# Techno-economic studies of telecommunication networks

## Habilitationsschrift

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# Contents

# Abstract

End-users demand for more bandwidth, higher reliability, access anywhere and any time, which is forcing operators to upgrade their networks faster. On the other hand, the number of players in the telecom arena is increasing. From the single player existing in the 90's, the telecom arena contains now a plethora of players with differing domains, areas, targeted customers, service portfolio, etc. Hence, operators nowadays are facing a stronger market competition, which impact their number of customers, expected revenues, etc.

This new market scenario encourages operators to keep their service portfolio up-to-date as well as to upgrade their network to cope with all the new services, users, requirements, etc. Since both, competition and regulation limit the revenues of the offered services, the best way for operators to keep their benefits is to reduce their costs. For that purpose, Techno-Economic (TE) analyses are required.

TE analysis of communications networks is a rather young research area. This work helps to provide the basis for such studies contributing with new cost models, TE frameworks for migration and protection, as well as extending metrics for TE assessment. TE anal-

ysis embraces several *aspects* such as modelling, dimensioning and evaluation. This work presents for the first time, an overall and generic methodology for TE analysis, which is then adapted to different studies and at the end, it is applied to particular case studies.

TE analysis is supported by two main pillars: technology and economics. The first one holds the knowledge of telecommunication networks: technologies, implementation issues, limitations and allows proposing new solutions to overcome them. In this work, new contributions are proposed to e.g., reduce migration costs, increase the connection availability, and reduce the energy consumption of access networks. The second pillar provides the knowledge on economic metrics and models (e.g., cost models). This work applies different models to more complex operational expenditures as well as to the Total Cost of Ownership (TCO) evaluation. This work also provides a complete set of measures to consistently compare different protection schemes.

Most of the work focuses on access networks (together with aggregation networks in case of node consolidation). These networks are actually the bottleneck of the bandwidth delivery chain towards the user. The first contribution in this work develops a methodology to evaluate the cost of different Next Generation Optical Access networks in any type of area. This methodology allows comparing different solutions for various scenarios (with and without node consolidation, greenfield vs. brownfield scenarios, different user densities, etc.). Since most of the existing operators deploy optical networks at some point (Fiber To The x (FTTx)), this initial framework is further extended to evaluate and compare different migration strategies towards solutions offering at least 300 Mbps per user as expected in 2020. The proposed framework allows to identify the best migration time, duration, expected costs, etc. Triggered by the new access requirements regarding connection availability, the framework is also applied to protection schemes. The new framework enables to consider different protection schemes and compare other metrics than cost (e.g., connection availability, failure impact factor).

Access networks aim at interconnecting the central office to end points of the same type and requirements. In this way, operators have to run various access networks simultaneously (one for each types of end points): an access network for residential users, another one to interconnect Base Stations, etc. However, new optical architectures (e.g., Hybrid Passive Optical Network as an extension of NG-PON2 [1]) allows coping with an heterogeneous combination of end points (e.g., residential users, business users, Macro Base Stations, Small Cells). These networks, referred as converged access networks simplify the complexity of having several operational networks.

The fact that converged access networks support different end points implies also an increase of connection availability requirements as for example, required by Macro Base Stations or business users. Despite the reluctance of operators to invest on access network protection, this work proposes different schemes that with limited increase of cost achieve at least one 9 more on connection availability. This work contributes also with new protection schemes which have been compared in different areas using several proposed metrics. Moreover, access networks have been identified as the most consuming network segment [2]. The proposed protection schemes have been modified so that they are compatible with energy saving schemes in order to find a compromise between connection availability and low energy consumption.

In addition to access networks, which constitute the main part of this study, core networks are also addressed in this work from different perspectives: (i) as optical core networks that will run out of capacity and will need a network capacity extension ; (ii) as failure reparation has been identified as a main operational cost, how operators can reduce this cost; (iii) Software Defined Networking (SDN) and Network Function Virtualization (NFV) planning taking costs into account.

The methodologies proposed for the TE analysis of new solution evaluation, network migration and comparison of different solutions can be directly applied to new studies or easily adapted to other domains as for example network virtualization.

# Abbreviations

| | | |
|---|---|---|
| **A** | A/C | Air Conditioning |
| | ADSL | Asymmetric Digital Subscriber Line |
| | AM | Automotive Manufacturer |
| | AON | Active Optical Network |
| | ARPU | Average Revenue per User |
| | AWG | Array Waveguide Grating |
| **C** | CAPEX | Capital Expenditures |
| | CO | Central Office |
| | CPP | Controller Placement Problem |
| | CU | Cost Units |
| **D** | DF | Distribution Fiber |
| | DU | Dense Urban area |

