (3)).

It is shown that the protocol tries to modify its behaviour when it detects a packet loss. Because the losses are random and not caused by the traffic generated, packet losses continue to occur, even though the protocol tries to reduce its sending rate (60%).

On the one hand, the results of T2 were useful to check the accomplishment of the Objective 2 (O2) — Adaptability of the protocol. On the other hand, these tests cannot be used to check the efficiency (O1) of the protocol, since they do not focus on efficient behaviour over a random loss network such as a wireless scenario. LFNs are not characterised for their loss ratio in the same way as wireless networks.

6.3. Friendly aggressiveness (O3) — analysis from tests 3

In the final set of tests, the main objective is to demonstrate the behaviour of the protocol when coexisting with other reference protocols, such as TCP or UDP, and also with other AATP flows (O3).

The design of the AATP protocol is focused on the maximum use of the capacity of the link (>80%), and the residual bandwidth is left for the other protocols (20%). This is accomplished with the Bandwidth Estimation mechanism and the aggressive behaviour of the Data Transfer process.

6.3.1. AATP vs. TCP

In this case, most of the capacity of the link is occupied by AATP (around 80%–85%) and as a consequence TCP is left with the residual bandwidth without causing losses (from 20% to 5%). This is because of the aggressiveness of AATP, which does not share the link equally with other non-aggressive protocols such as TCP.

6.3.2. AATP vs. UDP

In this case, AATP competes against another aggressive protocol, UDP. This is the most aggressive case scenario because UDP does not modify its sending rate even though losses occur. ATTP tries to modify its sending rate (from 95% to 60%) in order to reduce losses in the link. As UDP flow does not modify its behaviour, this situation causes congestion over the link and packet losses during the data transfer, which results in inefficiency.

6.3.3. AATP vs. AATP

In this last case, two AATP flows share the bandwidth of the link. The first flow launched experiences a greater link utilisation and fewer packet losses than the second one. The conflict between the two flows produces inefficiencies in the network, reaching 50% of sharing but without control.

After achieving the goals and demonstrating the objectives set, the AATP is currently undergoing an implementation process to be deployed in a production environment.

7. Conclusions and future work

The growth of Storage Area Networks in Cloud platforms has arisen from the need to share large amounts of information all over the world. Therefore, the need for a network that can transfer or move this information from one point to another both efficiently and reliably has increased. The context exhibits a Cloud Content Sharing Use Case where several limitations appear over Long Fat Networks due to their Bandwidth-Delay Product (high Bandwidth and high Round Trip Time). This causes problems in the existing TCP and UDP protocols.

On analysis of the requirements, the transport protocol is required to send large amounts of data (to the order of Hundreds of Gigabytes) due to the exchange of information between cloud environments. Furthermore, it is necessary to reach the full capacity of the connection efficiently and, due to the Bandwidth-Delay Product, to overcome the main TCP constraints in long-distance communications. In addition, this protocol has to act aggressively towards other transport protocols while, at the same time, adapt to network losses by performing a flow control.

In order to fulfil the aforementioned requirements, the AATP protocol has been designed and implemented to be efficient (O1), adaptable (O2) and friendly aggressive (O3). The two main characteristics to highlight from the AATP are (1) the mechanism to calculate the maximum bandwidth capacity of the communication through a Bandwidth Estimation process and (2) the capacity of the protocol to adapt its behaviour using an efficient Data Transfer process. Furthermore, this process is aggressive towards other protocols and adaptative to the changes in the network during and after a lossy episode.

The different tests (T1, T2 and T3) from both deployment phases (Phase 1 — Network Simulator and Phase 2 — Testbed on Field) are set to demonstrate the performance of the AATP protocol.

Efficiency is around 95% in the different scenarios deployed, accomplishing the O1 — Efficiency, shown in T1. It is noted that minor inefficiencies are caused by headers and implementation issues.

After a lossy episode, the protocol rapidly recovers 80% of its maximum sending rate and gradually increases until it reaches full capacity, being O2 — Adaptative, demonstrated in T2. Moreover, a comparison between the AATP with other protocols is made. Improved efficiency over the same link with different random losses (0% to 5%) is observed.

In comparison with TCP, AATP takes up almost all of the bandwidth (80%), leaving the residual bandwidth to TCP (20%). In another case, versus UDP-aggressive, both protocols try to take all bandwidth without sharing it, producing losses. This is because the UDP version used does not modify its sending rate in the same way as AATP. In the last case, where two AATP flows share the link, the results show that the protocol behaves aggressively and causes losses because both flows try to achieve the maximum bandwidth. It can be concluded that the AATP protocol accomplishes O3 — Aggressiveness, proved in T3.

After analysing all the tests results, it can be concluded that our objectives to provide Quality of Service for a Cloud data exchange use case are achieved. Future work aims at:

– Improving the protocol performance in lossy episodes by differentiating random losses from congestion losses in heterogeneous scenarios.
– Applying fairness flow prioritisation between AATP flows to fairly share the whole bandwidth of the network efficiently without causing losses and instabilities.

CRediT authorship contribution statement

Alan Briones: Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Project Administration. **Adrià Mallorquí:** Software, Resources Data Curation, Visualization. **Agustín Zaballos:** Conceptualization, Methodology, Validation, Supervision. **Ramon Martin de Pozuelo:** Conceptualization, Formal analysis, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Article

Wireless Loss Detection over Fairly Shared Heterogeneous Long Fat Networks

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Abstract: The quality of inter-network communication is often detrimentally affected by the large deployment of heterogeneous networks, including Long Fat Networks, as a result of wireless media introduction. Legacy transport protocols assume an independent wired connection to the network. When a loss occurs, the protocol considers it as a congestion loss, decreasing its throughput in order to reduce the network congestion without evaluating a possible channel failure. Distinct wireless transport protocols and their reference metrics are analyzed in order to design a mechanism that improves the Aggressive and Adaptative Transport Protocol (AATP) performance over Heterogeneous Long Fat Networks (HLFNs). In this paper, we present the Enhanced-AATP, which introduces the designed Loss Threshold Decision maker mechanism for the detection of different types of losses in the AATP operation. The degree to which the protocol can maintain throughput levels during channel losses or decrease production while congestion losses occur depends on the evolution of the smooth Jitter Ratio metric value. Moreover, the defined Weighted Fairness index enables the modification of protocol behavior and hence the prioritized fair use of the node's resources. Different experiments are simulated over a network simulator to demonstrate the operation and performance improvement of the Enhanced-AATP. To conclude, the Enhanced-AATP performance is compared with other modern protocols.

Keywords: transport protocol; heterogeneous long fat networks; wireless; fairness; loss episode; bottleneck

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1. Introduction

Nowadays, communications take place over heterogeneous networks composed of wired and wireless sections. The number of wireless end devices connected to the Internet is increasing exponentially because of the massive use of mobile phones. Moreover, the bandwidth required is also increasing because of the global presence of the latest multimedia technologies such as 4K and Virtual Reality/Augmented Reality (VR/AR) [1]. The presence of the wireless sections directly influences the network's characteristics and data transmission quality. The main inconveniences of using wireless connection for communication protocols are bandwidth degradation, the interruption of the transmission caused by the nature of the media, and the network resource inefficiency caused by obstacles, interferences, or the mobility of the node [2].

The presence of access wireless sections in the last mile of the Long Fat Networks (LFN), networks composed of core wired sections with high Bandwidth (BW), high values of Round-Trip Time (RTT), and a Bandwidth-Delay Product (BDP) greater than 12,500 bytes (10^5 bits) [3] is increasing the complexity of this type of networks, which are also denominated Heterogeneous Long Fat Networks (HLFNs).

Concretely, the transport layer protocols are affected because their semantics are end-to-end, meaning that there is a lack of awareness of the sections of the network at the endpoints. During the design of the first transport protocols, in the course of the Internet conception in the 1970s [4], some premises were assumed. First of all, legacy transport protocols are not able to distinguish the cause of a packet loss episode, assuming that the packets are discarded by an intermediate router because of congestion; the possibility of this being caused by media inefficiencies is not considered. Furthermore, these traditional protocols assume that independent connections are wired without contemplating the possibility of sharing the media, as is the case in wireless environments. Finally, other related problems include the random multiple packet losses caused by interferences or the fading of a channel, or the introduced delay due to asymmetric link capabilities.

Consequently, increased traffic volumes and the large deployment of wireless networks are detrimentally affecting the transport protocol basis and its performance [5–8], as is the case of the worldwide used Transmission Control Protocol (TCP) [9,10] and some of its variants [11–13]. These limitations also affect Adaptative and Aggressive Transport Protocol (AATP) [14].

The goal of this work is to achieve a high-performance data transmission over a wired-wireless communication that fairly shares the network resources of a node, although real-time transfers are out of the scope because of the packet-burst operation of the AATP.

The main contributions of this paper are as follows. First, distinct wireless transport protocols are analyzed, and different metrics are examined to design a mechanism to differentiate between congestion and channel losses. Similarly, different fairness indices are considered to define a procedure for the fair distribution of the bandwidth among distinct flows connected to an endpoint. Second, the AATP is upgraded (Enhanced-AATP) by introducing the aforementioned features for wireless loss detection and for the controlled fair distribution of the network resources of an end-device. For this, the designed Loss Threshold Decisor (LTD) mechanism, based on the Jitter Ratio metric, is proposed for the decision-making process of the protocol to discern between the losses caused by network congestion or those caused by channel fault. In addition, the defined Weighted Fairness mechanism is introduced to enable the fair coexistence of multiple flows. Finally, the protocol is deployed over the network simulator Steelcentral Riverbed Modeler [15]. A set of tests are designed and run to demonstrate how the Enhanced-AATP outperforms HLFNs and its capacity to manage different flows from the point of view of an endpoint. In conclusion, its performance is compared with modern transport protocols.

The rest of this paper is structured as follows. In Section 2, the background of the paper is explained. In Section 3, the related work is presented, focusing on wireless transport protocols, their reference metrics, and their wireless mechanisms, also including distinct fairness indices. A review of the AATP protocol basis is provided in Section 4. Section 5 describes the Enhanced-AATP with the modifications and mechanisms introduced. Section 6 details the experiments deployed over the network simulator, showing the results of the improvements. Finally, Section 7 concludes the paper.

2. Background

The Adaptative and Aggressive Transport Protocol (AATP) [14] protocol was designed to work over LFNs, focusing on solving the Cloud Data Sharing Use Case defined by a Cloud company. Within this Use Case, servers from far separated Storage Area Network (SAN) regions exchange large amounts of data over high-speed networks through a private wired WAN. For recent deployments, this Cloud company decided to evolve the Use Case by introducing wireless access in the last mile of their client edges (Figure 1). A similar Use Case, more focused on processing, is discussed in [16].

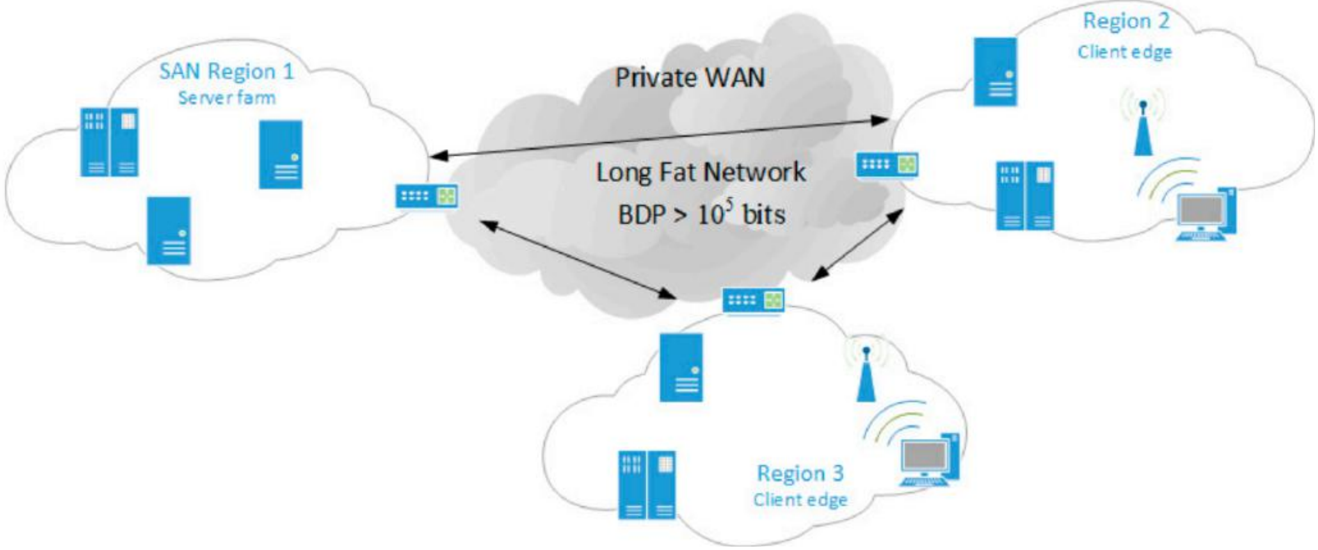


Figure 1. Cloud Data Sharing Use Case over Heterogeneous Long Fat Networks (HLFNs).

In addition to transferring information between servers from different server farms, it also exchanges large amounts of stored data between cloud servers and endpoints. These end nodes can be connected through a wired or a short-range wireless connection. Given the short-range wireless connection and the endpoints' data transfer profile (large amount of stored data), mobility during the transfer is not expected, nor are there a high number of intermediate nodes due to the network topology.

On the one hand, the AATP protocol provides a high-performance data transmission and quick recovery in case of a loss episode. However, on the other hand, its performance is affected over lossy wireless networks because the protocol does not recognize random channel losses. Its lower operation requires an adaptation to deal with the complexity of the Cloud Data Sharing Use Case over Heterogenous Long Fat Networks. In addition, given the possibility of having different AATP flows connected to the same end-device or server, the unfriendly behavior of the AATP is required to be modified to achieve intra-protocol fairness. To overcome these drawbacks, it is necessary to propose solutions for the paradigm of HLFNs.

For these reasons, a review of the State-of-the-Art of the most outstanding transport protocols designed for wireless networks is detailed. Specifically, it focuses on the operation of these protocols, the reference metrics, and their mechanisms to deal with the inconveniences of the radio media. Finally, different fairness indices are considered to define a mechanism for the fair distribution of the bandwidth among the distinct flows connected to an endpoint.

3. Related Work. Metrics Selection Process

The main cause of losses in wired networks is the congestion of one of the intermediate devices [17]. To correct this situation, the endpoint reduces its sending rate to reduce network saturation. However, when a loss occurs in a wireless network, it can be caused by a change in channel conditions (fading, interferences) [2]. In HLFNs [3], these drawbacks are more critical. In this section, distinct metrics are analyzed and are selected to be included in the protocol for the decision-making process. Moreover, in the case of wireless shared media, the fair distribution of the network resources, from the nodes' point of view is more difficult to control [18] because of its channel characteristics.

3.1. Wireless Oriented Transport Protocols. Wireless Channel-Loss Metric

Relating the actions taken by a protocol to network statistics is an interesting approach for the decision-making process on network events. The Performance-oriented Congestion

Control (PCC) [19], defined by Mo Dong et al., makes controlled decisions based on empirical evidence, pairing actions with directly observed performance results.

In order to evaluate the metrics and mechanisms for wireless loss-tolerant transmissions, diverse transport protocols solutions and their congestion controls have been studied. Cheng Peng Fu and S.C Liew proposed TCP Veno [20], based on TCP Reno and TCP Vegas [21,22]. This protocol calculates the Round-Trip Time (RTT) periodically, recording the minimum RTT of the communication, known as Base RTT or Best RTT, and the last RTT, known as Actual RTT. TCP Veno bases its loss episode decision on the comparison of these two RTT values, also taking into account the Congestion Window and the bottleneck of the connection.

