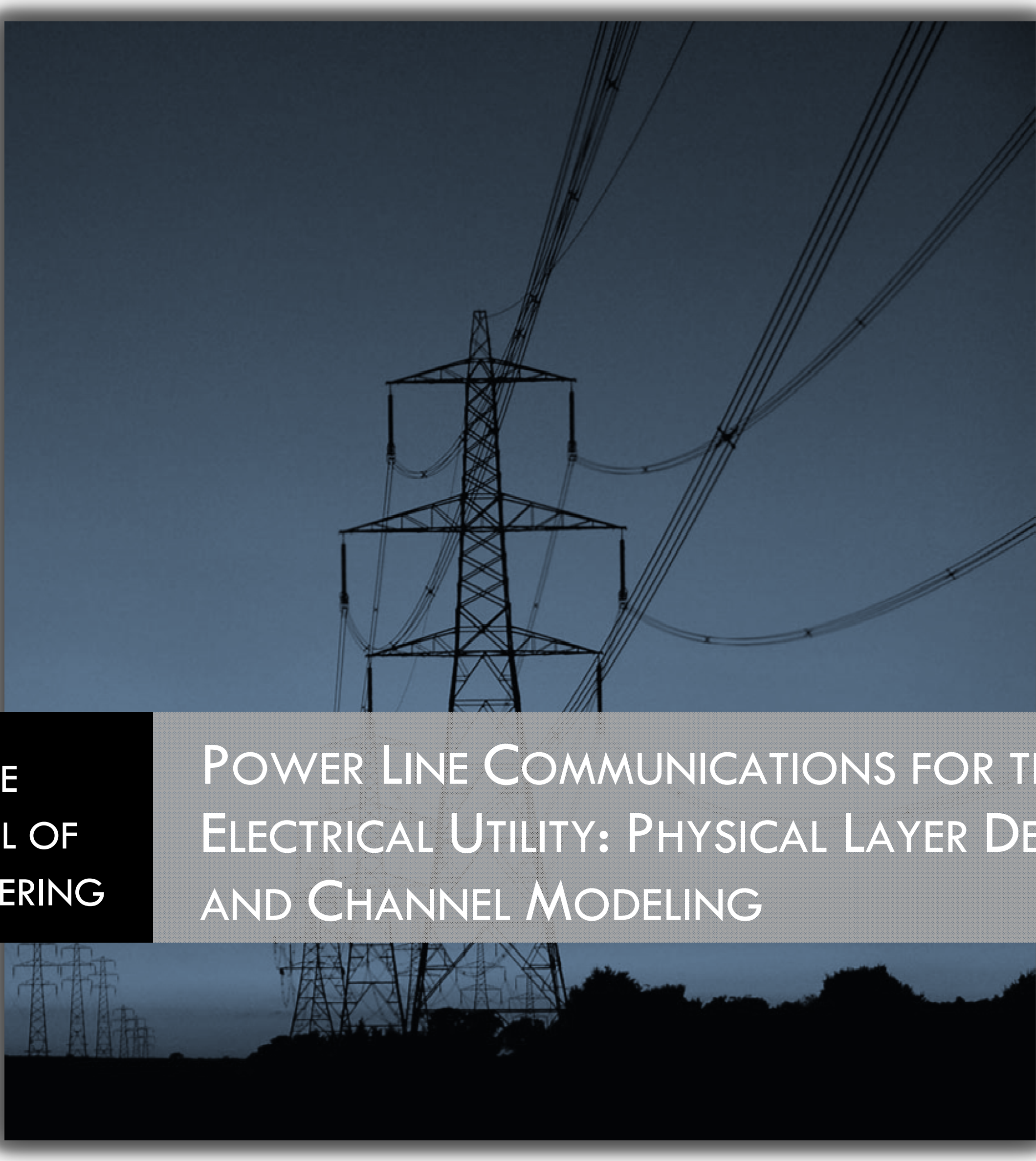

LA SALLE SCHOOL OF ENGINEERING

POWER LINE COMMUNICATIONS FOR THE ELECTRICAL UTILITY: PHYSICAL LAYER DESIGN AND CHANNEL MODELING

PhD Thesis | Ricard Aquilué de Pedro

Power Line Communications for the Electrical Utility: Physical Layer Design and Channel Modeling

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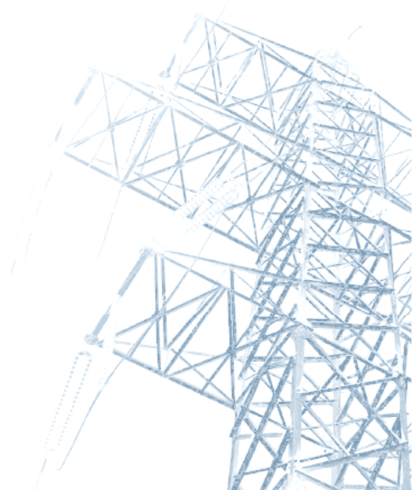

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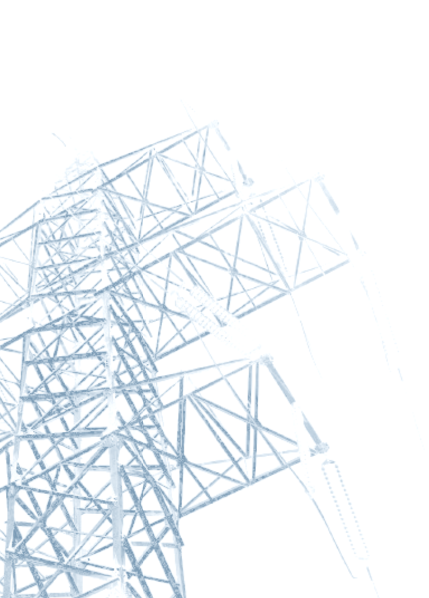

