

Chapter 6

Benchmarking

In order to compare the multi-ring and multi-PON solutions described previously, we perform a dimensioning and benchmarking study in terms of cost/effectiveness.

In addition, any OPS-based solutions, when mature for commercial deployment, will naturally have to compete with SONET/SDH, and with other recent metro technologies such as Ethernet (IEEE 802.3) or Resilient Packet Rings (RPR, IEEE 802.17) [96]. Therefore, we do not restrict ourselves to detailing the multi-PON and multi-ring performance, but also compare them to non-OPS technologies. Results in the following sections received important inputs, in terms of traffic scenarios and of network architectures, by manufacturer and operator members of the DAVID project, which made available their internal confidential information to all partners.

Our contributions on this task deal with the resource dimensioning of multi-PON, multi-ring and RPR solutions. To complete the benchmarking environment, in this chapter we also include the contributions of the other partners which focus on defining the network scenario (network operator partners), dimensioning the passive multi-ring, SDH and Ethernet solutions and evaluating the CAPEX and OPEX costs (both tasks performed by the manufacturer partners). Therefore, the use of *we* in the following sections refers to all DAVID project partners.

6.1 Methodology and network scenario description

The methodology consisted of fixing an initial traffic matrix and applying it to the different network architectures. Through computer simulation and analytical models, we determine the resources required in each network architecture (number of transceivers, number of wavelengths, number of optical amplifiers, etc.) to have similar performance (packet loss rate, delay, jitter). Figure 6.1 schematically illustrates this methodology.

The study is restricted to a common network scenario with one Hub and 16 nodes distributed over a 100-km ring network. Four different node types are considered: 1 server node, 2 big nodes, 4 medium nodes, and 9 small nodes. We also considered three different mean traffic volumes: 20 Gbit/s (20G), 40 Gbit/s (40G) and 80 Gbit/s (80G). In addition we fixed the ratio between the up- and downstream traffic in the

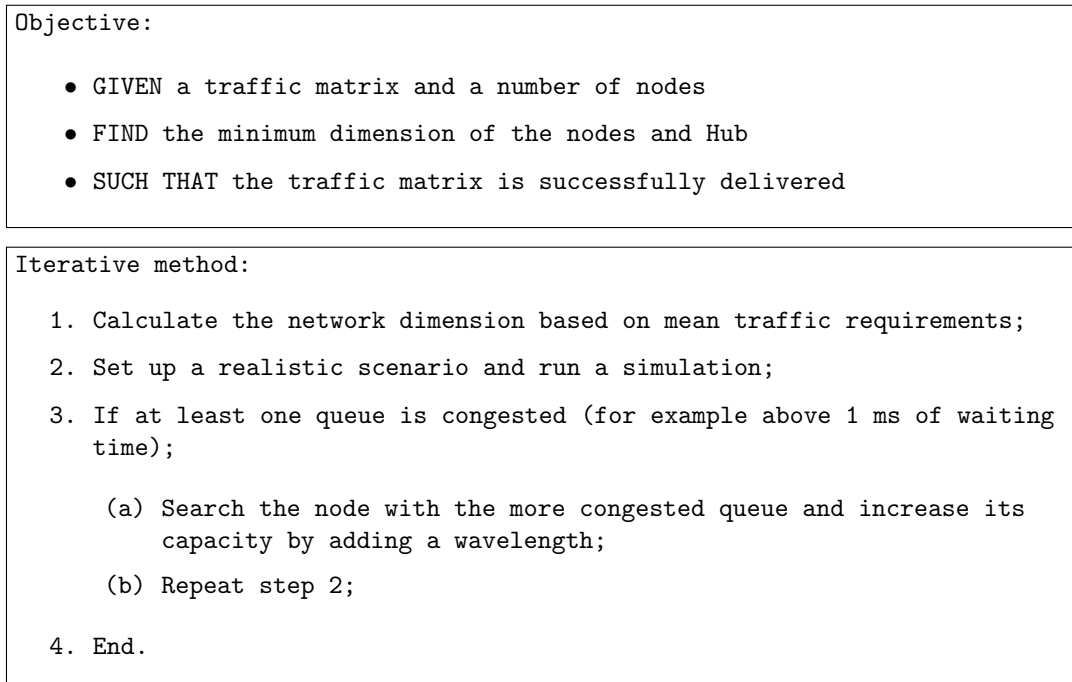


Figure 6.1: The network dimensioning methodology

Table 6.1: Node types and traffic assumptions

| Node type | Quantity | Upstream traffic | Downstream traffic |
|-----------|----------|------------------|--------------------|
| Server | 1 | 20.0% | 2.4% |
| Big | 2 | 3.2% | 8.4% |
| Medium | 4 | 1.6% | 4.8% |
| Small | 9 | 0.8% | 2.4% |
| Total | 16 | 40.0% | 60.0% |