A multipath feature is introduced in mVeno [23] by Pingping Dong et al. to improve the performance of the protocol by using the information from the subflows that belong to a TCP connection. The objective is to adaptively adjust the transmission rate of each subflow and acting over the congestion window, decreasing one-fifth of it, in the case of a packet loss event.

With reference to the TCP Reno mechanism, Taha Saedi and Hosam El-Ocla proposed the Congestion Control Enhancement for Random Loss (CERL) [24,25] and its revisited version, CERL+ [26], to improve the performance over wireless networks. CERL+ proposes a modification of TCP Reno at the sender-side by using a dynamic threshold of the RTT. With the average RTT, the protocol calculates the length of the bottleneck's queue to evaluate the congestion status and distinguish a random loss. The main drawback pointed out by its authors is the requirement of precise time synchronization between the sender and receiver.

Saverio Mascolo et al. built TCP Westwood [27] and its evolution TCP Westwood+ [28]. This protocol differentiates the loss episodes by defining a coarse timeout for congestion loss and by setting the reception of three duplicated ACKs (DUPACKs) as the indicator of channel loss during the bandwidth estimation process. An upgraded slow-start for Westwood was proposed to improve its performance [29].

The Dynamic TCP (D-TCP) [30], proposed by Madhan Raj Kanagarathinam et al., extracts the end-to-end performance statistics (traffic intensity, link capacity, packet sending rate) of the connection to calculate the available bandwidth of the network. In case of abrupt changes or lossy conditions, D-TCP can adapt its operation by fixing a dynamic congestion window factor N. By adaptatively modifying the CWND, based on the factor N, the protocol avoids losing performance during a spurious packet loss event.

Venkat Arun and Hari Balakrishnan defined Copa [31], a practical delay-based protocol. Even if it is not focused on wireless environments, this protocol proposes a mechanism by fixing a target rate. This target rate provides a reference for high throughput and low delay. By relating the minRTT (the minimum RTT calculated in a long period of time) to the standing RTT (the smallest RTT over a recent-time window), the protocol adjusts its congestion window in the direction of the reference target rate. Moreover, Copa has a competitive mode to compete with buffer-filling protocols, based on the information extracted from the last 5 RTTs to check if the queue has been emptied.

Yasir Zaki et al. presented Verus [32], which is a protocol that focuses on the delay over high variable cellular channels. This protocol establishes a delay profile, which reflects the relationship between the congestion window and the delay variations, which is determined through the RTT, over short epochs. Verus uses this relationship to increment or decrement the congestion window based on short-term packet delay variations.

Neal Cardwell et al. presented TCP BBR [33], one of the most high-performance TCP protocols, which manages the maximum BW with the minimum RTT. Given the inefficiency of BBR in exploiting the Wi-Fi bandwidth, a modification is proposed by Carlos Augusto Grazia et al., which is called BBRp [34]. This inefficiency lies in the impossibility of performing frame aggregation because TCP BBR implements its own solution of the TCP pacing algorithm. Tuning the BBR pacing speed allows the congestion control to correctly aggregate packets at the wireless bottleneck with almost optimal TCP throughput.

To fulfill the needs of high-bandwidth requirements of last multimedia technologies (4K, VR/AR) over wireless connections, Li Tong et al. presented the protocol TCP-TACK [35]. This protocol bases its operation on two types of ACKs, the Instant ACK (IACK) and the Tamed ACK (TACK). The first one, IACK, is meant to get rapid feedback, which provides information about instant events (loss, state update.). The second one, TACK, is more focused on statistics (losses, available bandwidth, receipts, etc.). In this way, the number of ACKs sent to the network is reduced by over 90%, decreasing the overhead control and leading to an improvement of the goodput around 28%. Furthermore, TCP-TACK proposes an advanced way of calculating the minimum RTT using the smooth One-Way Delay (OWD) using relative values, reducing the information sent to the network without affecting the performance.

E. H. K. Wu and Mei-Zhen Chen designed Jitter TCP (JTCP) [36], which is based on the concept of the Jitter Ratio. Considering the sending time and receiving time of the packets, the Jitter ratio relates to the effect of the queued packets at the bottleneck the delay introduced between packets at the destination. The Jitter Ratio is compared to the Queue Decision maker (k/w), which is defined as the number of queued packets (k) considered as a congestion trace after all the packets of a congestion window (w) have been sent. If the Jitter Ratio is greater than the Queue Decision maker, this implies that the loss episode is due to congestion. If it is lower than Queue Decision maker, the loss episode is caused by the channel. JTCP defines one queued packet ($k = 1$) as a trace of congestion because TCP control flow increases its throughput by one packet per iteration. The operation with $k > 1$, more than one packet, is not analyzed or evaluated.

Jyh-Ming Chen et al. proposed an enhancement for the Stream Control Transmission Protocol called Jitter Stream Control Transmission Protocol (JSCTP) [37]. The JSCTP keeps the semantics and operation from the SCTP, adding a calculus of the aforementioned Jitter Ratio proposed in the JTCP for the loss episode decision. To filter the case $Jr = 0$, the Jitter Ratio is smoothed.

The TCP Jersey, presented by Kai Xu et al., [38], and its evolution, TCP New Jersey, estimate the total bandwidth of the connection and, with the information provided by the timestamps of the ACK received, decide if the loss episode is due to congestion or the channel. These protocols include the flag Explicit Congestion Notification (ECN), which uses the information provided by the intermediate routers on their queue status to make the final decision. Different protocols rely on these feedback mechanisms from the network devices, which are out of the scope of this paper because these functionalities are not usually enabled on the intermediate routers. V. B. Reddy and A. K. Sarje proposed TCP-Casablanca [39] for these types of mechanisms to decide the type of losses by considering the flag set by the intermediate routers. These routers have a biased queue management to identify the retransmitted packets.

New data-driven designed protocols are out of the scope of this work, as is the protocol algorithm Indigo [40] from Francis Y. Yan et al., which applies machine learning, given the requirements needed to train the protocol and the amount of data needed for this process. Indigo uses a machine-learned congestion control scheme from the data gathered from Pantheon [41], which is a community evaluation platform for academic research on congestion control from Stanford University. Indigo observes the network state each time an ACK is received, adjusting its congestion window every 10 ms while updating its internal state.

After analyzing the most outstanding transport protocols for wireless loss-tolerant transmissions, Table 1 depicts the wireless loss decision metrics used by each analyzed protocol. The analyzed protocols propose the combination of different metrics related to the Round-Trip Time (or Delay-based), Jitter, information from different flows and the queue, buffer, or congestion, and status of the network or the intermediate routers to find out the cause of a loss over a wired-wireless network.

Table 1. Wireless loss decision elements from the wireless loss-tolerant transport protocols.

Transport Protocol	Network Status	RTT	Intermediate Queue Length	Jitter	ACK Action	ECN	Machine Learning
PCC [19]	X						
TCP Veno [20]		X	X				
mVeno [23]		X					
CERL+ [26]		X	X				
TCP Westwood+ [28]	X				X		
D-TCP [30]	X		X				
Copa [31]		X					
Verus [32]		X					
BBRp [34]	X	X					
TCP-TACK [35]		X			X		
JTCP [36]			X	X			
JSCTP [37]			X	X			
TCP New Jersey [38]			X			X	
TCP-Casablanca [39]			X			X	
Indigo [40]	X						X

The metrics related to the information provided by the network nodes (ECN) are discarded from the metric decision due to the fact that this information from the network may not be accessible. Data-driven machine learning techniques are also discarded, given the requirements requested to train the protocol and the amount of data needed for this process.

In addition, delay-based solutions are not considered because of the buffer-fill profile of the AATP protocol. The use of the Round-Trip Time is also discarded, given the high delay of HLFNs, the ACK actions, and the synchronization requirement.

Finally, given the packet burst operation of the AATP, the time difference among the packets received provides information about the status of the bottleneck, which can be directly related to the jitter. The jitter provides information about the intermediate nodes packet queue. None of the Jitter Ratio-based protocols consider the possibility of adding more than one packet per iteration.

In this paper, in order to overcome the aforementioned drawbacks, the Enhanced-AATP proposes a Loss Threshold Decision maker (LTD) mechanism. The LTD is compared to the Jitter Ratio, considering the possibility of adding more than one packet per iteration. The Jitter Ratio increments its value as the saturation of the intermediate nodes increases, providing information about a possible congestion episode.

3.2. Fairness Indices. Intra Fairness Multi-Flow Metric

The concept of fairness is analyzed, and distinct indices are evaluated by the AATP enhancement to obtain a controlled fair share of the network's resources by different flows connected to the same node.

The fairness concept refers to how fair the treatment is between the different nodes that are sharing a specific resource. In the environment of networks and the Internet [42], the concept refers to the fairness in the distribution of the throughput that can reach each of the flows that share a point-to-point connection. Modern protocols have required the introduction of a fairness system as in the case of BRR [43].

Usually, most of the networks are IP best-effort, in which there is no point-to-point control of the resources and in which losses can occur due to congestion or channel failure, directly affecting the quality of the connection. However, to achieve proper fairness, the different flows must be treated fairly, equally, and impartially. Another possible approach is to give preferential treatment to the flows that require more resources at the request of the system or the user [44].

Shi, H. established in [45] a way to measure the fairness of a system (or of the individuals in a system), where various types of indices are used to quantify this notion of equality and fair treatment. These indices quantify fairness based on certain metrics (throughput is one of the most used) that are evaluated by each of the flows. In this way, the initial assumption is made that there is a type of resource whose total is C_x, which has to be distributed among n individuals. In this way, the location $X = \{x_1, x_2, \ldots, x_n\}$ is obtained, where x_i is the amount of the resource provided to element i. Thus, $\sum_{i=1}^{n} x_i \leq C_x$ must be satisfied, where C_x is the total amount of the resource that can be provided. In this way, a function f(X) must be defined to give a quantitative value of the system's fairness. Said function f(X) should meet the following requirements:

- R1: f(X) should be continuous in $X \in \mathbb{R}_n^+$.
- R2: f(X) should be independent of n.
- R3: The range of values of f(X) should be mappable to [0, 1].
- R4: f(X) should be scalable to multi-resource cases.
- R5: f(X) should be easy to implement.
- R6: f(X) should be sensitive enough to the variation of X.

To compare the different fairness indices, other significant aspects are defined to consider:

- Definition: The index must meet the definition of fairness.
- Measurable: Fairness must be measurable quantitatively.
- Unfairness: The method should make it possible to detect which individuals are not treated fairly.
- Priorities/Weights: The method must allow weight assignation to give priority to some individuals over others.
- Control: Fairness control and possible index requirements for information on system data are also considered.
- Function f(X) requirements: The definition of the function f(X) meets the six aforementioned requirements (continuous, independent, mappable, scalable, implementable, and sensitive).

The indices analyzed are Jain's Fairness Index, Entropy Fairness, Max-Min Fairness, Proportional Fairness, Tian Lan's Index, and Envy-Based Fairness, which are compared in Table 2.

Table 2. Fairness indices comparison [45].

Index	Jain's	Proportional	Entropy	Tian Lan's	Max-Min	Envy-Based
Definition	Yes	Yes	No	Yes	Yes	Yes
Measurable	Yes	No	Yes	Yes	No	Yes
Unfairness	No	No	No	No	No	Yes
Priorities/Weights	No	Yes	No	No	Yes	No
Control	Centralized	Centralized	Centralized	Centralized	No	No
Function f(X) requirements	R1, R2, R3, R5, R6	No	R1, R2, R5, R6	R1, R2, R3, R6	No	R1, R2, R3, R4

The index that meets the most requirements is Jain's Fairness Index. The fairness calculation, according to Jain's Fairness Index (JFI) is calculated from the J function:

$$J = \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{N \cdot \sum_{n=1}^{N} r_n^2} \quad (1)$$

where r_n is the amount of the resource that is given to flow n for each of the N flows that make up the system. The values that the function can take are in the range [0, 1]. A value of $J = 1$ indicates that there is total fairness in the whole system, while a value of $J = 0$ indicates that the system is totally unfair. From this function, samples can be taken periodically to obtain a discrete function that depends on time and is able to analyze the trend of the system, obtaining the following equation:

$$J(t) = \frac{\left(\sum_{n=1}^{N} r_n(t)\right)^2}{N \sum_{n=1}^{N} r_n(t)^2}. \tag{2}$$

Although this method helps to give a general idea of the fairness of the system, not giving weights to the flows does not help us to find at which points the fairness is not fulfilled [46]. For example, it has been found that a difference between $J = 0.9$ and $J = 0.8$ has a different effect on the behavior of the different flows compared to a difference between $J = 0.6$ and $J = 0.5$; although in both cases, the difference is 0.1 [42]. Furthermore, the JFI assumes that all flows are equally capable of consuming the resources for which they are competing, although in reality, this may not be the case.

In this paper, a modification of the JFI is proposed for a Weighted Fairness (WF) calculation in the Enhanced-AATP, which considers the possibility of prioritizing flows.

The modifications proposed in this section for the improvement of the AATP over heterogeneous networks directly affect the base operation of the protocol, which is reviewed in the following section.

4. AATP Review

In this section, the Aggressive and Adaptative Transport Protocol (AATP) [14] is reviewed to provide a recap of the protocol operation and its mechanisms before introducing the improvements.

A specific Cloud company set high-level data exchange requirements between their servers' farms deployed in Storage Area Networks (SANs) from remote branches in different regions. The AATP protocol was designed to overcome the limitations of transport protocols over Long Fat Networks [3]. In order to achieve an optimal communication performance, the protocol was designed with the following characteristics:

- Connection-oriented: The objective is to avoid TCP's synchronicity and its rigid overhead. For this reason, the AATP proposes an in-band control of the packets over IP. Compared to TCP and UDP, the use of the Selective ACK and its control of the gaps (lost packets) provides an asynchronized controlled data exchange and lost packets are requested.
- Efficient: The Bandwidth Estimation process calculates the maximum bandwidth capacity of the communication, reaching the upper limit of the link during data transfer (>95%).
- Adaptable: The protocol reacts to a loss episode, reducing its throughput. After detecting the end of the loss episode, the protocol increases its throughput directly to reach 80% of the calculated link capacity. After that, the protocol increases it gradually to avoid causing congestion.
- Friendly aggressive: The protocol is focused on the maximum use of the capacity of the link (>80%), and the residual bandwidth is left for the other protocols (<20%).

For the initial BW estimation, 10 bursts are sent following the technique of packet trains (groups of two to 20 packets). The Source sends the packets of each block (burst) consecutively. After that, the Destination sends a confirmation message on receipt of the last packet of the block.

For each burst, the reception times of the first and last packets are recorded, and the difference (Qb_i) is calculated. Once information on the size of the packets (b) in bits and the packets that have been received (N) is obtained, the bandwidth of the link (BW_i) for that burst can be calculated

$$BW_i = \frac{b \cdot (N-1)}{Qb_i}. \tag{3}$$

Once the Destination has received the ten bursts, ten values of the estimated bandwidth are obtained, using the arithmetic mean of these values as the definitive one (BW).

$$BW = \frac{\sum_{i=1}^{10} BW_i}{10} \tag{4}$$

At the beginning of the data transfer, the initial transmission speed (Sending Rate—SR) is set, fixing it at a percentage of the maximum bandwidth one (BW). It depends on the desired aggressiveness.