ABSTRACT

The world of Power line communications (PLC) can be divided into three main types: low voltage PLC (LV-PLC), medium voltage PLC (MV-PLC) and high voltage PLC (HV-PLC). These last years, LV-PLC has attracted a great expectation since its wideband capabilities has made this technology a suitable choice for last-mile access and in-home communications. Moreover, LV-PLC also includes a utility oriented low frequency and low speed applications, such as automatic meter reading (AMR), load distribution, dynamic billing and so on. On the other hand, MV-PLC and HV-PLC, historically oriented to teleprotection and telecontrol tasks, are being considered as a reliable communication channel. The development of digital equipment and the standardization efforts are making those channels an attractive medium for electrical utilities telecommunications services, since the network, as well as in LV-PLC, is already deployed.

In this PhD dissertation, the three different PLC topologies are reviewed and the different communications techniques in such channels exposed. Then, a deep technological review of existing AMR solutions for the European CENELEC band, as well as HV-PLC systems is given, showing that existing AMR systems deliver low frequency diversity and HV-PLC systems are anchored in old fashioned standards.

This work walks around the three topologies, specifically, CENELEC band utility oriented applications, channel measurement and modeling and channel measurement and physical layer design, regarding LV-PLC, MV-PLC and HV-PLC respectively. Existing CENELEC compliant systems deliver low or none frequency diversity mechanisms, yielding in a low robustness against colored noise and interference. This work propose a multicarrier based physical layer approach that, while keeping the complexity low, delivers high performance allowing a great level of frequency diversity. Focusing on MV-PLC, a hybrid deterministic-statistical channel model for urban underground rings is developed and, finally, in HV-PLC systems, this work proposes, based on measurements and field tests, a wideband physical layer in order to increase data rate while keeping low both the power spectral density and possible interference to other systems.

CONTENTS

LIST OF FIGURES AND TABLES

ACRONYMS

AM: Amplitude Modulation

AMR: Automatic Meter Reading

ASK: Amplitude Shift Keying

AWGN: Additive White Gaussian Noise

BER: Bit Error Rate

BPL: Broadband Power Line

BPSK: Binary Phase Shift Keying

CEPCA: Consumer Electronics Powerline Communication Alliance

CP: Cyclic Prefix

CPE: Customer Premises Equipment

DCSK: Differential Code Shift Keying

DCTP: Digital Carrier Transmission over Power line

DCTS: *Departament de Comunicacions I Teoria del Senyal*, Department of Communications and Signal Theory

DHCP: Dynamic Host Configuration Protocol

DPLC: Digital Power Line Carrier

DSB-AM: Double Side Band – Amplitude Modulation

DS-SS: Direct Sequence – Spread Spectrum

EHV: Extremely High Voltage

EMC: Electromagnetic Compatibility

EPR: Ethylene Propylene Rubber

ES: Electrical Substation

ETSI: European Telecommunications Standards Institute

EU: Electrical Utility

FFT: Fast Fourier Transform

FH-SS: Frequency Hopping – Spread Spectrum

FSK: Frequency Shift Keying

FTP: File Transfer Protocol

GPS: Global Positioning System

GRECO: *Grup de Recerca en Electromagnetisme I Comunicacions*, Research Group in Electromagnetism and Communications

HE: Head End

HF: High Frequency

HV: High Voltage

HVAC: High Voltage Alternating Current

HV-PLC: High Voltage – Power Line Communications

ICI: Inter-Carrier Interference

IEC: International Electrotechnical Commission

IEEE: Institute of Electrical and Electronics Engineers

IFFT: Inverse Fast Fourier Transform

IIIT: *Institut für Industrielle Informationstechnik*

IP: Internet Protocol

ISI: Inter-Symbol Interference

ISP: Internet Services Provider

LV: Low Voltage

LV-PLC: Low Voltage – Power Line Communications

MAC: Medium Access Control

MBOK: Mary Biorthogonal Keying

MC: Multicarrier

MC-CDMA: Multicarrier – Code Division Multiple Access

MC-DS-CDMA: Multicarrier – Direct Sequence – Code Division Multiple Access

MCM: Multicarrier Modulation

MC-SS: Multicarrier – Spread Spectrum

MV: Medium Voltage

MV-PLC: Medium Voltage – Power Line Communications

MWNA: Microwave Network Analyzer

OFDM: Orthogonal Frequency Division Multiplexing

OPERA: Open Power Line Communications European Research Alliance

PEP: Peak Envelope Power

PHY: Physical

PLC:	Power Line Communications
PN:	Pseudo-Noise
POP:	Point of Presence
PPS:	Pulse per Second
PSD:	Power Spectral Density
PSK:	Phase Shift Keying
PTSN:	Public Telephone Switched Network
QAM:	Quadrature Amplitude Keying
RADIUS:	Remote Authentication Dial-In User Server
RCS:	Ripple Carrier Signaling
RE:	Repeater
RF:	Radio Frequency
RMU:	Ring Main Unit
RTTE:	Radio Equipment and Telecommunications Terminal Equipment
SCM:	Single Carrier Modulation
S-FSK:	Spread – Frequency Shift Keying
SS:	Spread Spectrum
SSB-AM:	Single Side Band – Amplitude Modulation
TS:	Transformer Station
UHV:	Ultra High Voltage
UPA:	Universal Powerline Alliance
URL:	*Universitat Ramon Llull*, Ramon Llull University
VoIP:	Voice over Internet Protocol
VSF-OFCDM:	Variable Spreading Factor – Orthogonal Frequency and Code Division Multiplexing
XLPE:	Cross-Linked Polyethylene