network and the number of nodes per type on the ring. This is summarized in Table 6.1. Finally, we considered 55% of the total generated traffic coming from the backbone through the gateway, while 80% of the traffic generated at the nodes was destined to the gateway. The network characteristics considered in this study were chosen to reflect typical metro scenarios encountered by operators. The ring length of 100 km was chosen to be compatible with the node cascadeability constraints derived in [98], while the number of nodes was chosen to match the limiting size of SONET/SDH rings. The diversity in the node types and their respective traffic volumes are believed to be representative for mid term metro networks.

Two dimensioning studies have been considered. The first one regards the comparison between the multi-PON and the multi-ring architectures. The second one regards the comparison between the multi-ring architecture and the passive multi-ring architecture, SONET/SDH, Ethernet and RPR.

Table 6.2: Major components quantities for mean traffic for 80G scenario

| Device | multi-PON | multi-ring no space reuse | multi-ring |
|----------------------|-----------|------------------------------|------------|
| Fiber | 423 km | 400 km | 400 km |
| Multiplexer port | 1144 | 1456 | 1376 |
| 10 Gbit/s TxS | 160 | 160 | 144 |
| 10 Gbit/s RxS | 44 | 44 | 40 |
| Wavelength converter | 8 | 18 | 17 |

6.2 Multi-PON versus multi-ring

To perform this evaluation, we firstly analyze the optical hardware dimensioning based on mean traffic requirements for both multi-PON and multi-ring networks. For the latter, we also consider the possibility to remove the space reuse capability of the ring topology. Packet-level medium access control protocol simulations, using various scheduling algorithms are then run to compare component and network requirements under more realistic statistical traffic fluctuations, using a maximum packet delay criterion of 1000 time slots.

The scenario assumes 80 Gbit/s total traffic capacity to and from the 16 nodes of a metro network. All 16 nodes can be supported in a single PON, but must be partitioned into two 8-node rings. This is due to the power budget limitations of the active node structure studied in [98]. The Hub traffic goes via its own ring or PON to and from the core network. This means that the architectures comprises:

- 1 PON of 16 nodes + 1 PON for the connection to the core network;
- 2 rings of 8 nodes + 1 ring for the connection to the core network.

To minimize the complexity of this study, and to enable comparisons between multi-rings and multi-PON to be made analytically, the physical topology of the metro network is taken to be a circle of radius R km, with all nodes plus the Hub switch equally spaced around it. Such a perfect structure is certainly not normal, but it is no more unique nor less meaningful for comparing multi-ring and multi-PON than any other arbitrary, real-life node distribution.

The quantities of the most costly components are summarized in Table 6.2 for PONs using frame-based scheduling and for multi-ring with and without space reuse, including the PON and ring connections to the core network.

Traffic-dependent component quantities are calculated from the mean values of the traffic matrix in table 6.1. Because all TxS/RxS are assumed to be 10 Gbit/s, this therefore requires 3 wavelength channels from the hub. The total downstream traffic from Hub to node PON is 48.0 Gbit/s (Table 6.1), requiring 5 channels. So 8 channels are needed downstream from the Hub in total, hence requiring 8 wavelength converters. The numbers of TxS and RxS needed by each node are similarly derived