The data are sent by bursts, which are separated by a period ($\mathrm{T_{burst}}$) determined by the *RTT* or the minimum temporal resolution that can be offered by the operating system (*OS*) and the hardware (*HW*) on which the process operates. This time will be calculated in milliseconds or microseconds.

$$\mathrm{T_{burst}} = \max(OS/HW\mathrm{res.}, RTT) \tag{5}$$

Once we know the speed at which the packets are initially sent (in packets per second) and have determined the separation between bursts, the number of packets sent in each burst is

$$\mathrm{Packets_{burst}} = SR * \mathrm{T_{burst}}. \tag{6}$$

The receiver decreases or increases the *SR* value depending on whether or not any packets have been lost in the last burst, which is calculated by

$$SR = \begin{cases} \dfrac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}, LostPackets = FALSE \\ \dfrac{SR}{1 + 0.125 \cdot \frac{SR \cdot P_{size} \cdot 8}{BW}}, LostPackets = TRUE \end{cases}, \tag{7}$$

where P_{size} is the size of the packet in bytes. When losses are detected, the higher the use of the link, the greater the reduction in the *SR*.

The value of the Inc_p, packet increment (packets), follows the philosophy of UDT [47] and uses a DAIMD (AIMD with decreasing increases) logarithmic function. This function is based on the usage of the estimated link capacity. On the one hand, when the *SR* value (converted to bps) is far from the estimated link capacity (meaning low efficiency), the increase of packets per each burst is high to achieve greater throughputs fast. On the other hand, as the link utilization keeps growing (meaning higher efficiency), and the increase of packets to be sent per each burst gets smaller. This strategy has been proved to be stable and efficient [48]. The Inc_p value is determined by

$$Inc_p = 10^{\log{(BW-(SR \cdot P_{size} \cdot 8))} - M}, \tag{8}$$

causing a logarithmic growth of the *SR*. In relative terms of the link's capacity usage, the growth of the *SR* always experiences the same behavior (in a zero-loss scenario) thanks to the logarithmic function. P_{size}—in bytes—and 8 are conversion factors to get the *SR* value in bps. When the use of the link is low, the increase in the speed of transmission is greater, and vice versa.

The value M is a magnitude modifier that reduces the orders of magnitude of the power function. It is necessary to reduce these orders of magnitude because if they were not reduced, the final *SR* value would be enormous and vastly surpass the estimated bandwidth. Thus, the M value aims to adapt the number of packets to be increased per burst depending on the estimated bandwidth utilization. It is a design value that can be fine-tuned, but it should be large enough to moderate the results of Equation (8) and get reasonable *SR* values. As an example, the logarithmic function of UDT is always reduced by nine orders of magnitude. We do not use the same value because the UDT formula calculates packets per second, while the AATP formula calculates packets per burst. In our case, after several iterations of simulations, we found that a value of 7 was big enough to achieve high increases in *SR* values in situations where the estimated link utilization was below the 80% of its estimated value. When the link's utilization is equal to or greater than 80%, the order of magnitude to be reduced must decrease linearly as efficiency increases. This way, the M value helps to shape the *SR* logarithmic growth more aggressively at low-performance episodes and more steadily at high-performance ones. The calculation of M is based on the following formula

$$M = \begin{cases} 7, & \frac{SR \cdot P_{size} \cdot 8}{BW} < 0.8 \\ (\frac{SR \cdot P_{size} \cdot 8}{BW} \cdot 10) - 1, & \frac{SR \cdot P_{size} \cdot 8}{BW} \geq 0.8 \end{cases}, \quad (9)$$

being more aggressive when efficiency is worse than 80% to achieve high-throughput levels without saturating the connection. Figure 2 shows the growth of the *SR* value (in Mbps) over a 1 Gbps link in an ideal situation without losses and an estimated bandwidth of 1 Gbps.

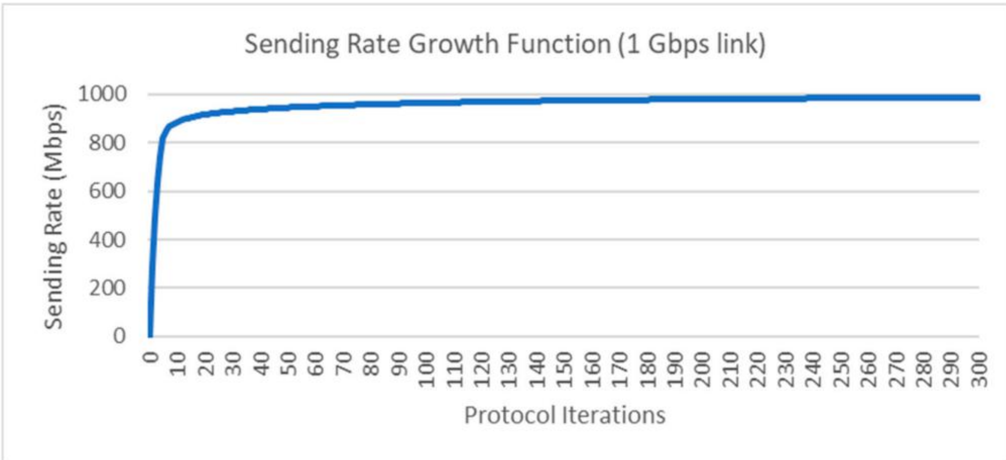


Figure 2. Sending Rate Growth Function over 1 Gbps link in an ideal situation without losses. Sending Rate (Blue).

Although the objectives of the protocol are clear (efficient, adaptative, and friendly aggressive) and accomplished, the AATP presents two main drawbacks if the protocol is used over Heterogeneous Long Fat Networks:

- Lossy episodes are all assumed as a congestion episode, without differentiating channel losses from congestion losses in heterogeneous scenarios. The efficiency of the protocol decreases because the Sending Rate is reduced in a channel loss episode and the time to recover the high-performance throughput directly affects its capability.
- There is no fair flow prioritization to fairly share the node network resources efficiently without causing losses and instabilities because there is no control between both flows.

5. Enhanced-AATP

The Enhanced-AATP is an improvement of the AATP protocol, which proposes solutions to solve the aforementioned drawbacks of the protocol over Heterogeneous Long Fat Networks. As stated before, the protocol AATP is efficient and adaptable in networks with high bandwidth and high delays (LFNs), but when it is used in heterogeneous networks, it is not able to differentiate distinct types of losses. Moreover, because of its aggressiveness, the protocol is unfair with other AATP flows.

The objective of the Enhanced-AATP is to adapt the protocol to achieve high performance over HLFNs and fairly sharing the network resources with the other flows that coexist in the same node. In this section, the operation of the Enhanced-AATP, together with its two new functionalities, is presented:

- Loss differentiation mechanism. The protocol identifies if the loss episode is due to congestion or a channel failure through a Loss Threshold Decision maker (LTD), which bases its operation on a Jitter Ratio comparison.
- Prioritized fair share of node network resources. This mechanism manages the Enhanced-AATP flows exchanged information with one node to achieve the deserved speed for each of them regarding their prioritization.

These imply a modification of the data exchange process of the protocol and its mechanisms, introducing the Loss Threshold Decision maker functionality and the Weighted Fairness mechanism.

5.1. Data Exchange Process

The Enhanced-AATP data exchange process is detailed to show the data process and how the metrics are measured. Figure 3 shows the protocol operation and how the information is sent and processed.

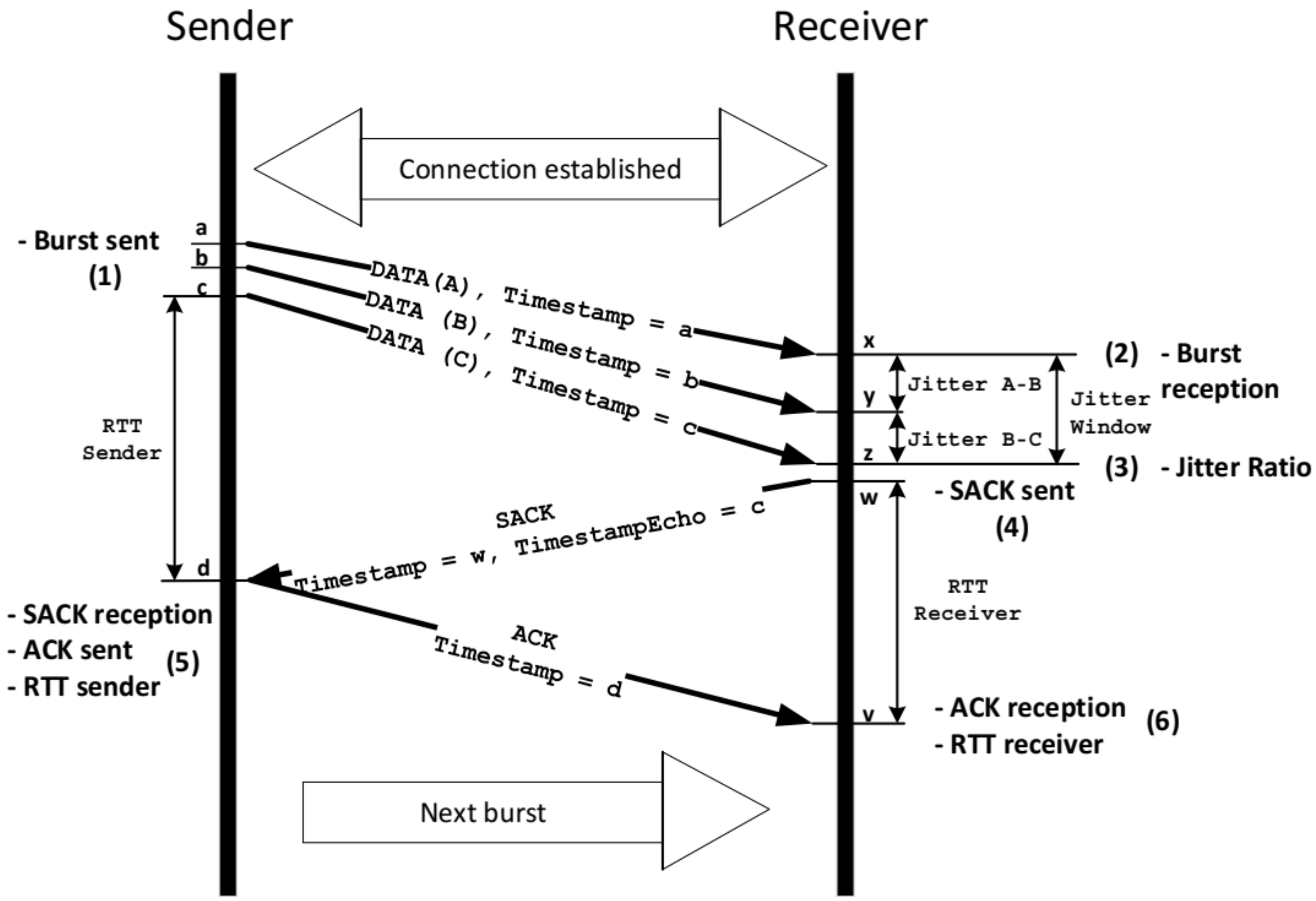


Figure 3. Enhanced-AATP data exchange process.

Following the numbers (1) to (6) of Figure 3, the data exchange process of the Enhanced-AATP is explained:

(1) After the connection is established and the Estimated Bandwidth is measured, the Sending Rate is decided (% of the Estimated Bandwidth). The Sender sends a burst to the Receiver, recording the timestamp of each packet sent.
(2) The Receiver registers the time reception of each packet.
(3) After receiving the last packet of the burst, the Jitter Ratio is calculated

$$Jr = \frac{(t_{rxLastPkt} - t_{rxFirstPkt}) - (t_{txLastPkt} - t_{txFirstPkt})}{(t_{rxLastPkt} - t_{rxFirstPkt})} = \frac{(z - x) - (c - a)}{(z - x)}. \quad (10)$$

Given the aforementioned limitation of the case *Jr* = 0, the Enhanced-AATP will use the $smooth_{jr}$.

$$smooth_{jr} = (1 - \alpha) \cdot smooth_{jr} + \alpha \cdot Jr \quad (11)$$

where α is an arbitrary value between 0 and 1. Depending on it, the weight of the last iteration will count proportional to the defined value.

(4) At this point, the Receiver sends a SACK message confirming the reception of the burst and the Jitter Ratio.

(5) The Sender registers the Jitter Ratio and the reception time to calculate its *RTT*. At the same time, he replies to the Receiver with an ACK message to confirm that it will adjust the $\text{Packets}_{\text{burst}}$ to the new SR and T_{burst} (*RTT*).

$$RTT_{Sender} = t_{rxSACK} - t_{txLastPkt} = d - c \quad (12)$$

(6) The Selective ACK is acknowledged. The Receiver records the reception time to calculate its *RTT*. This information is taken for network statistics in case a transfer is initiated in the other way. The next burst is sent.

$$RTT_{Receiver} = t_{rxACK} - t_{txSACK} = v - w \quad (13)$$

5.2. Loss Differentiation Mechanism—Loss Threshold Decision Maker (LTD)

After detailing the data exchange process, the operation of the loss differentiation mechanism is defined. The Enhanced-AATP introduces the Loss Threshold Decision maker (LTD) as a way to distinguish the cause of the losses produced during the communication. At this point, given the HLFNs characteristics, it is necessary to obtain a reference metric that is not affected by the high delay of this type of networks and that is asynchronous to the endpoints. The metric used for the loss decision is the smoothed Jitter Ratio ($smooth_{jr}$), which is defined in (11).

Since the Jitter Ratio is the reference metric to check the origin of a loss episode, it is necessary to determine the threshold. As soon as a queue is formed in the bottleneck device due to a saturation episode, it is detected by the Destination node through the value of the Jr, thus preventing an overflow in the buffer and packet discard. The Jr value calculation is increased because the time between packet arrivals at the Destination is greater as a result of the formation of queues at the bottleneck. Following the network's operation process, if the bottleneck device is fully saturated after a new burst is sent and it starts to drop packets; these additional packets will provoke an overflow in the intermediate device, causing a congestion loss episode.

In the case of the aforementioned JTCP and JSCTP, the *Jr* is fixed to one packet over the congestion window because the basis is TCP. In the case of the Enhanced-AATP, this design value is different because of the way the protocol operates as it can increase its Sending Rate by more than one packet per burst. The Loss Threshold Decision maker (*LTD*) is defined by the number of increased packets in the burst over the total number of packets of the burst.

$$LTD = \frac{\#Inc_p}{\#Packets_{burst}} \quad (14)$$

The reason for this *LTD* proposal is because in each iteration without losses, a number of new packets ($\#Inc_p$) are included in the burst ($\#Packets_{burst}$). If a congestion loss occurs, it means that the buffer of the bottleneck is overflowing as a result of the new packets included in the last burst.

The defined LTD is compared to the $smooth_{jr}$. This comparison will differentiate when a loss episode is because of a misfunction of the channel or the congestion in the network or when the $smooth_{jr}$ rises as the intermediate router generates a packet queue caused by saturation. When the $smooth_{jr}$ remains stable because there are no packet queues in the intermediate router (no saturation), the channel has most likely suffered a failure (fading, interference).

Depending on the situation detected, the Enhanced-AATP reacts differently to the loss episode. Four different states are defined, which are detailed in Table 3 and described below.

Table 3. Enhanced-AATP operation states.