ACKNOWLEDGEMENTS[1]

First of all, many thanks to Dr. Joan Lluís Pijoan, who encouraged me to pursue the PhD at the end of my Master studies and for doing his best while pushing me through this exciting, lonely and fulfilling journey. I don't want to forget the rest of the Research Group in Electromagnetism and Communications (GRECO) and Communications and Signal Theory Department staff: Carles Vilella, Miquel Ribó, David Badia, Joan Ramón Regué, David Miralles, Simó Graells, Javier Pajares, Pablo Rodriguez and Albert Miquel Sánchez, for making my PhD a great and unforgettable adventure. I would like to have a special mention to my officemates and friends, Ismael Gutierrez, Pau Bergada and Marc Deumal, great engineers and better persons, for sharing those funny moments, those great illusions… Good luck and may the force be with you…

Furthermore, I would like to express my gratitude to the "Powerliners" at Institut für Industrielle Informationstechnik (IIIT), Universität Karlsruhe, in Germany, Timo Kistner and Michael Bauer, and to the other IIIT staff, especially to Prof. Dr. Klaus Dostert for his hospitality and the others PhD students for make me feel as if I were at home.

Finally, I also would like to mention Germán Sánchez and José Comabella, from Endesa Network Factory S.L., a great model of support to the pure research and development from the private sector, for the great work we have done together.

1 The author wants to acknowledge the pre-doctoral grantship of the "*Departament d'Universitats, Recerca i Societat de la Informació de la Generalitat de Catalunya*" especially the program "*Beques doctorals per la formació de personal investigador (FI)*" from which the author has been beneficiary; and the Spanish Government projects REN2003-08376-C02-01 and CGL2005-24213-E, that have partially funded the initial work of this thesis.

AUTHOR'S PRESENTATION

Ricard Aquilué received the BSc and MSc degrees in Telecommunications Engineering from La Salle School of Engineering, Ramon Llull University, in Barcelona, Spain, in 2003 and 2004, respectively. Since 2006 he is a FI PhD Fellow from the Catalan Government (*Departament d'Universitats, Recerca i Societat de la Informació de la Generalitat de Catalunya*). He joined the Research Group in Electromagnetism and Communications (GRECO) that belongs to the Department of Communications and Signal Theory (DCTS) in 2003, where he has participated in several public and private research projects, mainly in high frequency (HF) ionospheric communications and power line communications. Nowadays he continues in the DCTS at the same university, combining research and management activities, mainly focused on the fields of power line communications, adaptive multicarrier systems and software defined radio.

From September 2003, he participated actively into the Antarctic project "Characterization and modeling of the Antarctic ionospheric channel: Advanced HF communications" funded by the Ministry of Education and Science from the Spanish Government, where he worked in the design and implementation on the software radio based channel sounding system and data transceiver. Also, related to this project, from January to March, 2006, he realized a two months stay in the Spanish Antarctic Base "Juan Carlos I". (For more details, the reader is referred to reference [1] and Appendix A.1, where previous work related to HF can be found).

At the beginning of 2006, consequence of a private funded project from Endesa Distribución Eléctrica S.L., the author moved to power line communications, specifically on low voltage power line automatic meter reading technology. Related to this research field, he did a three months research stage at *Institut für Industrielle Informationstechnik* (IIIT), *Universität Karlsruhe*, Germany. Then, due to a second project, this time from Endesa Network Factory S.L., he focused his research activities to medium and high voltage power line communications, regarding modulation design and channel modeling.

CHAPTER 1

1. INTRODUCTION

1.1. HISTORY OF POWER LINE COMMUNICATIONS FOR THE ELECTRICAL UTILITY

The power grid has been used as a communications medium since the beginnings of 20th century, when the power grid main exploitation purpose was the transmission of voice in the high voltage (HV) network [2][3]. Rapidly, other applications such as operations management, monitoring and troubleshooting, that required bidirectional flow of messages, took an important role in the HV communication scenario. Since telephone network could not be found in every point and its reliability was not enough to cope with the requirements of the services mentioned before, these services were deployed on the power lines. Moreover, the use of telephony or any other kind of leased line wouldn't be economical for large distances.

The electrical utilities (EUs) operations on the high voltage lines can be grouped into three classes:

1. Operation management
2. Monitoring
3. Limitation and removal of failures

Operation management tasks take care for the optimum energy distribution, trying to generate what is to be consumed, keeping enough energy to cope with demand peaks and avoiding the excess of reserves around the network. In case of failure in the HV network, the fast and reliable exchange of data between power plants, transformer stations and substations, switching equipment and coupling points to neighboring networks is a key factor when trying to minimize the impact of that failure to the rest of the network. The monitoring of that data, regarding the network state, is carried out by means of tracking energy requirement, voltage and frequency, yielding to a fast reaction capability in front of networks failures.

In the past, the data was transmitted by an operator through the telephone network but, in the course of time, the automatic, reliable and fast transmission of all the data mentioned before became an important issue of the EUs. Since most of them have always seen the HV network as its natural medium to transmit the management and monitoring information, EUs, pushed by the necessity of having their own data networks, led to the quick development of power line carrier (PLC) systems [4].