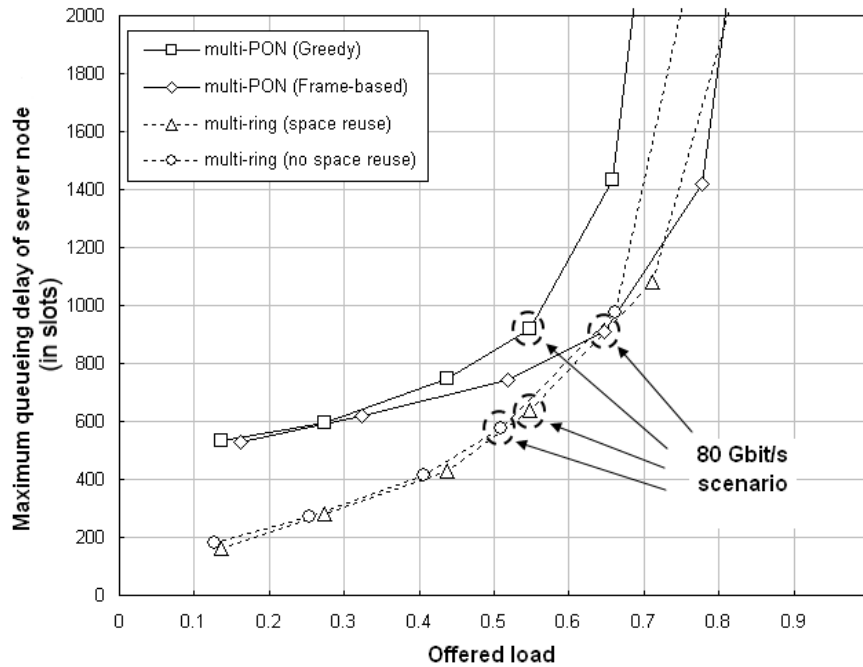


Figure 6.2: The considered switch architecture

from the Tx and Rx capacities per node. The numbers of Tx's and Rx's needed for the core connection are derived from the total capacities to and from the Hub.

For multi-ring more wavelength converters are required partly because the traffic is fragmented between two 8-node rings but mainly because 3R regeneration/wavelength conversion are needed at the Hub input as well as the output. Spatial reuse provides modest component savings. The major component savings between multi-PON and multi-ring are in wavelength multiplexers.

The packet scheduling simulations begin with the component resources that would be installed to support the mean traffic capacities. But packet delays caused by self-similar traffic sources and matching algorithm inefficiencies, which particularly affect the server node, require more resources (channels, Tx's and Rx's) to be added, in discrete increments, until a maximum queueing delay below 1000 time slots is obtained. Figure 6.2 shows the maximum delay vs. offered load curves (i.e. delay vs. traffic capacity) for the 4 resulting multi-PON and multi-ring networks, each now requiring different installed capacities. The loads corresponding to the 80 Gbit/s scenario are ringed. These are the only points for which each network supports precisely 80 Gbit/s mean traffic with minimum resources to guarantee less than 1,000 slot maximum delay. Multi-PON with frame-based scheduling (and a Hub with slot-by-slot switching between channels) require the smallest of the 4 network capacities and hence achieve the highest load for the allowable 1000 slot queueing delay. 11 downstream channels and hence converters are needed in total, instead of 8, which increases the network capacity to 110 Gbit/s. Multi-ring and PONs using a greedy scheduling algorithm all require greater network capacity, and hence provide lower loads, than multi-PON using frame-based scheduling.

The results indicate that the multi-PON solution can provide cost reduction over multi-ring. This is mainly due to the partitioning of the nodes into two 8-node rings. New physical layer simulations carried out in [42] indicate that, using the components and system parameters measured in the corresponding subsystems of the DAVID demonstrator, 16 nodes can be cascaded in a single ring. In this eventuality, the multi-ring approach seems comparable or superior than multi-PON.

6.3 Multi-ring versus passive multi-ring, SDH, Ethernet, and RPR

6.3.1 Benchmarked solutions

To compare the multi-ring approaches (both passive and active node structure, PMR and MR acronyms respectively) with the classical Ethernet, RPR and SDH approaches, the node structures shown in Figure 6.3 are adopted. For the Ethernet solution (Figure 6.3a), we considered a star topology where each access node was connected directly to a central Hub through an unshared point-to-point fiber connection (doubled for protection). For both the SDH (Figure 6.3b) and RPR (Figure 6.3c) cases, we considered an opaque structure: optical Multiplexers (MUX) and Demultiplexers (DMUX) filter the optical channels which correspond to parallel rings terminated at each node. In the SDH approach, a single Cross-Connect (XC, switching at the STM-1 or STM-4 granularity) allows to connect to multiple rings as well as to provide add/drop access. The Hub in this case also is an SDH Cross-Connect (again switching at the STM-1 or STM-4 granularity) terminating/generating all wavelengths of the rings and of the gateway. To achieve protection capability, this structure is doubled. By nature, RPR relies on a single physical ring topology. To provide access to multiple wavelengths, multiple RPR chips are provided. Interconnection between the various RPR rings is achieved through an IP/MPLS Router, which also provides add/drop access to each of the thus stacked wavelength-rings. At the Hub, RPR interfaces are needed for all wavelengths and for connecting the gateway. The RPR architecture inherently has protection capabilities, since each physical ring is in fact composed of two counter-rotating rings. All node architectures include DABs to aggregate the data traffic coming from/going to the client layer.