State	Loss Episode	$Smooth_{jr}$ vs. LTD	Process	Actions
S0	No	$smooth_{jr} \leq LTD$	Sending Rate ↑	No loss episode Throughput increased
S1	No	$smooth_{jr} > LTD$	Sending Rate ↗	No loss episode Jr indicates possible congestion Throughput moderately increased
S2	Yes	$smooth_{jr} \leq LTD$	Sending Rate ≡	Loss episode due to channel Throughput kept Lost packet requested
S3	Yes	$smooth_{jr} > LTD$	Sending Rate ↓	Loss episode due to congestion Throughput reduced Lost packet requested

(S0) **No loss episode and $smooth_{jr} \leq LTD$.** The sending rate is increased, depending on the efficiency registered.

$$
\begin{gathered}
SR = \frac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}; \\
Inc_p = 10^{\log(BW - (SR \cdot P_{size} \cdot 8)) - M}; \\
M = \begin{cases} 7, & \frac{SR \cdot P_{size} \cdot 8}{BW} < 0.8 \\ (\frac{SR \cdot P_{size} \cdot 8}{BW} \cdot 10) - 1, & \frac{SR \cdot P_{size} \cdot 8}{BW} \geq 0.8 \end{cases};
\end{gathered} \tag{15}
$$

(S1) **No loss episode and $smooth_{jr} > LTD$.** On receipt of this information, the sending rate is moderately increased (M = 9), as if the sending rate was reaching the limit.

$$
\begin{gathered}
SR = \frac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}; \\
Inc_p = 10^{\log(BW - (SR \cdot P_{size} \cdot 8)) - 9};
\end{gathered} \tag{16}
$$

(S2) **Loss episode and $smooth_{jr} \leq LTD$, meaning a channel loss episode.** The sending rate is kept at the same speed. As soon as the communication starts working again without losses, the lost packets are requested again.

$$
\begin{gathered}
SR = \frac{(T_{burst} \cdot SR) + Inc_p}{T_{burst}}; \\
Inc_p = 0
\end{gathered} \tag{17}
$$

(S3) **Loss episode and *smooth$_{jr}$* > *LTD*, meaning a congestion loss episode.** The sending rate is reduced. As soon as the communication starts working again without losses, the sending rate is increased.

$$SR = \frac{SR}{1 + 0.125 \cdot \frac{SR \cdot P_{size} \cdot 8}{BW}}; \tag{18}$$

5.3. Fairness Mechanism

In order to procure a fair share of network resources from the destination, the fairness mechanism is presented. The adopted Fairness index is the Jain Fairness Index (JFI). The only requirement that is not fulfilled by the JFI is the weighted priorities of the flows. As a result of this reason, the JFI is modified to provide it to the Enhanced-AATP. The metrics to consider in the Weighted Fairness calculation are:

- Internal factors.
  - Number of Flows (N).
  - Priority of each flow n (p_n). Its value can be any integer between 1 and 8 (both inclusive). This way, the priority value can be mapped to other QoS classifications (IP Precedence and 802.1p).
- External factors.
  - Estimated Bandwidth (BW) [bps].
  - Network status (characteristics, statistics, and behavior).
- Real throughput of a flow n (V_n) [bps]. Where SR is the packets sent per second [packets/second], P_{size} is the packet size [Bytes] and 8 to convert bytes to bits.

$$Vn = SR \cdot P_{size} \cdot 8 \tag{19}$$

- Allocated throughput for a flow n (Vm_n) [bps]. This formula provides the allocated throughput assigned to the flow n regarding its priority (p_n), the sum of all priorities ($\sum_{i=1}^{N} p_i$), and the available bandwidth (BW).

$$Vm_n = \frac{p_n}{\sum_{i=1}^{N} p_i} \cdot BW \tag{20}$$

- Efficiency (r_n) of a flow n. It determines the percentage of the throughput achieved by the flow regarding the allocated speed.

$$r_n = \frac{V_n}{Vm_n} \tag{21}$$

With these defined metrics, the Weighted Fairness (WF) can be calculated as follows, being the JFI the base:

$$WF = \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{N \cdot \left(\sum_{n=1}^{N} r_n^2\right)} = \frac{\left(\sum_{n=1}^{N} \frac{V_n}{Vm_n}\right)^2}{N \cdot \left(\sum_{n=1}^{N} \left(\frac{V_n}{Vm_n}\right)^2\right)} = \frac{\left[\sum_{n=1}^{N} \frac{V_n}{\frac{p_n}{\sum_{i=1}^{N} p_i} \cdot BW}\right]^2}{N \cdot \left[\sum_{n=1}^{N} \left(\frac{V_n}{\frac{p_n}{\sum_{i=1}^{N} p_i} \cdot BW}\right)^2\right]}. \tag{22}$$

If the WF value is 1, there is a fair share of the resources. Otherwise, if the WF value is 0, the system is not working properly. In contrast to the JFI, this way of calculating the fairness considers the real throughput of each flow, the priority provided to these flows, and their allocated throughput decided by the system, considering the estimated bandwidth.

The protocol is able to modify its operations and flow behavior because of the WF and its performance.

The main modification is the number of packets to be increased or reduced at the time of calculating the Sending Rate (no lossy episode; S0 and S1) to adapt the flow to the deserved speed. It is done with the Adapter (Δ_n).

$$SR = \frac{(T_{burst} \cdot SR) + c_p + \Delta_n}{T_{burst}}; \tag{23}$$

$$\Delta_n = A \log_2\left(\frac{Vm_n}{V_n}\right), \tag{24}$$

where Vm_n is the allocated throughput of the flow, V_n is the real throughput of the flow, and A is the Transcendence factor. A logarithmic function is used to shape three different behaviors. Firstly, if the current throughput of the flow is below its maximum, packets per burst should be increased. This is achieved because, in this case, $\frac{Vm_n}{V_n} > 1$ so $\log_2\left(\frac{Vm_n}{V_n}\right) > 0$. Secondly, if the current throughput of the flow is above its maximum, the number of packets per burst should decrease to achieve fairness. This is also possible because when $\frac{Vm_n}{V_n} < 1$, $\log_2\left(\frac{Vm_n}{V_n}\right) < 0$. Thirdly, if the throughput of the flow is equal to its maximum, it behaves fairly, so packets per burst should not be increased or decreased. This behavior is also satisfied because when $\frac{Vm_n}{V_n} = 1$, $\log_2\left(\frac{Vm_n}{V_n}\right) = 0$. A simple quotient $\left(\frac{Vm_n}{V_n}\right)$ could not be used, because the result would always be positive, so packets per burst would always increase. A subtraction $(Vm_n - V_n)$ would satisfy the three behaviors, but it would depend on the absolute values of throughput instead of relative values of utilization, which would result in excessive values of Δ_n. For this reason, the use of a logarithmic function was chosen.

Despite that, the values obtained in the logarithmic function might be too small when compared to the values of Inc_p, making the fairness mechanism insignificant when compared to the congestion control. Thus, the Transcendence factor A is needed to give relevant importance to the fairness mechanism, with a comparable influence on congestion control. The higher the value of A, which should be related to the WF, the higher the value of Δ_n. This implies a more aggressive increase in the Sending Rate or a decrease when Δ_n is negative and $|\Delta_n| > Inc_p$, reducing the convergence time to balance the weighted distribution of resources. This fact can affect the stability of the system due to sudden changes.

The value of A is a design parameter that can be adjusted. The greater the value is, the greater the importance of the fairness mechanism over the congestion control. In our case, the A factor is defined by

$$A = \frac{\gamma}{N} * BW^{1+\beta} \cdot (WF - 1)^2, \tag{25}$$

thus, relating it to the WF, the number of flows (N), and the estimated bandwidth (BW). The A factor is directly proportional to the estimated bandwidth because more packets can be sent per burst at a higher bandwidth. Moreover, it is inversely proportional to the number of flows because the packets to be increased or decreased per burst should be distributed among all flows. It is related to the WF too, in a way that when the system is behaving more fairly (WF value close to 1), the fairness mechanism has less relevance, while in unfair scenarios (WF value not close to 1), it has a greater impact.

γ and β are design parameters that help to fine-tune the degree of aggressiveness of the Transcendence factor (A). $\gamma = 1$ and $\beta = 0$ are standard values to relate the A factor directly to BW and inversely to N. In our case, after several iterations of simulations, $\gamma = 5$ and $\beta = 0.05$ are the used values in our tests that provide a suitable balance between the Inc_p and Δ_n parameters as well as faster convergence in fairness.

Instability occurs when the designation of a Sending Rate is higher or lower than the ideal one, thus requiring a new iteration to achieve the ideal speed of each flow. The degree of instability is related to the suddenness of the change in the Sending Rate. If the value of A is not high, the convergence time is longer, since slight modifications are made on the SR. However, the probability of instability in the system is reduced since there are no sudden changes in the Sending Rate, causing a fine-tuning.

Once the Weighted Fairness mechanism is introduced, the congestion control needs to slightly modify Equations (7)–(9) as each flow aims to reach its allocated throughput (Vm) and not the total Bandwidth of the link (BW).

$$SR = \begin{cases} \frac{(T_{burst} \cdot SR) + Inc_p + \Delta_n}{T_{burst}}, & S0|\ S1|\ S2 \\ \frac{SR}{1+0.125 \cdot r}, & S3 \end{cases} \tag{26}$$

$$Inc_p = \begin{cases} 10^{\log(Vm-V)-M}, & S0 \\ 10^{\log(Vm-V)-9}, & S1 \\ 0, & S2 \end{cases} \tag{27}$$

$$M = \begin{cases} 7, & r < 0.8 \\ (r \cdot 10) - 1, & r \geq 0.8 \end{cases} \tag{28}$$

6. Enhanced-AATP Evaluation and Performance Simulations

In this section, the Enhanced-AATP protocol is simulated and evaluated by the Steelcentral Riverbed Modeler [15]. The new functionalities are tested through different experiments to validate its operation and performance.

The Riverbed Modeler testbed scenario is detailed in Figure 4, which simulates a Long Fat Network with different possible configurations. In most scenarios, the bottleneck has a bandwidth of 148.608 Mbps (OC-3 link), and the maximum bottleneck capacity tested in the simulations is 1 Gbps. The packet size is fixed at the MTU of the media technology, and the propagation delay is the speed of light in the backbone. The minimum base RTT of the WAN link is 20 ms, so the Bandwidth-Delay Product (BDP) is always greater than 12,500 bytes (10^5 bits)).

Although the connection between both routers consists of a single link, distinct random generation seeds are defined in the simulator to introduce variability in the network. The environment is configured to simulate the characteristics and behavior of a Heterogeneous Long Fat backbone, depending on the requirements of the experiment (different speeds, random losses, delay depending on the distance).

The Testbed is composed of a Storage Area Network (SAN) region and a Client edge. In the SAN side, there are servers from the server farm connected through a wire to the gateway that gives access to the WAN (a), and in the Client edge, two nodes are deployed. One is an Enhanced-AATP node (eaatp_sender), and the other node (other_client) is introduced to provoke different scenarios (different types of cross-traffic, interference generation). The cross-traffic can be a TCP flow with a Variable Bit Rate (VBR) or a UDP flow with a Constant Bit Rate (CBR). These nodes from the Client side can be connected through a wire (b) or a short-range wireless (WiFi—802.11n) (c), while the speed and Ethernet technology can be varied depending on the experiment and the objective to be achieved.

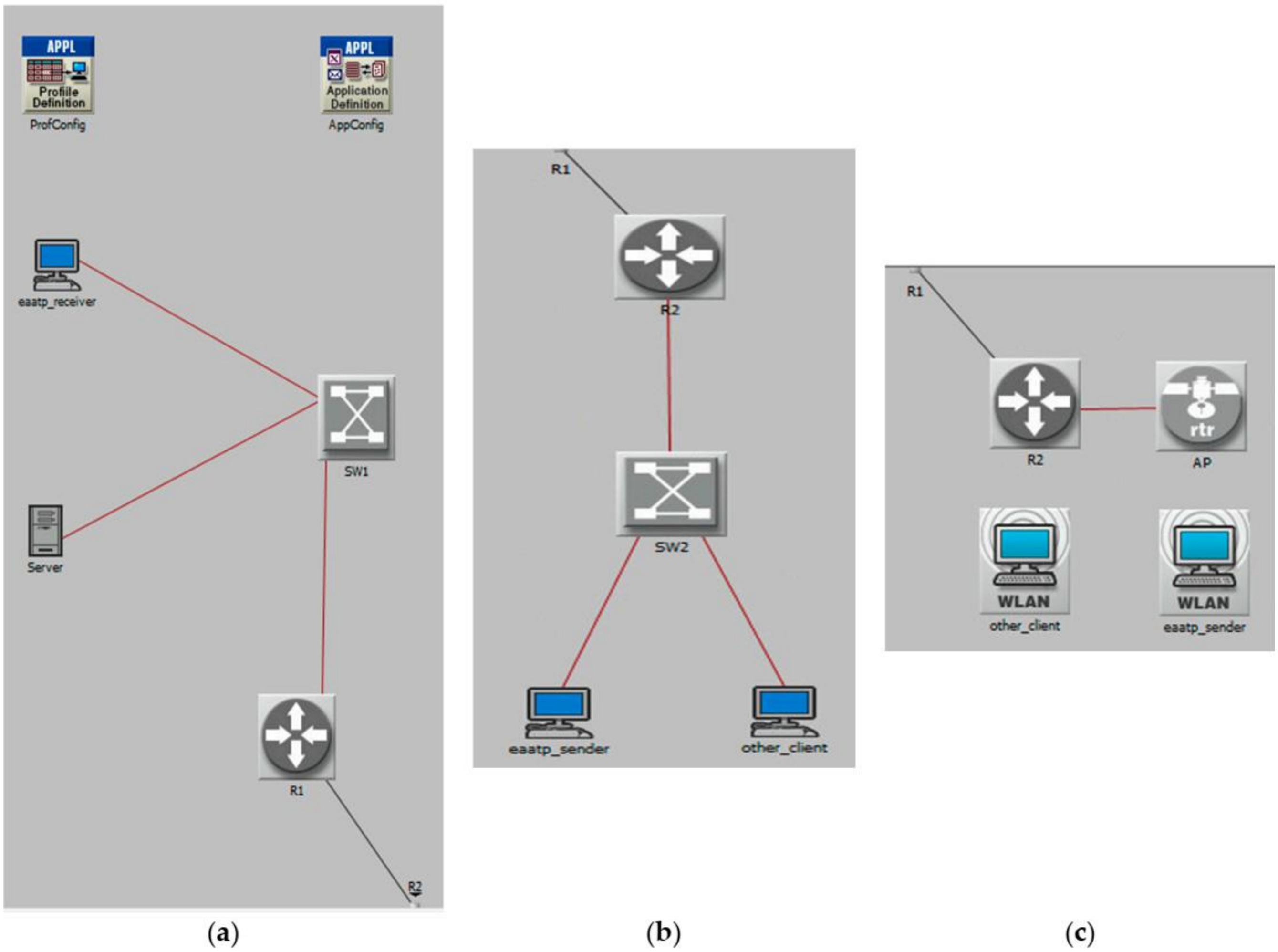


Figure 4. Testbed scenario over a Steelcentral Riverbed Modeler. (**a**) Storage Area Network (SAN) side and Client edge with (**b**) wired endpoints or (**c**) short-range wireless endpoints.