1.1.1. POWER LINE CARRIER

The power grid was not originally designed to transmit data through its circuits; however, the reliable data transmission is possible with low power, over a relatively broad available spectrum. In HV networks, the PLC frequency range is upper limited by standard at 500 kHz [5][6] and lower limited by the same at 40 kHz, lower frequencies can be achieved in practice (15 kHz – 25 kHz, limited by the coupling capacitor), though.

At the beginning, the task handling was done by means of voice. The voice frequency band (300 - 2400 Hz) had to be transmitted successfully under marginal conditions. Only amplitude modulation (AM) was suitable to transmit data through the HV links. The equipment requirements for transmitting and receiving a simple double-sideband AM (DSB-AM) without suppressed carrier are considerably less than the ones required for the same approach with suppressed carrier. Although suppressing the carrier means a reduction of intermodulation risk when dealing with multiple channel PLC, this approach was not considered for PLC due to the high receiver cost, and DSB-AM without suppressed carrier was used until about 1940.

The increasing lack of free frequency range, forced the EU to replace their DSB-AM links with single-sideband AM (SSB-AM). An SSB-AM system occupies half the bandwidth that a DSB-AM does. This migration to SSB-AM systems caused the current typical 4 kHz channelization of the HV frequency range.

In the course of time, the quality of service that the EUs desired from their data network became difficult to achieve, even impossible, by means of voice channels. Moreover, human based systems transmitting the data through voice channels couldn't support a real full-time monitoring of critical data as they were supposed to. The measurement and transmission of the network state and management operations could be triggered much faster, reliable and easier using digital systems. These digital systems didn't get the redundancy level that can be found inherently in human voice (the corruption of one single data bit can lead to critical errors), and although there was quite good knowledge of coding techniques, the hardware platforms didn't allow their implementation. Actually, the data protection technique used on these channels was based on majority vote at the receiver site from the multiple replicas of the information sent by the transmitter.

At the beginning of their deployment, the digital systems' data rates were low, i.e. 50 bps in a 120 Hz bandwidth using amplitude shift keying (ASK) or frequency shift keying (FSK). This allowed the transmission of 33 digital channels in one 4 kHz voice channel. Soon, the data rates rose from 50 bps to 100 bps and 200 bps. With the increase of the power grid automation level, the needed data rates requirements grown to support the transmission of such a complex system. Higher rate digital transmission channels with 600, 1200 and 2400 bps had to be used. At 2400 bps, the whole 4 kHz channel was used [4].

Nowadays, PLC systems are based on the combination of analog and digital techniques. This presents a higher degree of flexibility for the customer. At the same time, it solves the problem of relatively low reliability of the digital PLC for tasks such as teleprotection and overcomes the rate limitation of the analog PLC.

If focusing in data transmission, the state of the art of PLC still comprises both analog and digital systems. Analog systems (designed by analog or digital technology) use SSB-AM with suppressed carrier on 4 kHz channels in order to keep compatible with legacy equipment. These analog systems allow the transmission of voice and data by means of a digital modulation stage before the SSB-AM modulator, with speeds up to 2400 bps. On the other hand, digital systems allow access to data servers, data networks and management applications (Figure 1).