6.3.2 Resource dimensioning

Taking into account the functionality and limitations of each network architecture, we performed benchmarking studies dimensioning the capacity required in each node and at the Hub to obtain similar performance. For this study we did not include any consideration of protection.

In Figure 6.4, we show the node capacity (in Gbit/s) required in each metro solution considering the three traffic volumes, while Table 6.3 illustrates the needs in terms of transport resources: fibers (including the connection between the Hub and

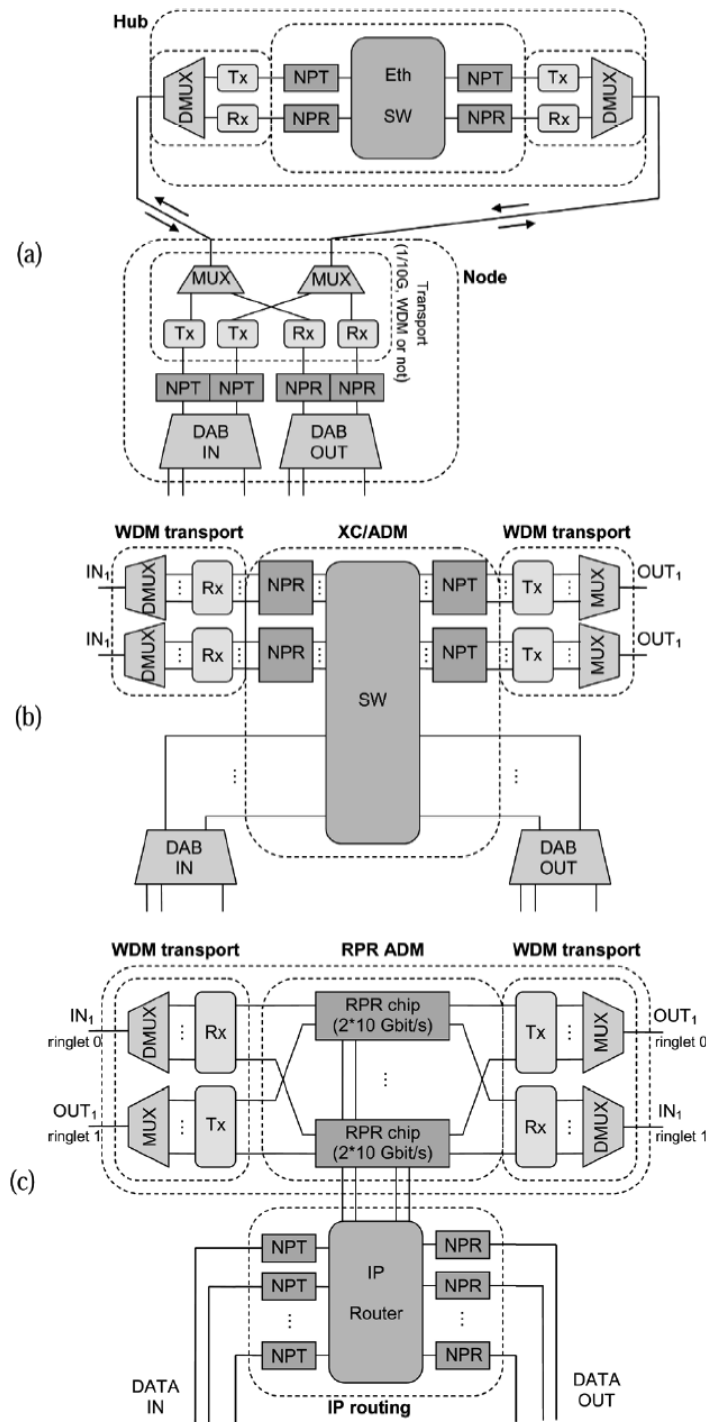


Figure 6.3: Node structures. (DMUX: wavelength demultiplexer; MUX: wavelength multiplexer; NPR: network processing receiver; NPT: network processing transmitter; SW: STM-1/STM-4 switch; Eth SW: Ethernet switch; XC: cross-connect; DAB: data aggregation board. a) Point-to-point Ethernet Hub + Node. b) SDH node. c) RPR node.