The experiments and their objectives are listed below:

1. **Maximum performance in wireless.** The objective is to verify the efficiency of the protocol over wireless. This experiment exhibits the maximum performance of the Enhanced-AATP protocol over different wireless speed connections without other flows or random losses. The scenario is Figure 4a connected to Figure 4c.
2. **Random loss episode detection.** The objective of this experiment is to demonstrate the channel loss identification and the proper operation of the protocol in this specific case (Table 3—(S2) Channel loss). This experiment shows that the protocol identifies the different random loss episodes occurred and reacts by keeping its Throughput and Sending Rate. The scenario is Figure 4a connected to Figure 4c.
3. **Loss Threshold Decision maker (*LTD*).** The objective is to prove the correct differentiation of distinct types of losses. Moreover, the optimal LTD value is evaluated. In this experiment, distinct cross-traffic (load) and different random losses are introduced. The operation of the protocol and the LTD performance are presented, differentiating congestion losses and channel errors that occurred during the communication. The scenario is Figure 4a connected to Figure 4c.
4. **Fairness mechanism.** The objective of this experiment is to demonstrate the fair share of the network resources through the implementation of the weighted fairness mechanism. In this experiment, different flows are set in order to share the media. The scenario is Figure 4a connected to Figure 4b.

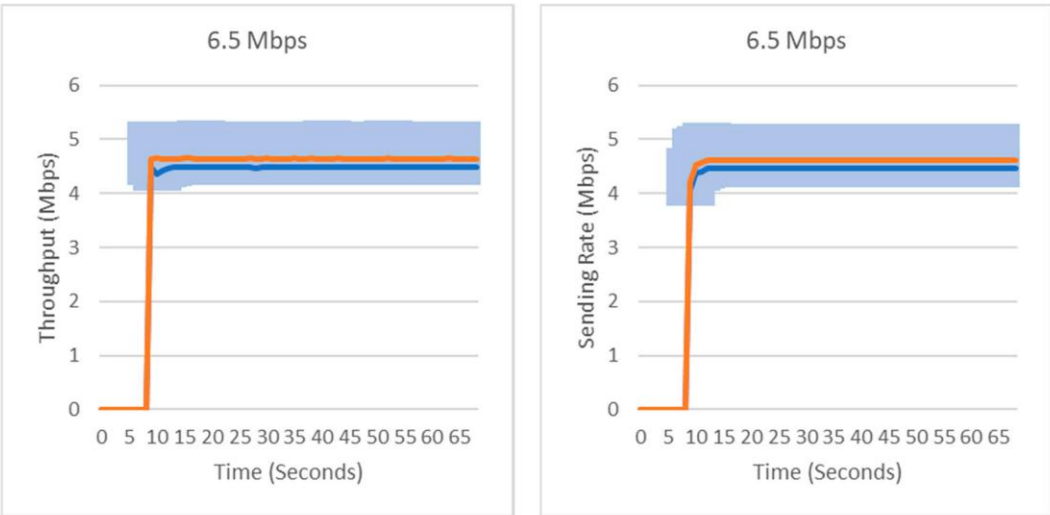
5. **Enhanced-AATP performance comparison.** The objective of this last experiment is to compare the Enhanced-AATP performance (throughput, one-way delay and losses) with the modern protocols analyzed. A specific scenario is deployed.

The outcomes shown are the mean results of different executions (around 1000 in total, 30 simulations run per test, except the *LTD* value test, which implied 650 simulations), assuring a maximum error deviation of ±1.5% with a confidence interval of 99%.

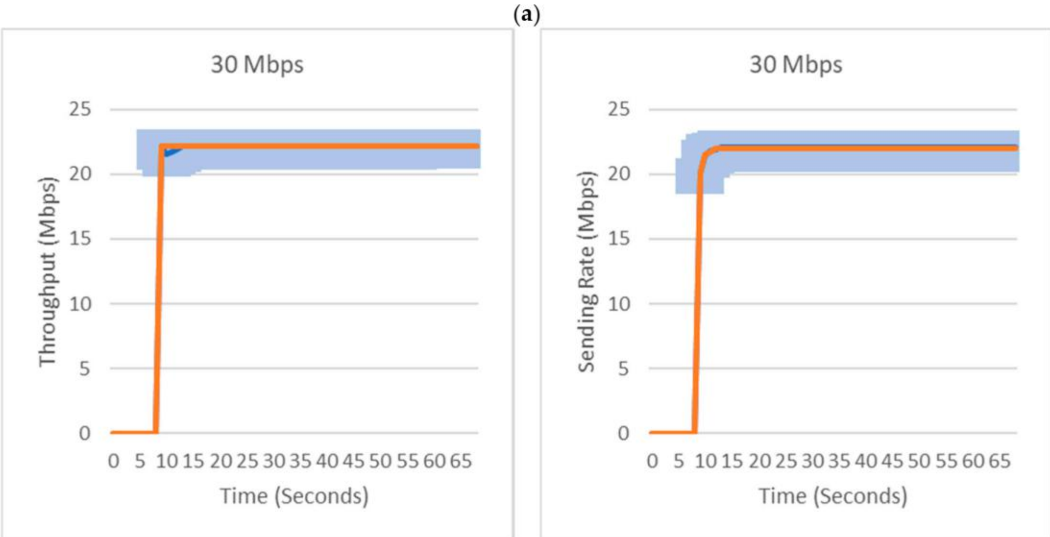
6.1. Maximum Performance in Wireless Connections

The performance of the Enhanced-AATP over heterogeneous networks without cross-traffic nor random losses is studied in this set of tests, where the bottleneck is the wireless section at different link speeds. The scenario is Figure 4a connected to Figure 4c.

Figure 5 exhibits the Enhanced-AATP performance, showing the average (orange) and the median with second and third quartiles (blue) of the Throughput and Sending Rate over different link speed scenarios. The selected wireless link speeds are 6.5 Mbps (a), 30 Mbps (b), 120 Mbps (c), 300 Mbps (d), and 600 Mbps (e). The duration of the transfer is 60 s.

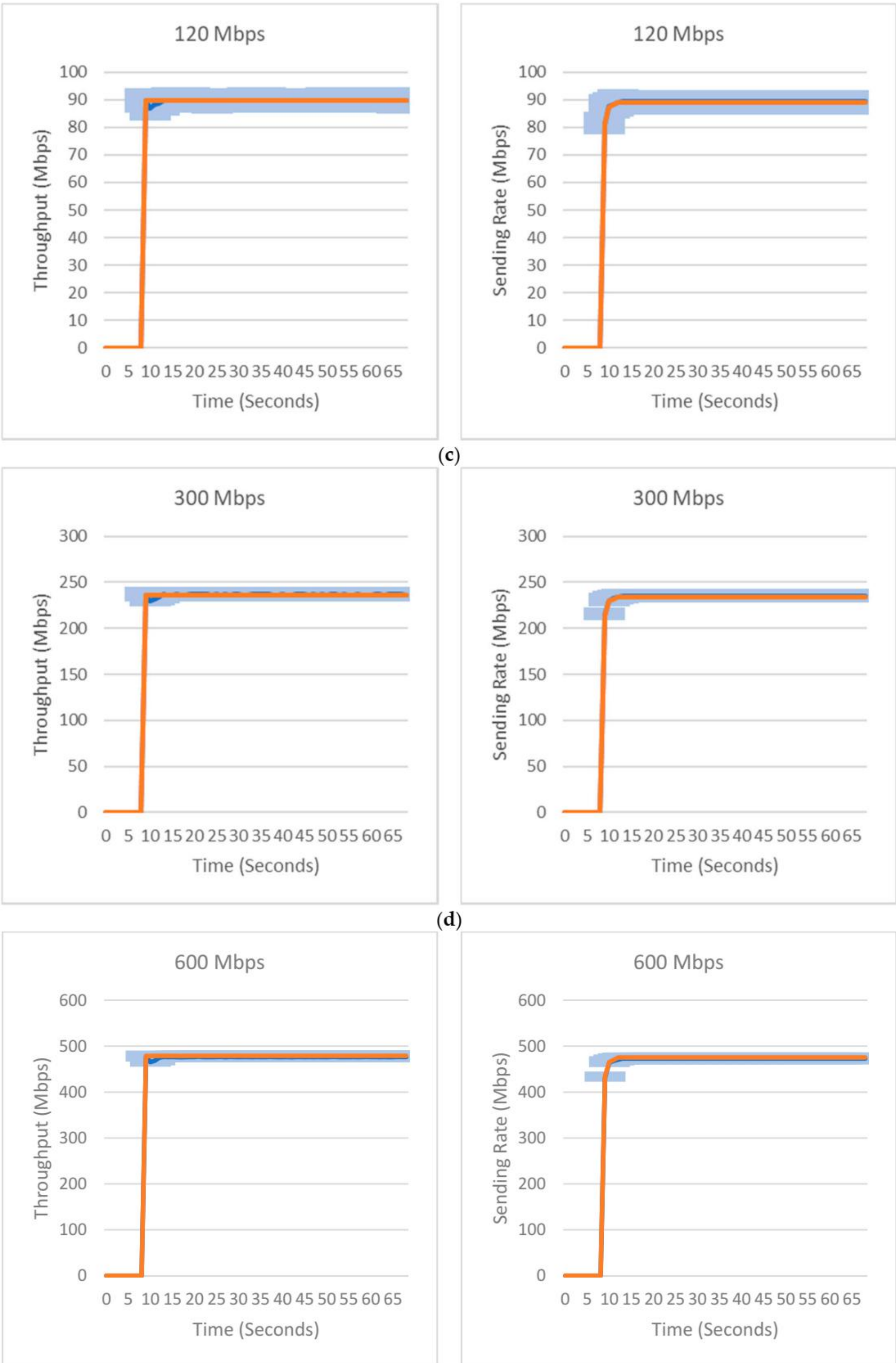


(**a**)



(**b**)

Figure 5. *Cont.*



(e)

Figure 5. Enhanced-AATP performance over different wireless networks without cross-traffic and random losses. Average Throughput and Sending Rate (orange), the median with quartiles (blue). (**a**) 6.5 Mbps link capacity, (**b**) 30 Mbps link capacity, (**c**) 120 Mbps link capacity, (**d**) 300 Mbps link capacity, and (**e**) 600 Mbps link capacity. No losses occurred.

From Figure 5, the summary in Mbps is extracted in Table 4 to compare them with the maximum capacity of the link in each bottleneck situation. Given the limitation of the CSMA/CA, as Apoorva Jindal and Konstantinos Psounis presented in [49], in any realistic topology with geometric constraints because of the physical layer, the CSMA-CA is never lower than 30% of the optimal used to access the media in wireless. In the case of Enhanced-AATP, the maximum bandwidth used in these links goes from 72% to 80%, keeping to the aforementioned limitation and working with higher efficiency over high-bandwidth links due to the design of the protocol for Long Fat Networks.

Table 4. Enhanced-AATP performance over different wireless networks.

Link Capacity (Mbps)	Average Sending Rate (Mbps)	Efficiency (% over Maximum Link Capacity)
6.5	4.68	72.03%
30	22.31	74.37%
120	90.47	75.39%
300	237.89	79.30%
600	482.71	80.45%

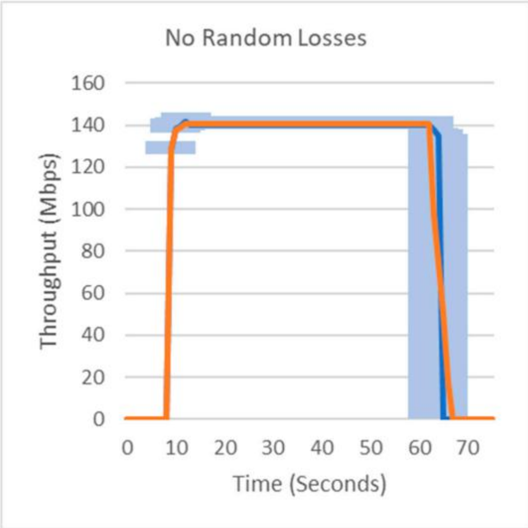
6.2. Random Loss Episode Detection

In order to check the Enhanced-AATP mechanism to detect random losses, distinct tests are run simulating loss episodes of different periods of time. In this case, the bottleneck is placed on the wired section (OC-3 (148.608 Mbps)) to avoid the effect of the CSMA/CA shown in the previous set of tests, without affecting the loss detection mechanism and its performance. The scenario is Figure 4a connected to Figure 4c.

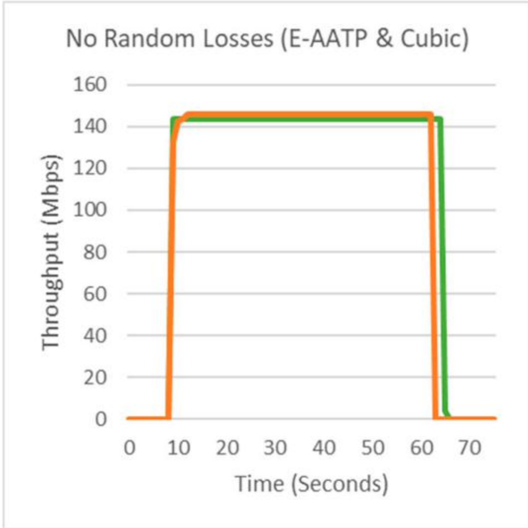
In order to depict the Enhanced-AATP's random loss identification and behavior using the LTD mechanism, its operation is shown together with other TCP protocol's behavior without the LTD maker (TCP Cubic). The main goal of this comparison is to show how the Enhanced-AATP identifies the channel losses occurred (fadings with 100% of losses), while TCP introduces load to the network and also reacts to the fading, reducing its throughput as it was caused due to a congestion in the network. It also affects the transmission time.

Figure 6 illustrates the Throughput obtained by the Enhanced-AATP, average (orange), and the median with second and third quartiles (blue) and TCP Cubic (green), and the time required to send 1 GB in different channel loss situations. First, a case without losses is shown (a) to be the reference in time spent and Throughput performances. After that, the random loss episodes experiments are 10 random losses of 0.5 s (b), 10 random losses of 1 s (c), and 5 random losses of 2 s (d).

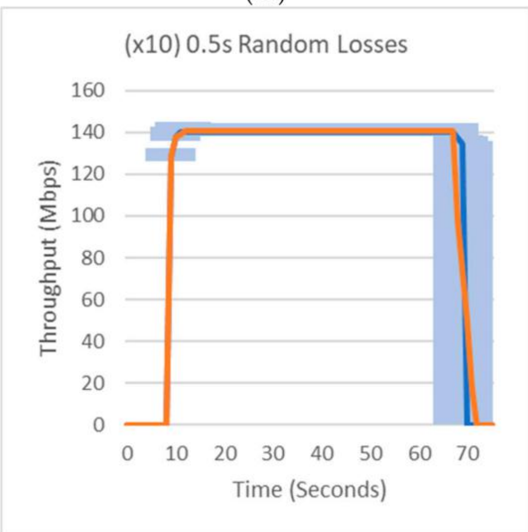
Packet queues are not formed because no bottleneck saturation occurs, so the Jr value is not increased. When a channel loss episode occurs (100% of losses), through the $LTD - smooth_{jr}$ comparison, the protocol identifies it and keeps the Throughput achieved before the losses, as shown in the graphs above. Figure 6 shows the behavior of the Enhanced-AATP protocol in different random loss situations.