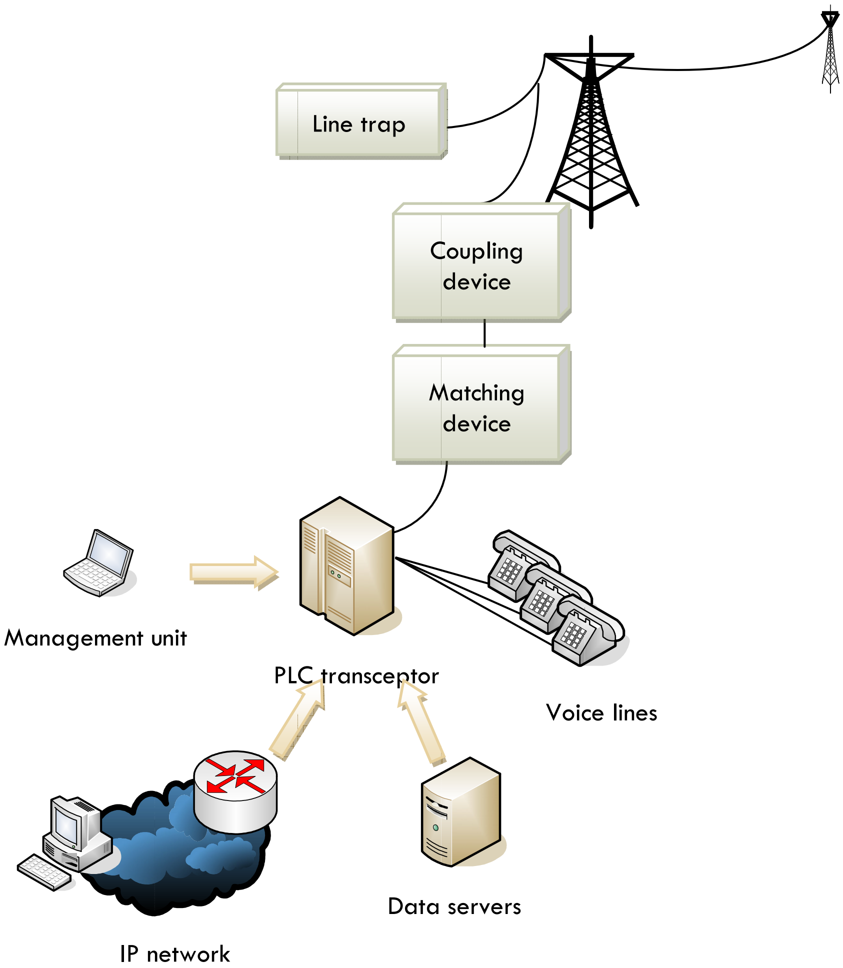

Figure 1 PLC transceptor.data transmission applications

Current digital systems based on quadrature amplitude modulation (QAM) single carrier modulation (SCM) can reach a net bit rate of up to 80 kbps in a 16 kHz bandwidth [7]. Orthogonal frequency division multiplexing (OFDM), the most efficient multicarrier modulation (MCM), begins to play an important role in HV communications due to its inherent robustness against multipath effects and narrowband interferers. OFDM is becoming the choice for manufacturer's next generation HV power line communications equipment, delivering a data rate of 256 kbps available to the user in a bandwidth beyond the typical 4, 8 or 16 kHz, extending the usable carrier frequency range up to 1 MHz [8].

Beside traditional core services mentioned before, (operation management, monitoring and limitation and removal of failures), EUs would like to satisfy increasing need of new internal services, taking benefit from the use of their own power grids, like [9]:

- Demand prediction
- Transformer overload analysis
- Outage Localization
- Support for advanced grid control & automation
- Network Optimization
- Security related communication (video / audio)

Nowadays, the standards regarding HV communications are obsolete. IEC-TC57 Workgroup 20 recently started to work on the new standard including HV digital carrier transmission over power line (DCTP) or digital power line carrier (DPLC).

1.1.2. RIPPLE CARRIER SIGNALING

Regarding the medium and low voltage levels (MV and LV), the main data application performed on these networks is load distribution. MV and LV networks were used as a communication medium for the first time around 1930. Initial ripple carrier signaling (RCS) practical applications were performed in Potsdam, Germany, at 1930, under the framework of a Siemens' project called Telenerg. The first practical use of this technology was also carried out in Germany, in Stuttgart and Magdenburg, in 1935 by AEG.

While the HV level presents a relatively easy to match (200 – 400 Ω) friendly overhead lines for data transmission for frequencies up to 500 kHz and even 1 MHz, MV and LV are hostile environments with unpredictable branching (LV) and connected loads that decrease the channel input impedance down to tens even tenths of ohm. This scenario calls for a high power injection dimensioned for the network peak load (this causes the impossibility of transmitting data in the uplink), in order to cover the maximum MV and LV area. Since every active consumer adds its load to the network, a highly populated network can represent a very low load. Due to the large number of different network configurations, the exact transmit power values cannot be given, but transmission powers between 10 and 100 kW are common. To let the information flow from the power supply to the customers, the audio band frequency range was chosen for signaling. That frequency (often below 1 kHz) passed through the MV to LV transformers experiencing only a minor attenuation. The data rates were obviously very low, but enough for task regarding load distribution command transmission. However, this transmission has to be highly reliable, even with no feedback channel available.

Initially, multiple frequency RCS systems were used: the receiver has to correctly detect the exact combination of frequencies before triggering its related function. Since generating and injecting single frequency signals into the network was seen to be more cost effective, in 1940 RCS systems began their migration to this approach. Due to its low generation complexity, ASK was the modulation scheme used in single frequency networks. The duration of an RCS ASK modulated telegram could take from 28 to 180 seconds. 10 to 60 impulses (with a guard time after each impulse) were transmitted per telegram. Such lasting signals offer a high robustness against transient interferers and impulse events. In order to increase the safety of RCS systems, the digital message is coded onto a high dimension codeword before transmission. Since there are forbidden binary combinations of that codeword, this technique permits the detection and even the correction of received messages. Moreover, if this is not enough, the transmitted message will be retransmitted at intervals of several minutes [4].

Recently, EUs realized that RCS is still a good solution for load balancing management but their technical limitations cannot cope with current utilities needs like telecontrolling and telemetering, most especially after the deregulation of the energy market, e.g., selective addressing (with RCS all customers in the same MV-LV mesh are addressed in parallel). Moreover, with the telecommunications market liberalization EUs can use their own infrastructure, the power line grid (specially the MV and LV networks), to deliver communications services. Figure 2 shows the power line access topology proposed by OPERA (Open PLC European Research Alliance) [10]. In this new scenario, several technologies try to exploit the MV and LV channel in a non standardized way. The multivendor interoperability issue represents a serious problem for the PLC industry development.