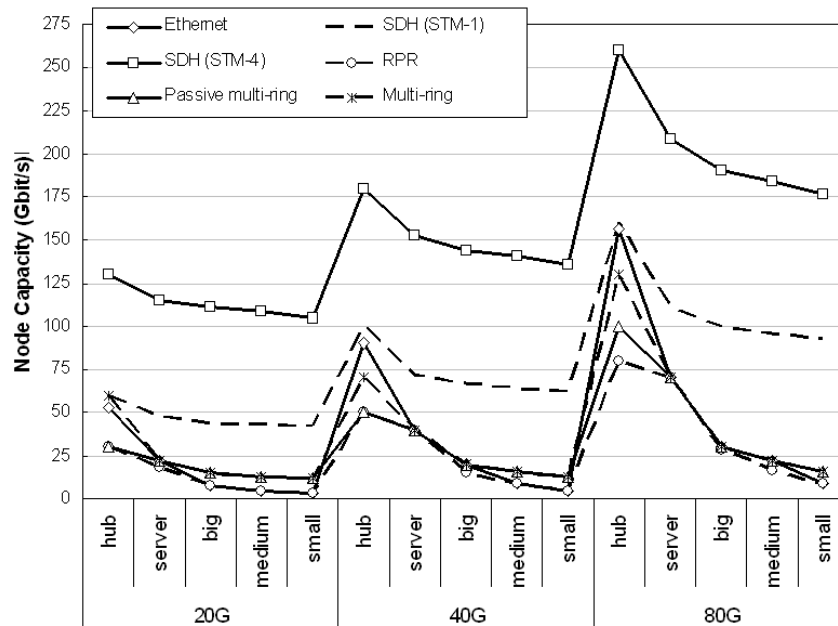


Figure 6.4: Node capacity (in Gbit/s) required in the different network architectures for the three traffic volumes

the gateway), wavelengths (either 1 Gbit/s or 10 Gbit/s channels), and transceivers (either 1 Gbit/s or 10 Gbit/s TRx).

Figure 6.4 offers important results concerning the required resources as well as the scalability of the architecture when the traffic increases. In the SDH case, the major part of the node size is used for transit traffic (hence the smaller relative differences in required capacity between node types) which causes over-dimensioning. This stems from the fact that at least one circuit must be established between each source-destination pair in the network. This effect can be considerably reduced by using SDH circuits just between nodes and the Hub in a star topology rather adopting the ring-approach. In contrast, for the active multi-ring architecture, the required node capacity is nearly optimal thanks to the flexible design and the optical by-pass capability. Nonetheless, the waveband concept (which avoids the need of a full 32-wavelength selector in each ring node) imposes an over-dimensioning of the Hub. The packet-based passive multi-ring, RPR and Ethernet solutions are very similar in terms of dimensioning. Ethernet has a slight gain in nodes due to the possibility to use low bit rate interfaces, but a drawback at the Hub due to the non-shared transport resources and the star topology. For instance, it requires 44 fibers for the 40G scenario. From Figure 6.4, the RPR solution seems the better one since all nodes, as well as the Hub require less capacity with respect to the other solutions. Nevertheless, the opaque structure of the RPR forces a high number of transceivers as show in Table 6.3.

Table 6.3: Transport resources required in the different architectures

| | Device | Ethernet | SDH (STM-1) | SDH (STM-4) | RPR | PMR | MR |
|-----|-------------|----------|----------------|----------------|-----|-----|----|
| 20G | Fiber | 31 | 2 | 2 | 3 | 2 | 2 |
| | 1G channel | 46 | 0 | 0 | 0 | 0 | 0 |
| | 10G channel | 6 | 6 | 13 | 3 | 6 | 6 |
| | 1G TRx | 46 | 0 | 0 | 0 | 0 | 0 |
| | 10G TRx | 6 | 72 | 176 | 21 | 24 | 33 |
| 40G | Fiber | 44 | 2 | 2 | 3 | 2 | 2 |
| | 1G channel | 60 | 0 | 0 | 0 | 0 | 0 |
| | 10G channel | 12 | 10 | 18 | 5 | 10 | 7 |
| | 1G TRx | 60 | 0 | 0 | 0 | 0 | 0 |
| | 10G TRx | 12 | 110 | 231 | 40 | 29 | 36 |
| 80G | Fiber | 72 | 2 | 2 | 3 | 2 | 2 |
| | 1G channel | 64 | 0 | 0 | 0 | 0 | 0 |
| | 10G channel | 26 | 16 | 26 | 8 | 19 | 13 |
| | 1G TRx | 54 | 0 | 0 | 0 | 0 | 0 |
| | 10G TRx | 26 | 167 | 307 | 61 | 41 | 50 |