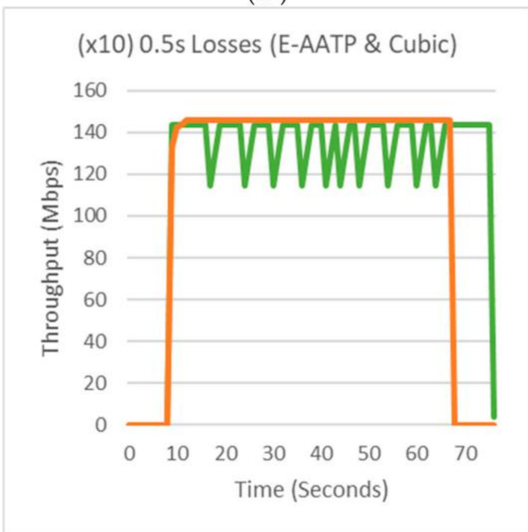
(**a1**)



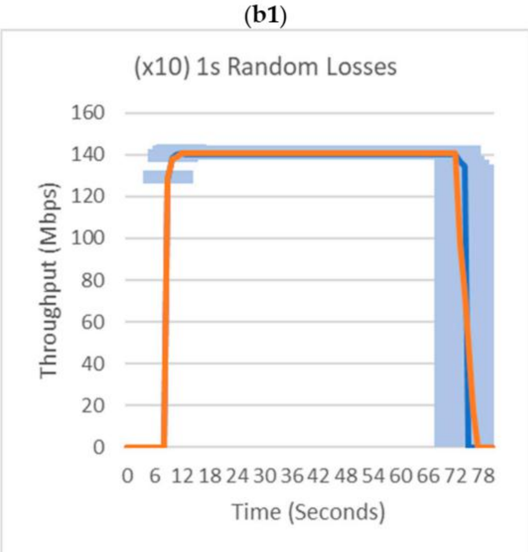
(**a2**)



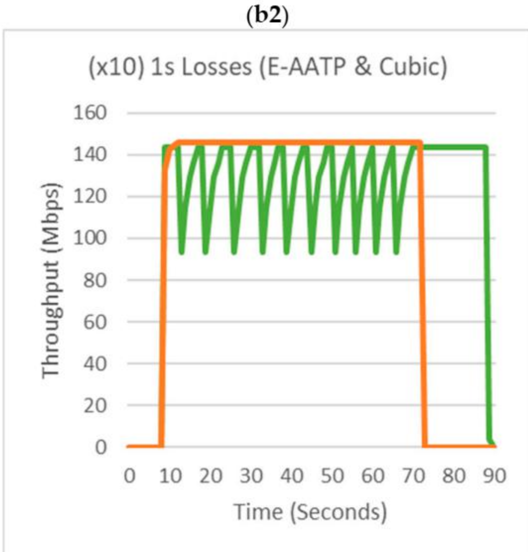
(**b1**)



(**b2**)

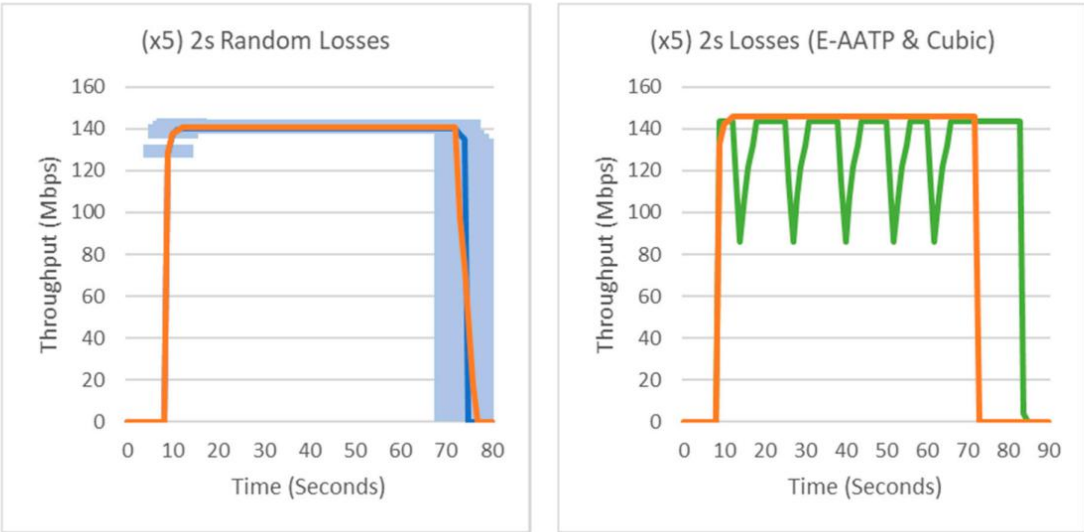


(**c1**)



(**c2**)

Figure 6. *Cont*.



(**d1**) (**d2**)

Figure 6. Enhanced-AATP performance with random losses. Enhanced-AATP Throughput (orange), its median with quartiles (blue) and TCP Cubic Throughput (green). (**a1**) No random loss—Averaged Enhanced-AATP, (**a2**) No random loss—Enhanced-AATP and TCP Cubic, (**b1**) 10 random loss episodes of 0.5 s—Averaged Enhanced-AATP, (**b2**) 10 random loss episodes of 0.5 s—Enhanced-AATP and TCP-Cubic, (**c1**) 10 random loss episodes of 1 s—Averaged Enhanced-AATP, (**c2**) 10 random loss episodes of 1 s—Enhanced-AATP and TCP-Cubic, (**d1**) 5 random loss episodes of 2 s—Averaged Enhanced-AATP and (**d2**) 5 random loss episodes of 2 s—Enhanced-AATP and TCP-Cubic.

- Figure 6a is the reference performance for the protocol because no losses occur. The Enhanced-AATP spends 54 s with a mean throughput of 145.36 Mbps. TCP Cubic spends 57 s with a mean throughput of 140.96 Mbps.
- In Figure 6b, 10 episodes of 0.5 s of random losses are introduced, being a total channel loss time of 5 s. In Figure 6(b1), the protocol keeps the throughput (145.38 Mbps) and spends approximately 5 more seconds than the reference. In Figure 6(b2), the Enhanced-AATP operation is shown together with the TCP protocol (TCP-Cubic), which modifies its throughput (135.03 Mbps) due to the losses, spending 11 s more.
- In Figure 6c, 10 episodes of 1 s of random losses are introduced, being a total channel loss time of 10 s. In Figure 6(c1), the protocol keeps the throughput (145.38 Mbps) and spends approximately 10 more seconds than the reference. In Figure 6(b2), the Enhanced-AATP operation is shown together with the TCP protocol (TCP-Cubic), which modifies its throughput (129.29 Mbps) due to the losses, spending 24 s more.
- In Figure 6d, 5 episodes of 2 s of random losses are introduced, being a total channel loss time of 10 s. In Figure 6(d1), the protocol keeps the throughput (145.35 Mbps) and spends approximately 10 more seconds than the reference. Figure 6(d2) shows the Enhanced-AATP operation together with the TCP protocol (TCP Cubic), which modifies its throughput (131.38 Mbps) due to the losses, spending 19 s more.

From Figure 6, the success detection rate for 100% channel losses (fading) is 1 because, compared with the TCP behavior shown, the Enhanced-AATP protocol keeps its throughput during a channel loss episode. If the detection was not successful (<1), the Enhanced-AATP's throughput would experience decreasing episodes. Moreover, the performance of the Enhanced-AATP (Mbps) and the average transmission period (seconds) for each random loss episode test are extracted in Table 5. In addition, TCP Cubic's performance (Mbps) and transmission period (seconds) are shown. Moreover, the time noted between parentheses in both Transmission period fields indicates the extra time dedicated by the protocol in reference to the case without random losses.

Table 5. Enhanced-AATP and TCP Cubic performance with different random loss episodes.

Loss Episode	Enhanced-AATP (Mbps)	Transmission Period Enhanced-AATP (Seconds)	TCP Cubic (Mbps)	Transmission Period TCP Cubic (Seconds)
No random losses	145.36	54	140.96	57
10 random loss episodes of 0.5 s	145.38	59 (+5 s)	135.03	68 (+11 s)
10 random loss episodes of 1 s	145.38	64 (+10 s)	129.29	81 (+24 s)
5 random loss episodes of 2 s	145.35	64 (+10 s)	131.38	76 (+19 s)

In the case of the Enhanced-AATP, the average transmission period is equal to the average transmission period without loss episodes plus the channel losses' duration, demonstrating the high performance (>97%) operation of the protocol during distinct channel loss situations (Figure 6b–d). The Enhanced-AATP depicted together with TCP Cubic provides a view about how the fadings affect the performance of TCP protocols (in (Figure 6(c2), more than a 10 s difference is noted between the Enhanced-AATP and TCP Cubic). Thanks to this experiment, the proper operation of the Loss Threshold Decision maker mechanism to identify the random losses of the channel is demonstrated.

6.3. Loss Threshold Decision Maker (LTD)

In this experiment, the $LTD - smooth_{jr}$ comparison is tested to demonstrate the capacity of the Enhanced-AATP to differentiate the type of loss episode occurred. Distinct and varied loss episodes occur during the simulations run with best-effort TCP/UDP cross-traffic load is introduced. The control over the cross-traffic is limited because of simulator restrictions to manage the generic TCP (traffic trying to reach the maximum possible throughput, but with a Variable Bit Rate (VBR) traffic behavior profile due to its congestion control) and UDP flows (with a Constant Bit Rate (CBR) traffic behavior profile). The scenario is Figure 4a connected to Figure 4c.

Figure 7 shows the performance of the Enhanced-AATP with random losses episodes and cross-traffic sending a file of 1 GB, showing the average percentage of the link used by the Enhanced-AATP (blue) and the average percentage of the link used by the cross-traffic (gray). The experiments simulated are: no random losses with TCP VBR cross-traffic (a), no random losses with 20% UDP CBR cross-traffic (b), 1-s random loss ($\times$5) with a TCP VBR cross-traffic flow (c), 1-s random loss ($\times$5) with a 20% UDP CBR cross-traffic flow (d), 2-s random loss ($\times$5) with a TCP VBR cross-traffic flow (e), and 2-s random loss ($\times$5) with a 20% UDP CBR cross-traffic flow (f).

Figure 7 depicts the result of the Enhanced-AATP in distinct cross-traffic loads and random losses situations. The aggressive behavior of the VBR and CBR flows in Riverbed act without considering the status of the network.

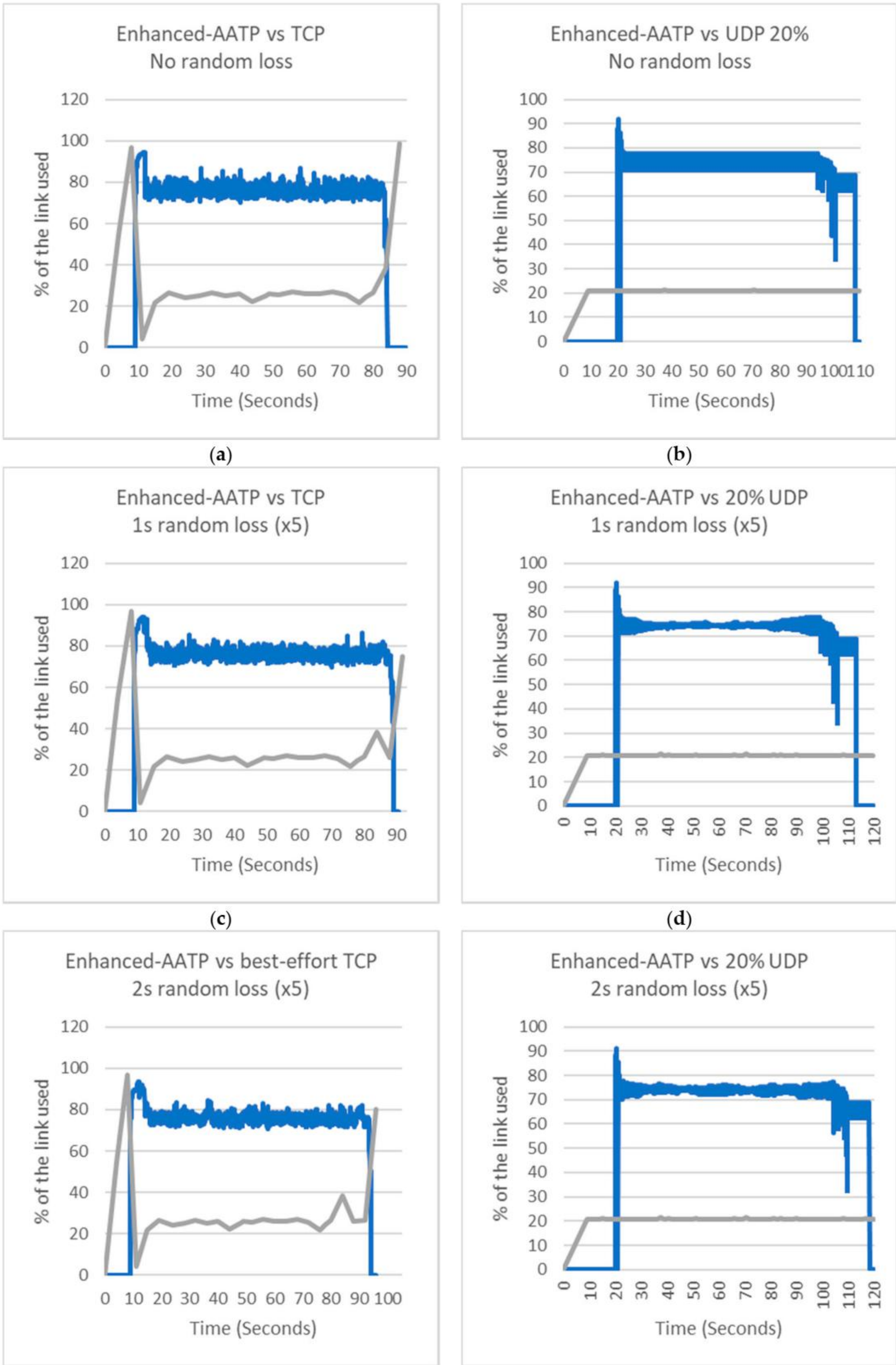


Figure 7. Enhanced-AATP performance with TCP/UDP cross-traffic and random losses. Average percentage of the link used by the Enhanced-AATP (blue), Average percentage of the link used by the cross-traffic (gray). (**a**) No random loss episodes with TCP cross-traffic—11.65% of average losses, (**b**) No random loss episodes with 20% UDP cross-traffic—14.36% of average losses, (**c**) Five random loss episodes of 1 s with TCP cross-traffic—16.11% of average losses, (**d**) Five random loss episodes of 1 s with 20% UDP cross-traffic—18.48% of average losses, (**e**) Five random loss episodes of 2 s with TCP cross-traffic—20.14% of average losses, and (**f**) Five random loss episodes of 2 s with 20% UDP cross-traffic—22.29% of average losses.

- Figure 7a show the result of the experiment when the Enhanced-AATP faces a TCP flow (trying to get the maximum bandwidth aggressively) without random losses. The TCP cross-traffic reaches around 24% of the residual bandwidth left by the Enhanced-AATP because of its aggressiveness, although TCP is trying to reach more. The improved protocol tries to take the maximum bandwidth possible, as the TCP flow tries to obtain the maximum bandwidth but in a less aggressive form, causing minor fluctuations of the Enhanced-AATP speed with a PLR of 11.65%. Considering the losses occurred because of the bandwidth conflict without random losses, in Figure 7c,e, the random losses are introduced (100%), and the PLR increases up to 16.11% (+4.46%, ≈5 s of 100% losses) in (c) and 20.14% (+8.49%, ≈10 s of 100% losses) in (e). The increment corresponds to the percentage of time while the random losses are occurring.
- Figure 7b shows the result of the experiment when the Enhanced-AATP faces a 20% UDP flow, which does not reduce its speed but directly affects the performance. In this case, the UDP does not modify its throughput, even when losses occur, generating moderate fluctuations of the Enhance-AATP throughput and more congestion losses, causing a PLR of 14.36%. Considering the losses occurred because of the bandwidth conflict without random losses, in Figure 7d,f, the random losses are introduced (100%) and the PLR increases up to 18.48% (+4.12%, ≈5 s of 100% losses) in (d) and 22.29% (+7.93%, ≈10 s of 100% losses) in (f). The increment corresponds to the percentage of time while the random losses are occurring.