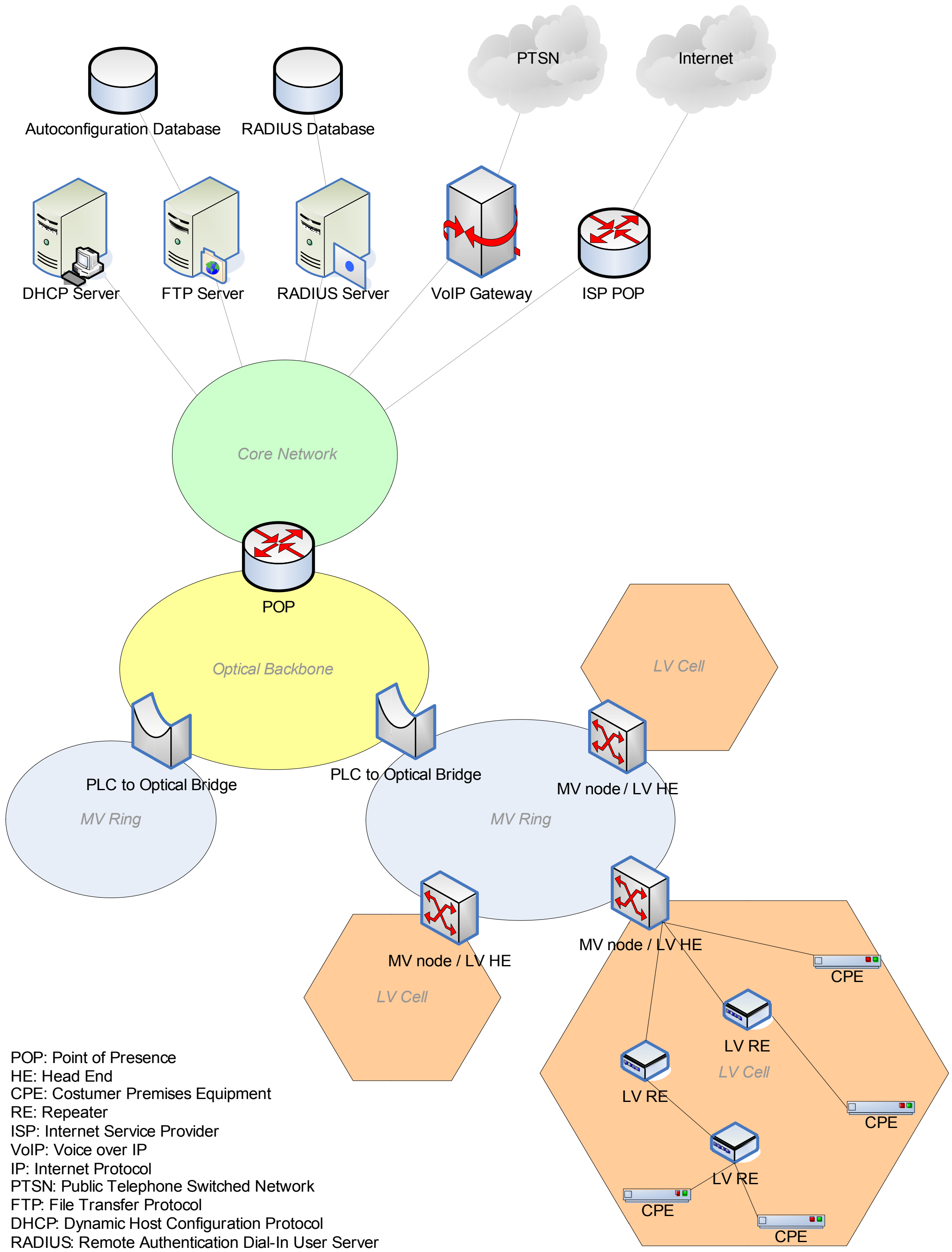

Figure 2 OPERA powerline access topology

1.1.3. TOWARDS THE STANDARDIZATION OF THE ACCESS AND IN–HOME PLC TECHNOLOGY

Standardization makes devices be compatible with each others. Devices compliant with different standards will not be able to coexist in the same grid. This is a serious impairment for power line communications (PLC) industry development and an inconvenient for end-users.

There are four main alliances or consortiums that are working (or have worked) on PLC physical (PHY) and medium access control (MAC) level specifications (Figure 3):

1. UPA (Universal Powerline Association). While supporting OPERA and its access specification, UPA works on its own in-home specification. Within others, UPA has the following members:

    - AcBel
    - Ambient
    - Arteche
    - Buffalo
    - BPL
    - Comtrend
    - Corinex
    - Current
    - Cypress
    - DS2
    - DukePower
    - Ilevo
    - Intersil
    - Itochu
    - Korea ERI
    - Logitec
    - Netgear
    - Pirelli
    - Toshiba
    - Watteco

2. Homeplug. Firstly focused on in-home networking (version1.0 and recently version AV for audiovisual applications) Homeplug has also released specifications regarding access (version BPL) and control (version CC). Within others, Homeplug has the following members:

    - Linksys
    - Comcast
    - Intel
    - Motorola
    - Samsung
    - Sharp
    - Gigle
    - Huawei
    - Intellon
    - Ariane Controls
    - COMTek
    - Current
    - Korea ERI
    - STMicroelectronics
    - Yitran
    - Belkin
    - D-Link
    - Electricite de France
    - Philips CE
    - ZyXEL
    - LG
    - Texas Instruments
    - 2Wire
    - France Telecom
    - Analog Devices
    - Fujitsu Siemens

3. CEPCA (Consumer Electronics Powerline Communication Alliance). CEPCA is working on in-home specification for audiovisual applications. Within others, CEPCA has the following members:

    - ACN
    - Analog Devices
    - Delta Electronics
    - Hitachi
    - Mitsubishi
    - Panasonic
    - Philips
    - Pioneer
    - Sanyo
    - SiConnect
    - Sony
    - ST&T
    - Toshiba
    - Xeline
    - Yamaha

4. OPERA (Open PLC European Research Alliance). OPERA project 1 has finished with a complete specification for access networks, involving both the LV and the MV grid. Within others, OPERA has the following members:

    - Swiss Federal Institute of Technology
    - University of Comillas
    - University of Dresden
    - University of Duisburg-Essen
    - University of Karlsruhe
    - University Politécnica Madrid
    - University Ramon Llull
    - Electricite de France
    - Energias de Portugal
    - Iberdrola
    - LinzAG Strom
    - Union Fenosa
    - Celg
    - CTI
    - DS2
    - Amperion
    - Dimat
    - Schneider Electric Powerline Communications
    - Eichhoff
    - Telvent
    - Robotiker

Figure 3 The four main entities involved in PHY and MAC PLC specifications

Regarding access and in-home services, PLC technology needs, in a short time frame, the specifications from the previous organizations to yield in one, or several well accepted standards, in order to avoid a serious damage to the PLC industry. Currently, one international standardization body, i.e. the IEEE (Institute of Electrical and Electronics Engineers), and two European bodies, i.e. the ETSI (European Telecommunications Standards Institute) and the CENELEC (European Committee for Electrotechnical Standardization) are concerned with access, in-home and their coexistence. ETSI and CENELEC work on same field addressing different standard aspects [9][11][12].