Table 6.4: Example of CAPEX analysis: cost relative to the passive multi-ring

| Device | Ethernet | SDH (STM-1) | SDH (STM-4) | RPR | PMR | MR |
|--------|----------|----------------|----------------|------|-----|------|
| 20G | -15% | +10% | +135% | -28% | 0% | +58% |
| 40G | +14% | +38% | +167% | -13% | 0% | +50% |
| 80G | +23% | +65% | +189% | +19% | 0% | +45% |

6.4 Example of CAPEX analysis

An extensive CAPEX analysis based on the resource requirements highlighted in the dimensioning studies of each architecture is performed within the DAVID project based on component costs obtained by confidential means and market survey. Since the results provided here are not part of our contribution, we only show an example of the CAPEX analysis (Table 6.4).

The costs are counted relative to the CAPEX for the passive multi-ring (PMR) architecture. RPR is the cheapest solution only for the initial capacity: when increasing network capacity, the optical transparency provided by the passive optical architecture enables to obtain lower CAPEX. Indeed, the PMR solution is quite competitive even for low traffic volumes, being the second cheapest solution behind RPR for the 40G traffic scenario and the cheapest solution for the 80G traffic scenario. The Ethernet and SDH solutions are in most cases not highly competitive, in both cases due to the non-sharing of resources.

The active multi-ring solution pays, with the initial assumptions (limited capacity), for the complexity of the nodes. In addition, the traffic matrix with a high proportion of extra-ring traffic (80%) is clearly a disadvantage for the active multi-ring solution which can not strongly exploit the optical space re-use mechanism.

It is important to note that the limited capacity penalizes the use of an optical Hub for both passive and active multi-ring networks. An architecture similar to the passive multi-ring solution but using an Ethernet switch at the Hub (like DBORN [73]) can be more appropriate for a first introduction of optical packets in metro networks.

Extending the initial traffic matrices up to 1Tbit/s scenarios (with 160G or 320G on 4 or 2 rings, where each ring should be further doubled for protection), the passive multi-ring shows the best CAPEX value. On the other hand, implementing correcting factors to the initial component cost assumptions to take into account some optics cost reduction (foreseen at production of higher volumes for optical components), the active multi-ring solution becomes an interesting solution [42].

6.5 Example of OPEX analysis

As for the CAPEX analysis, here we also show an example of the OPEX analysis based on the resource dimensioning requirements.

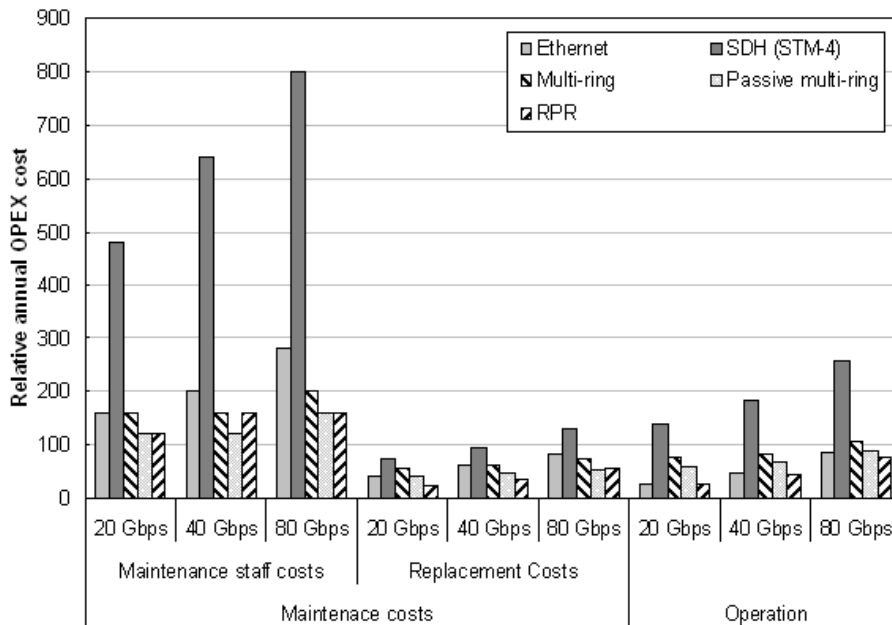


Figure 6.5: Example of OPEX analysis: relative annual OPEX cost comparison in the different network architecture for the three traffic volumes

A common model where annual costs have been calculated as a percentage of the equipment costs is adopted to calculate the OPEX values. OPEX includes various operational costs, ranging from administrative costs, over service development, to network planning costs etc. The comparison is limited to costs related to network operations and maintenance mainly because other cost factors are most likely to not significantly differ between the various architectures.