From Figure 7, the success detection rate for 100% congestion losses is 1 because, during the coexistence between Enhanced-AATP with cross-traffic flows, the Enhanced-AATP tries to get the maximum bandwidth, reducing the throughput from the other flows. Due to this bandwidth's conflict, a first level of convergence is reached (80%/20% distribution) and minor fluctuations occur due to the congestion produced by the two flows trying to obtain more bandwidth, which affects the network stability. In the case of a success detection rate lower than 1, the Enhanced-AATP's throughput would be maintained, and more losses would occur due to a higher congestion of the network.

At this point, given the proper operation of the Enhanced-AATP protocol differentiating the type of losses, it is necessary to check if the LTD Formula (14) is optimal to identify the type of loss occurred.

In Figure 8, the LTD performance is evaluated by linking the transmission period (orange) and the lost packets (blue), modifying the LTD original value from $\times 0.9$ to $\times 1.1$ in steps of 0.01. As shown in the graph, if the $smooth_{jr}$ is compared with the 90% of the obtained LTD value, the transmission period is increased while the total number of lost packets decreases. This means that some random losses are considered as congestion losses. On the other hand, if the $smooth_{jr}$ is compared with the 110% of the obtained LTD value, the transmission period is reduced. However, the lost packets are incremented, meaning that some congestion losses are treated as random losses, generating more saturation and more packets loss.

The objective is to find the optimal working point of the LTD for the consequent status of the network. Thanks to Figure 8, the optimal point in order to reduce the losses generated without increasing the transmission period is shown. The trade-off point between the transmission period and lost packets is the LTD value obtained by relating directly the increased packets with the total burst. This result confirms the reasoning associated with the LTD design. After a congestion loss episode, the new packets included in the packet burst are the possible cause of the packet losses.

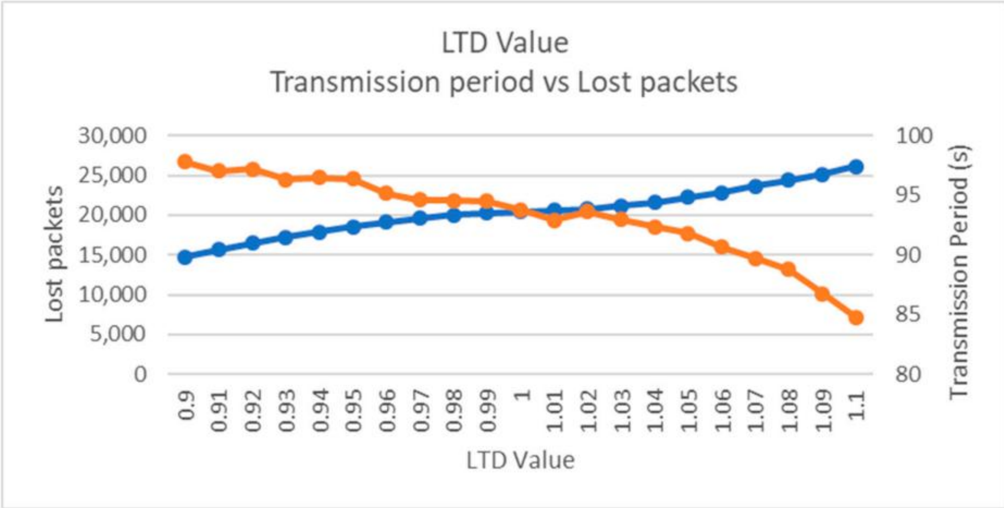


Figure 8. LTD value evaluation. Transmission period (orange) and Lost packets (blue).

6.4. Fairness Mechanism

In this experiment, different priority levels are set to distinct Enhanced-AATP flows that share the destination endpoint. The scenario is Figure 4a connected to Figure 4b. The objective is to check the correct prioritized fair share of the network resources. The cases tested by priorities are: 1-1 (equal priority), 1-8 (maximum priority), and 2-4-6 (three flows).

Figure 9 presents the results of the different cases.

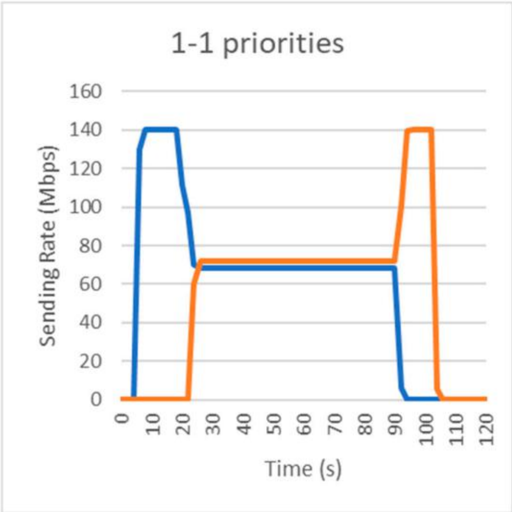
- The first case, graphs Figure 9a,b, proposes two flows with the same priority (1-1). The flows share the bandwidth (Flow 1 (blue) and Flow 2 (orange), around 50% use each), and the WF fluctuates only during the introduction of the second flow and at the end of the transmission, keeping the value of 1, which means a fair share of the resources.
- The second case, graphs Figure 9c,d, aims to have two flows with a maximum difference priority (1-8). The flows share the bandwidth (Flow 1 (blue—11%) and Flow 2 (orange—89%)), and the WF is kept at 1, considering the prioritization established in its calculation.
- The last case, graphs Figure 9e,f, aim to launch three flows with different priorities (2-4-6). The flows share the bandwidth (Flow 1 (blue—16%), Flow 2 (orange—33%), and Flow 3 (gray—50%)), and its WF has different fluctuations at the beginning before the flows converge to its assigned speed, always converging to 1, thus generating the fair share of resources.

The fairness mechanism introduced regulates the flows without large fluctuations in the system thanks to the modification of the Sending Rate Formula (19)–(20). The weighted fairness measures successfully ($WF = 1$) the correct fair share of the resources considering the priorities of the flows.

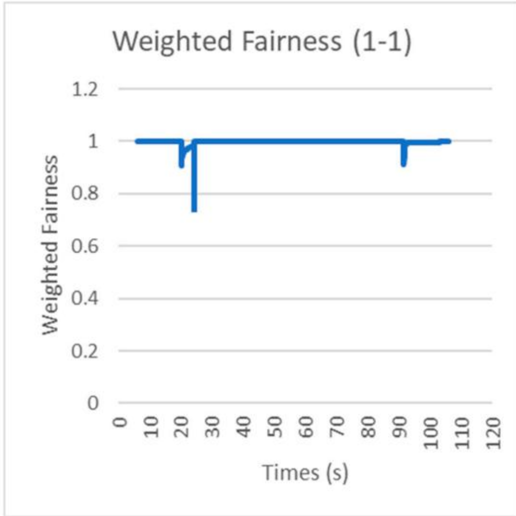
6.5. Enhanced-AATP Performance Comparison

The objective of this last experiment is to compare the Enhanced-AATP with other modern transport protocols. Concretely, the settled protocols TCP Cubic, BBR, Copa, Indigo, and Verus.

Pantheon of Congestion Control [41] is an evaluation platform for academic research on congestion control, so therefore, it is considered a scientific reference for transport protocol performance test. Furthermore, Pantheon directly assisted the publication of four other new algorithms [31,35,50,51]. Moreover, this platform is the source of the compared protocols' code.



(**a**)



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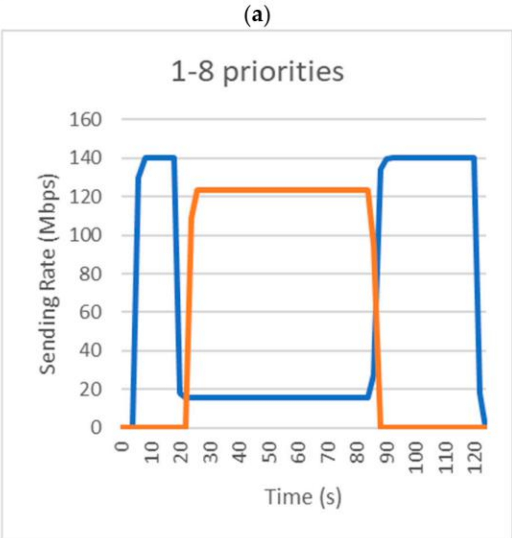

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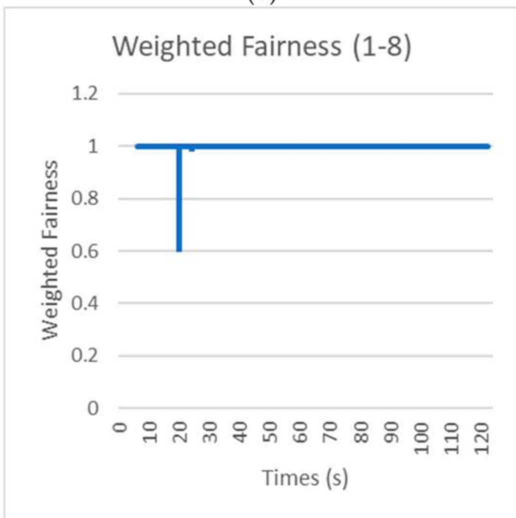

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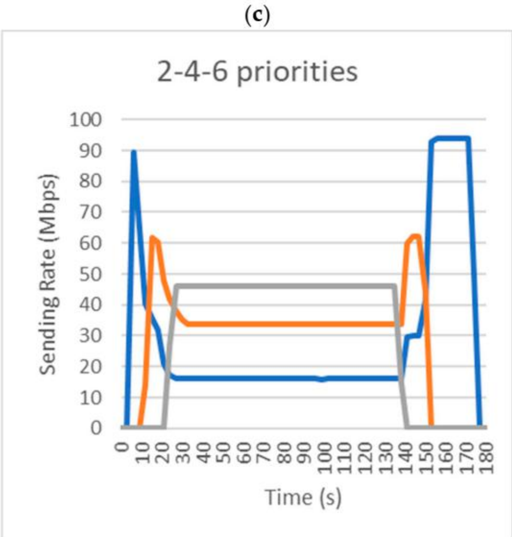

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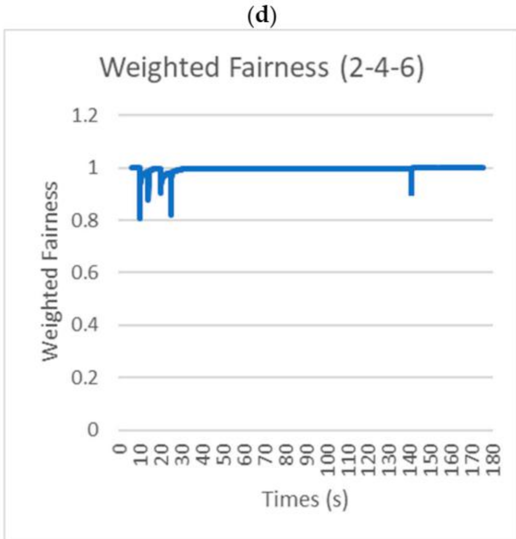

(**f**)

Figure 9. Fairness mechanism with priorities. Case 1-1: Sending Rate of Flow 1 (blue) and Flow 2 (orange) (**a**) and its Weighted Fairness 1-1 (blue) (**b**). Case 1-8: Sending Rate of Flow 1 (blue) and Flow 2 (orange) (**c**) and its Weighted Fairness 1-8 (blue) (**d**). Case 2-4-6: Sending Rate of Flow 1 (blue), Flow 2 (orange) and Flow 3 (gray) (**e**) and its Weighted Fairness 2-4-6 (blue) (**f**).

It is decided to emulate the most representative LFN scenarios from the last tests provided by the Pantheon platform over the Riverbed Modeler following its test methodology.

The chosen LFN scenarios (Figure 10) to be emulated are:

- L–I: GCE London to GCE Iowa (Bandwidth of 1 Gbps; latency of 45 ms)
- S–I: GCE Sidney to GCE Iowa (Bandwidth of 1 Gbps; latency of 85 ms)
- S–L: GCE Sidney to GCE London (Bandwidth of 1 Gbps; latency of 130 ms).

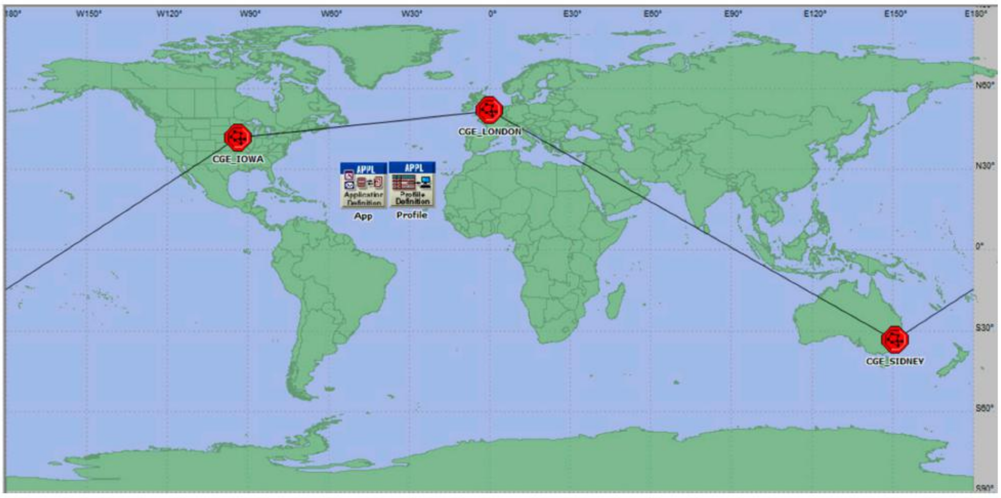

Figure 10. CGE Iowa-CGE London-CGE Sidney Riverbed scenarios following the structure.

Once the test environment is defined and emulated, the tests are deployed following Pantheon's methodology. This methodology consists of launching the same test five times over the three scenarios. Each test lasts for 30 s, running three flows using the same protocol with 10-s interval between two flows. The performance metrics results consider the three flows and average the results of the five runs. The performance metrics to be evaluated are the Average of the throughput achieved in percentage (29), the Delay Ratio (30), and the Packet Loss Ratio (PLR).

$$Mean\ Throughput\ (\%) = \frac{Average\ throughput\ (Mbps)}{Bandwidth\ of\ the\ link\ (Mbps)} \times 100 \tag{29}$$

In the case of the delay, the Delay Ratio is used, which is the average one-delay achieved related with the minimum one-way delay in order to check the introduced delay in the network by each protocol.

$$95th\ percentile\ one-way\ Delay\ Ratio = \frac{95th\ percentile\ average\ one-way\ delay\ (ms)}{Latency\ of\ the\ link\ (ms)} \tag{30}$$

For the Packet Loss Ratio (%), the lost packets sent are related to the total packets sent. This metric reflects the effects of the load produced by the three coexisting protocol flows that are trying to reach the maximum bandwidth.

$$Packet\ Loss\ Ratio\ (\%) = \frac{Lost\ packets\ sent}{Total\ packets\ sent} \times 100 \tag{31}$$

The first metric for the performance comparison is the throughput (Figure 11). From this graph, it can be extracted that the Enhanced-AATP achieves a mean throughput of the 80% of the bandwidth, providing better performance than most of the protocols. Similar behavior can be checked with TCP-Cubic, but performance decreases as the delay increases. BBR reaches better results, but these results are over the maximum bandwidth, which means that the protocol might be destabilizing the network.