The interested entities, such as the four mentioned before, will submit their specifications to the standardization bodies in order to contribute to the access and in-home standardization process. In order to adopt one, or several standards from one, or many proposals, a minimum consensus has to be reached, so discussions and compromises from the different players will be needed. Standardization bodies can only recommend a standard procedure to exploit the PLC channel, but the regulatory entities in each region or each country are the ones that will allow or not the PLC devices access to the market. The most relevant directives involved with PLC regulation are:

1. EMC[2] directive 2004/108/EG
2. Low Voltage Directive 73/23/EEC
3. RTTE[3] directive 1999/5/EC
4. And several directives concerned with the liberalization of the telecommunication sector.

Regarding the low frequency range of the European power grid, the European standard CENELEC EN50065 rules the PLC frequency range from 9 to 148.5 kHz. This standard manage that frequency range in 4 bands, named A, B, C and D band. The first one is reserved for the EU and its licensers, while the last three are intended for private use [13].

1.2. CONTENTS OF THE THESIS

After this introduction to the PLC and its role regarding EUs, a brief explanation of the PLC channel will be given, for the LV, MV and HV networks. Then, the work concerning the LV PLC will be presented. This work will focus on the state of the art of the AMR systems, and a new multicarrier based low complexity physical layer scheme. Current manufacturer solutions, as well as existing proposals in the literature, offer limited diversity or, on the other hand, they are too complex to be implemented at a large scale with reduced costs. A zero-crossing synchronized multicarrier based physical layer seems to be the current trend in robust AMR modem design.

Afterwards, the MV channel measurements and the formulation of a deterministic-statistical channel model will be introduced. Current MV channel topology model proposals deal with particular issues or are based on behavioral characterization (multipath models), providing a non complete or an imprecise channel model.

[2] Electromagnetic Compatibility
[3] Radio Equipment and Telecommunications Terminal Equipment

For this kind of scenario and focusing on the channel transfer function, by means of a structural characterization of the MV network devices, this work will propose a low complexity and high versatile MV network channel transfer function model.

Then the reader will be driven to the HV measurements and field tests, showing the characteristics of the HV communication channel and the performance of a multicarrier spread spectrum modulation in such environment. This work will show why the evolution of HV-PLC should point to the use of large bandwidth modulations in order to enhance the link capacity while keeping the power spectral density low, two of the main handicaps in the current HV-PLC implementations. Moreover, the reader will see how the combination of multicarrier modulations with spread spectrum techniques can beat all the existing and deployed systems in terms of user data rate while delivering high adaptive and quality of service capabilities.

Finally, the concluding remarks will be summarized and afterwards, the reader will find in the appendixes the three main papers regarding the LV, MV and HV work:

LV: PHYSICAL LAYER DESIGN

R. Aquilué, M. Deumal, J.L. Pijoan, L. Corbeira, "A Low Complexity Multicarrier Proposal for Medium Rate Demanding Automatic Meter Reading Systems", in Proc. IEEE Symposium on Power Line Communications and its Applications (ISPLC2007), Pisa, Italy, 2007.

MV: CHANNEL MODEL

R. Aquilué, M. Ribó, J.R. Regué, J.L. Pijoan, G. Sánchez, "Urban Underground Medium Voltage Channel Measurements and Characterization", in Proc. IEEE Symposium on Power Line Communications and its Applications (ISPLC2008), Jeju, South Korea, 2008.

HV: PHYSICAL LAYER DESIGN

R. Aquilué, J.L. Pijoan, G. Sánchez, "High Voltage Channel Measurements and Field Test of a Low Power OFDM System", in Proc. IEEE Symposium on Power Line Communications and its Applications (ISPLC2008), Jeju, South Korea, 2008.

Then, two extended versions of the two latter papers recently accepted for publication on the IEEE Transactions on Power Delivery will follow:

MV: CHANNEL MODEL

R. Aquilué, M. Ribó, J.R. Regué, J.L. Pijoan, G. Sánchez, "Scattering Parameters Based Underground Medium Voltage Power Line Communications Channel Measurements, Characterization and Modeling", accepted for publication in IEEE Transactions on Power Delivery, June 2008.

HV: PHYSICAL LAYER DESIGN

R. Aquilué, I. Gutiérrez, J.L. Pijoan, G. Sánchez, "High Voltage Multicarrier Spread Spectrum Field Test", accepted for publication in IEEE Transactions on Power Delivery, May 2008.

As well as the paper regarding HF ionospheric communications, which can be considered as an introductory work to frequency selective and interference limited environments:

HF: PHYSICAL LAYER DESIGN

R. Aquilué, P. Bergadà, M. Deumal, J.L. Pijoan, "Multicarrier Symbol Design for HF Transmissions from Antarctica Based on Real Channel Measurements", in Proc. IEEE Military Comunications Conference (MILCOM2006), Washington, United States, 2006.