The maintenance costs have been defined as all the costs related to the resolution of physical problems in the network such as fiber cuts or equipment failure. It can be calculated as the sum of replacement costs and the maintenance staff costs. The first part encompasses the cost of failed network elements and is proportional to its failure probability, while the second includes labour costs and obviously depend on the required amount of personnel. The operational costs include all the recurrent costs which are periodically necessary for undisturbed operation.

OPEX results for the different network architectures are depicted in Figure 6.5. The cost specific values are expressed as relative to the cost of 1 fibre.km

The OPEX costs for the SDH ring are considerably larger than for the other scenarios, since it includes many more network elements, most of them electronics. RPR on the other hand, being the option with the fewest number of network elements, presents the lowest OPEX costs. Yet it is closely followed by the passive multi-ring, Ethernet and active multi-ring solutions.

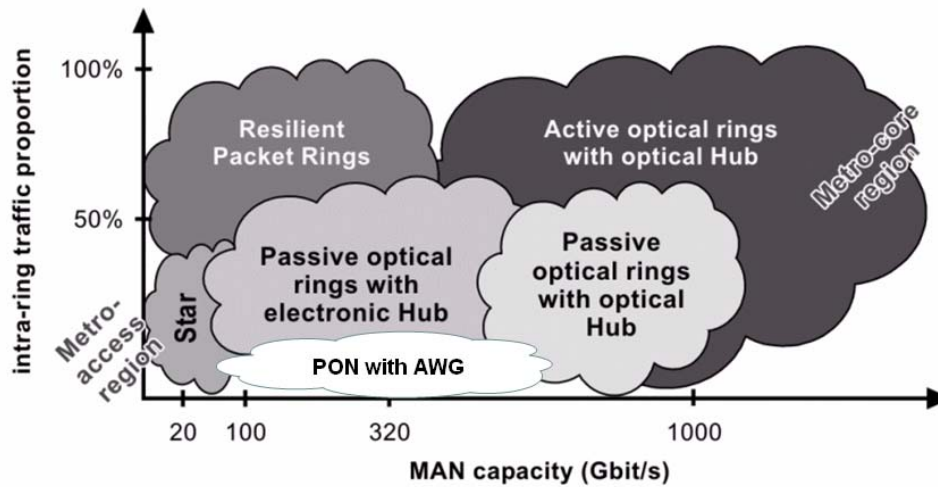


Figure 6.6: Possible introduction scenario of the different metro technologies

6.6 Conclusions and perspective

From the extensive benchmarking results -whose results have been summarized above- and despite all uncertainties of market analyzes and forecasts, we can foresee a possible introduction scenario of the different metro technologies with respect to the required capacity and the traffic repartition. Figure 6.6 depicts this scenario, whose tendencies could be summarized as follows:

- With low capacity (few tens of Gbit/s), two advantageous solutions can be identified: the star Ethernet (possibly with WDM to share fibre resources) when the ratio of intra-ring traffic is low, whereas RPR appears the most optimized solution thanks to space re-use capability.
- At a short/medium term with increasing access bit rate and resulting metro capacity in the range of tens to few hundreds of Gbit/s, passive optical ring structure with an electrical Hub is well suited, as in the DBORN architecture proposed by Alcatel [73]. Due to the lack of transparency, RPR requires a high amount of transceivers and filtering ports on the ring which makes the solution less competitive. The multi-PON architecture seems a good alternatives when large amount of information is changed between different PONs (i.e., modest intra-ring traffic).
- At a longer term, under the assumption of a strong introduction of high bit rate access networks (FTTx, GPONs), the capacity in the metro can reach hundreds of Gbit/s to 1 Tbit/s. In this case, the two DAVID solutions become competitive, thanks to the optical transparency both at the node and Hub levels.