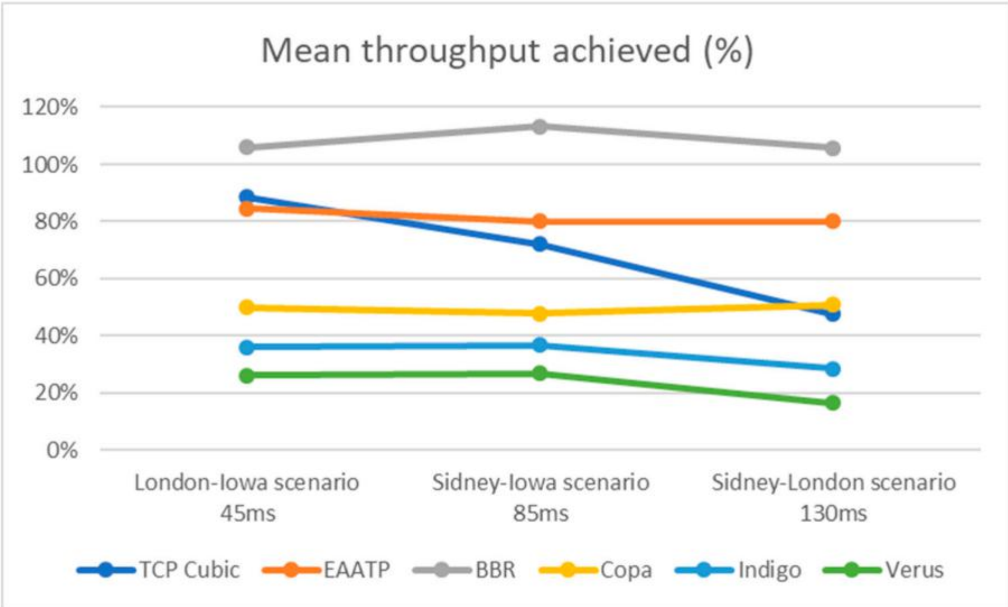

Figure 11. Mean throughput achieved (%) comparison.

In order to check how the throughput performance affects the network, the following figure (Figure 12) shows the Delay Ratio (average delay achieved compared with the minimum delay). In the case of the Enhanced-AATP, the delay introduced by the protocol is around 25% (1.25), which means that the network is stable. It can be seen that BBR destabilizes the network because its one-way delay multiplies per 4 the latency of the network in the lower delay scenario. Similar behavior can be seen with TCP Cubic, which doubles the one-way delay of the network (2.00) in the lower delay scenario.

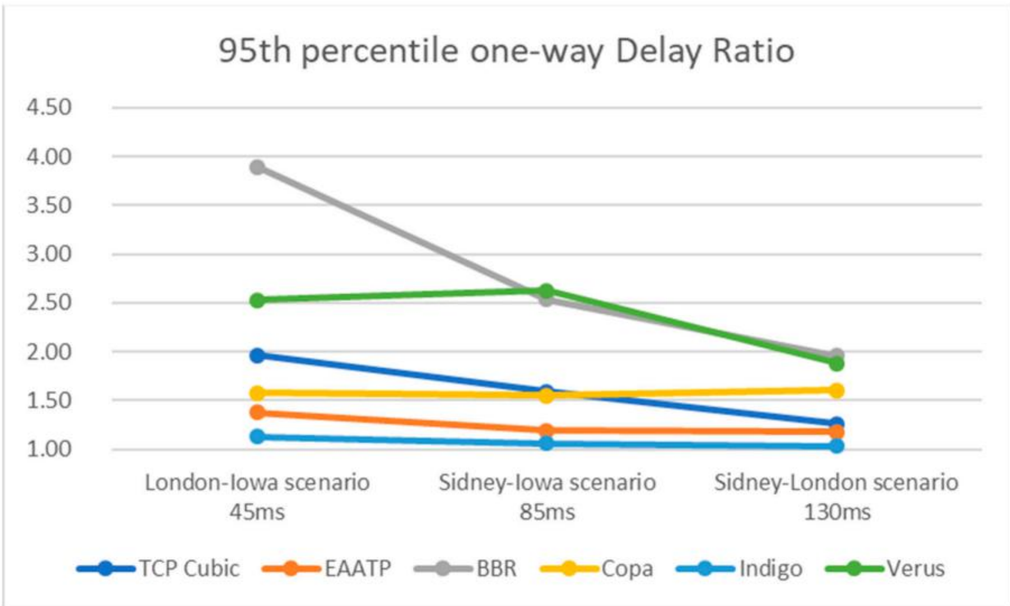

Figure 12. 95th percentile one-way Delay Ratio comparison.

The Packet Loss Ratio is checked in Figure 13 in order to confirm the effects of the protocols' behavior regarding the throughput and the delay. The losses introduced by the Enhanced-AATP are low (0.02%), as it happens with the most of the protocols. It is confirmed that BBR achieves better throughput to the detriment of the introduced losses (from 3% to 7%).

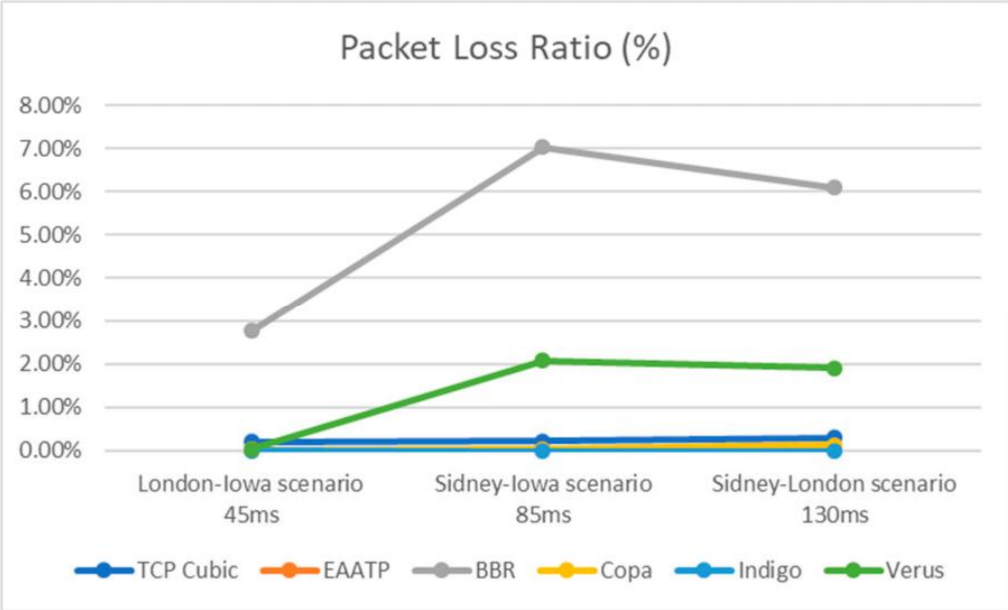

Figure 13. Packet Loss Ratio (%) comparison.

Finally, with the information provided by the last three figures, the following graph (Figure 14) shows the protocols' performance for each scenario, relating the 95th percentile one-way Delay Ratio and the Average Throughput achieved. Moreover, the Packet Loss Ratio is noted. This relativized view of the data enables us to contrast the protocols' performance joining the three scenarios' results. The objective is to provide a final performance comparison of the Enhanced-AATP with these protocols: TCP Cubic, BBR, Copa, Indigo, and Verus.

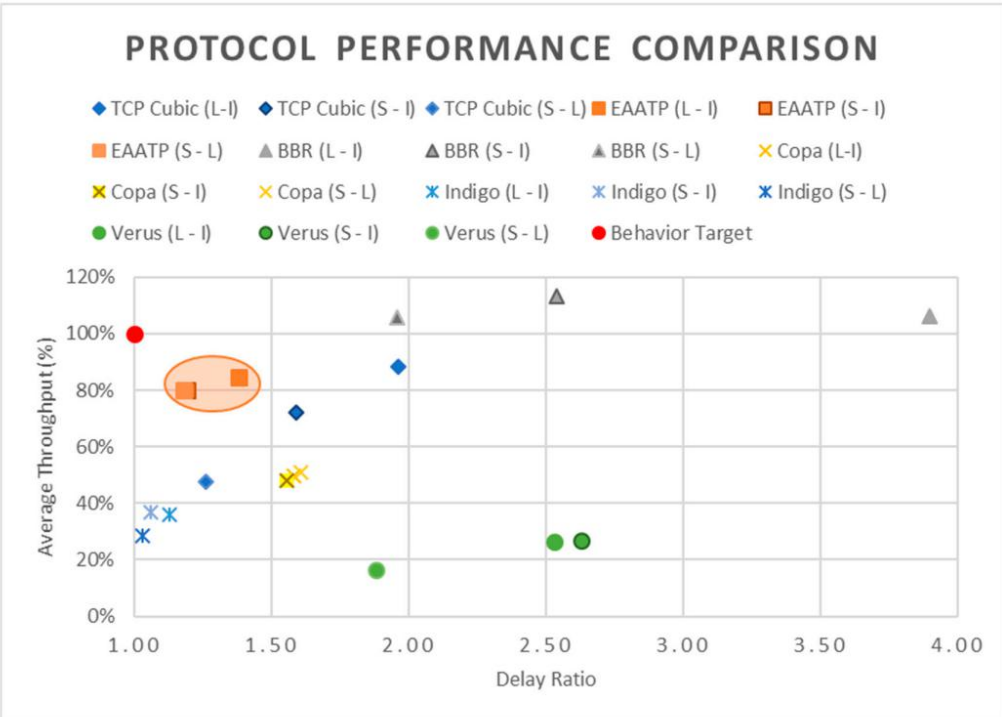

Figure 14. Protocol Performance Comparison (Throughput–Delay Ratio) over the three scenarios. Packet Loss Ratio (PLR) is noted. TCP Cubic: 0.24%; Enhanced-AATP: 0.02%; BBR: 5.30%; Copa: 0.06%; Indigo: 0.00%; Verus: 1.33%; Behavior Target: 0.00%.

The goal is to achieve the maximum throughput without affecting the delay neither causing losses. The Behavior Target (red circle) is the ideal protocol that achieves maximum throughput levels (100%) without affecting the congestion of the network (minimum one-way delay) nor generating losses during the data transfer. For the best performance, the protocols have to tend to the aforementioned behavior. Among the studied protocols, as the orange circle highlights, the Enhanced-AATP protocol achieves a high average throughput (80%) without destabilizing the network by slightly increasing (25%) the latency neither causing significant losses (0.02%).

Comparing the Enhanced-AATP with low delay protocols such as Indigo, the Enhanced-AATP obtains a greater throughput (Average Throughput: Indigo (35%)—Enhanced-AATP (82%)) causing a slightly increase of the delay (Delay Ratio: Indigo (1.1)—Enhanced-AATP (1.4)) without provoking significant losses (PLR: Indigo (0.00%)—Enhanced-AATP (0.02%)).

Moreover, comparing the Enhanced-AATP with high bandwidth protocols as BBR, the Enhanced-AATP does not reach that levels of throughput (Average Throughput: BBR (110%)—Enhanced-AATP (82%)) but has a stable behavior without strongly increasing the latency (Delay Ratio: BBR (2.8)—Enhanced-AATP (1.4)) and causing losses (PLR: BBR (5.30%)—Enhanced-AATP (0.02%)).

It can be concluded that the Enhanced-AATP protocol achieves the goal. The protocol maintains its throughput close to the limit without destabilizing the network thanks to the Bandwidth Estimation process, the LTD mechanism, and its operation states, which modify the Sending Rate depending on the network situation (Table 3). In addition, the Weighted Fairness mechanism provides a fairly controlled share of the network resources among the flows without causing significant losses due to the dispute of the bandwidth.

7. Conclusions

In this paper, we propose the Enhanced-AATP transport protocol as an improvement of the Aggressive and Adaptative Transport Protocol (AATP), which aims to modify operations and add new functionalities to achieve improved performance over fairly shared heterogeneous Long Fat Networks. One of these functionalities ensures the differentiation of the type of loss episode (congestion or channel), which then proposes a corresponding operation to solve the different types of loss. Moreover, a prioritized fair share of the network resources when multiple AATP flows are connected to the same node is achieved thanks to the new Weighted Fairness mechanism.

After analyzing the different proposals of distinct transport protocols, their metrics and mechanisms for wireless networks, the smooth Jitter Ratio ($smooth_{jr}$) is the reference metric chosen to distinguish the type of losses. The $smooth_{jr}$ relates the effect of the queued packets at the bottleneck and the delay among packets at the destination, also considering past values of the Jitter Ratio. This metric is not affected by the high delay introduced in the LFNs.

Having selected the Jitter Ratio metric, the Loss Threshold Decision maker (LTD) is designed. It is defined as the added number of packets in the burst over the total packet sent in the burst. By comparing it with the smooth Jitter Ratio ($smooth_{jr}$) of the received packets, the result of this comparison enables the protocol to discern between losses caused by network congestion or channel fault.

If the $smooth_{jr}$ is greater or equal to LTD, a congestion loss occurs; if the $smooth_{jr}$ is lower than the LTD, it is assumed that a channel failure caused the loss. As a result of this loss detection mechanism, the throughput is not reduced during a random loss episode, as it occurs during a congestion loss episode, thus reducing the loss recovery time and increasing the efficiency of the protocol.

The performance of the Enhanced-AATP and its operation over wireless connections is shown, as well as its capability to detect a random loss produced by the channel. Similarly, the capacity of the protocol to decide the type of loss occurred is exhibited over different scenarios. Finally, the optimal value of the LTD is demonstrated. All the experiments are deployed over the SteelCentral Riverbed Modeler simulator.

As a result of studying different indicators for a controlled fair share of the network resources of a node, the Jain Fairness Index (JFI) is chosen due to its characteristics and compliance with the requirements demanded. After adapting the JFI to consider the prioritization of the flows, the Weighted Fairness (*WF*) index is included in the operation of the Enhanced-AATP protocol. If the WF is equal to 1, it means that there is a fair share of resources; if not, it means that some unfair treatment is happening to one or more flows. Therefore, the protocol operation is adjusted to include a modifier related to the result of the WF to manage the flows for a fair system. Different simulations are run with different priorities and flows to demonstrate its performance. The *WF* suffers fluctuations during the beginning or end of a new flow.

It can be concluded that the Enhanced-AATP can effectively differentiate the types of losses occurred during a communication, adapting its operation to the situation, and assuring a fair sharing of the resources of the node over HLFNs.

Finally, the Enhanced-AATP's performance is compared with other transport protocols' performance. It should be highlighted that the protocol reaches a higher throughput than low delay protocols, slightly increasing the delay but keeping a similar low level of losses. Moreover, compared with high bandwidth protocols, the Enhanced-AATP reaches lower throughput levels (>80%) but does not destabilize the network, nor does it highly increase the latency (+25%) or cause significant losses (0.02%) as may occur with other protocols. This high performance is the result of including the proposed Loss Threshold Decision maker (in order to identify the type of losses occurred) and the Weighted Fairness mechanisms (fairly share of the server network resources) in the improved AATP operation, which modifies its behavior and, concretely, its Sending Rate depending on the network situation.

Our future work aims to introduce a way to detect the loss and recovery of the channel by way of preventing unnecessary packet transfers in order to save energy, and a method to create a distributed fairness system, as opposed to one that is controlled by the node where different Enhanced-AATP flows coexist. Finally, an exhaustive analysis of the relationship of the γ and β parameters of the Transcendence Factor (A) can be done to study its optimal performance and convergence.

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