CHAPTER 2

2. POWER LINE NETWORKS

The EU power grid can be divided into three stages:

1. Generation stage
2. Transport stage
3. Distribution stage

The generated energy flows from the power plants through the power line grid (Figure 4) until reaching the final customer. Typically, power is generated at tenths of kV. Before transporting this power towards its consumption point, a step-up electrical substation (ES), usually located close to the generation point, increases the voltage to the high voltage (HV) levels, decreasing the current flow in order to reduce the transmission losses [21]. At this point, one can define the frontier between the generation and the transport network. Those HV levels range from 100 kV up to 400 kV approximately. Although every line transporting power with voltages over 100 kV can be considered HV, transmission levels over 500 kV are often particularly referred as ultra HV levels. Step-down transformation can be done progressively as the power approaches its consumption point in step-down ESs. The ESs that transform MV levels to LV levels are referred as Transform Substations (TS) [22].

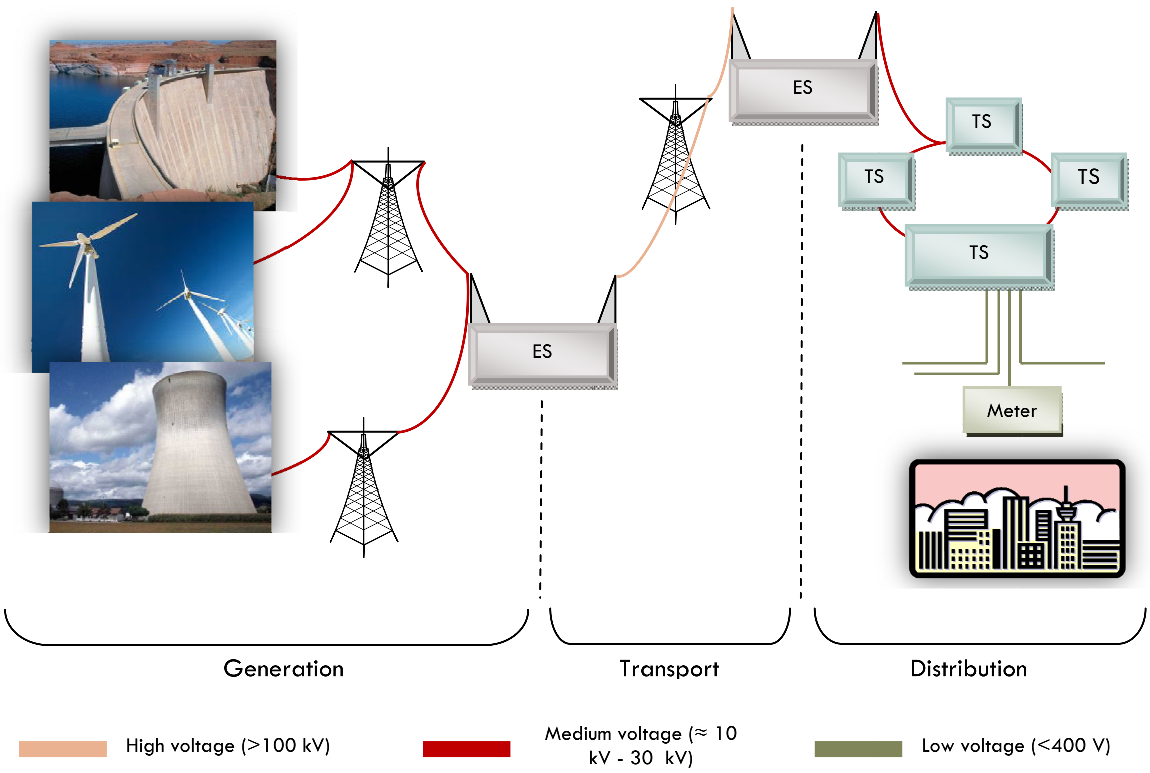

Figure 4 Power line grid

Regarding its localization among the power line grid, the ESs can be classified by the following way:

1. Generation ES: Located close to the generation points, they step-up the power plant outgoing level to the HV transport one, incorporating the generated power into the grid.

2. Transport ES: Interconnection node of a variable number of transport lines. They also can step-down levels from transport to subtransport voltages, both of them in the HV range.
3. Distribution ES and TS: They step-down the incoming HV transport level to medium voltage (MV) and (LV) levels (primary and secondary distribution), suitable for local distribution. The distribution ES, located near the end user, is the frontier between the HV and the MV level. The MV level can be distributed into commercial or residential areas to a posterior step-down into the LV range at TS or can be delivered directly to a high consumption industrial customer.

In Figure 5 one image of the "Egara" distribution ES (Endesa) is shown. At the right, the 110 kV to 25 kV step-down transformer can be found. At the left, there is a 110 kV to LV transformer. This one is in charge of feeding the ES. Behind, the switching, buses and protection devices can be seen, as well as the incoming HV line that feeds the ES.

Figure 5 "Egara" Distribution ES

Usually, an ES is operated remotely, so a reliable communication network is mandatory. An ES can perform one or more than one of the following functions:

- Voltage transformations.
- Switching functions:
  - Switching transport and distribution circuits into and out of the power grid.
  - Connecting and disconnecting power plants to the power network.
  - Providing automatic disconnection of line segments experiencing faults.
- Measure of the electric power quality through measurement transformers.
- Provide protection against power grid faults and other unexpected events such as lightings.
- Coupling of the communications equipment.

The TSs are those premises located at the distribution stage that separate the MV from the LV level. From the TS, several feeders depart to the customer premises [22].

2.1. HIGH VOLTAGE LEVEL

The HV level comprises the power grid transport stage. The typical levels that can be found in such network are shown in Table 1 [22][4].

[4] Only HV Alternating Current (HVAC) levels are took into account