| | | |
|---|---|---|
| **F** | FIT | Failures in Time |
| | FF | Feeder Fiber |
| | FSAN | Full Service Access Network |
| | FTTB | Fiber To The Building |
| | FTTH | Fiber To The Home |
| | FTTO | Fiber To The Office |
| **G** | GPON | Gigabit Passive Optical Network |
| **H** | HPON | Hybrid Passive Optical Network |
| **I** | IMPEX | Implementation Expenditures |
| | ITS | Intelligent Transport Systems |
| | ITU | International Telecommunication Union |
| | IRR | Internal Rate of Return |
| **L** | LLUB | Local Loop Unbundling |
| | LMF | Last Mile Fiber |
| | LOS | Loss of Signal |
| | LT | Line Terminal |
| | LTE | Long Term Evolution |
| **M** | MBS | Macro Base Station |
| | MCO | Main Central Office |
| | MNO | Mobile Network Operator |
| | MTTF | Mean Time To Fail |
| | MTTR | Mean Time To Repair |
| | MVNO | Mobile Virtual Network Operator |
| **N** | NFV | Network Function Virtualization |
| | NGOA | Next Generation Optical Access |
| | NG-PON | Next Generation Passive Optical Networks |
| | NPV | Net Present Value |
| | NO | Network Operator |

| | | |
|---|---|---|
| **O** | OLT | Optical Line Terminal |
| | ONU | Optical Network Unit |
| | OPEX | Operational Expenditures |
| | OSW | Optical Switch |
| **P** | P2P | Point to Point |
| | PIP | Physical Infrastructure Provider |
| | PON | Passive Optical Network |
| | PS | Power Splitter |
| | PV | Present Value |
| **Q** | QoS | Quality of Service |
| **R** | RfP | Request for Proposal |
| | RfQ | Request for Quotation |
| | RN | Remote Node |
| | ROI | Return Of Investment |
| **S** | SDN | Software Defined Networking |
| | SLA | Service Level Agreement |
| | SP | Service Provider |
| **T** | TCO | Total Cost of Ownership |
| | TDM | Time Division Multiplexing |
| | TE | Techno-Economics |
| | TRX | Transmitter |
| | TWDM | Time and Wavelength Division Multiplexing |
| **W** | WDM | Wavelength Division Multiplexing |

# Chapter 1

# Introduction

Operators are facing continuously the option to upgrade, expand, migrate and tear down their networks driven by the never-ending increase of terminals and offered services. The recent competitive telecommunication arena together with the important role of regulators, keeps the expected revenues limited. Hence, operators are carefully evaluating their costs in order to keep as much benefits as possible.

## 1.1 Background and motivation

Techno-economic analysis aims at providing an economic evaluation of a new solution (e.g., network architecture, protection scheme) based on process modelling and engineering design. Examples of questions to be answered are:

- Which technology should the operator use in this scenario?
- From which provider should I get my equipment?
- Which network process is the most costly?
- How can the operational costs be reduced?

- When should the network be upgraded/migrated?

In the same way that accounting is based on already expended resources, techno-economic analysis is based on expected expenses, which are mostly based on estimations: e.g., increase of cost (salaries, power cost, renting, leasing), cost of new components, forecasting increase of demands/users/services. Therefore, several analysis such as sensitivity and risk analysis should be also performed.

Techno-economic analysis has been applied to several disciplines: renewable energy [3, 4, 5], smart grids [6, 7], electrical vehicles [8, 9], etc. In this work, we propose a generic methodology to perform techno-economic evaluation of different telecommunication networks. On one side we look into next generation access networks able to cope with the required increase of bandwidth as well as protection schemes able to increase the connection availability while finding the lowest cost solution. We also look into core networks where optical networks may require dynamic nodes to offer a flexible increase of capacity. The proposed methodology, which initially aims at evaluating new network solutions, is also extended to evaluate and compare different migration scenarios and protection schemes.

Moreover, this work also proposes new fiber layout as well as new migration and protection schemes to reduce costs. These schemes are considered as case studies in the published papers as summarized in Chapter 3. In the following, we refer to our most relevant published journal and conference papers, which are the basis for this thesis, as **Jxx** and **Cxx**, respectively. For the complete list please see Section 1.3.

### 1.1.1 Access Networks

Optical access network technologies are being revised and extended continuously towards next generation solutions. Major standardization organizations and their members are working on the next generation or even the generation after the next generation of optical access (NGOA) network technologies. For example, the Full Service Access Network (FSAN) group [10] has detailed the next generation of the Gigabit Passive Optical Network (GPON), referred to as NG-PON1 [11], and is currently investigating the generation after the next generation, referred to as NG-PON2 [1]. However, the specification of a new technology generation that is the most cost efficient for a certain service area is still difficult since it should be compliant with the requirements given by the operators (in terms of service, network, business, and operational aspects), which are complicated to assess, especially the ones with strong time dependency. Overall, this could significantly impact operators in several ways. Hence, a generic methodology is required and has been proposed in this work, so that operators can find the best migration strategy compliant with their own requirements.

In addition, a new trend for network design (e.g., longer transmission distances that allow operators to serve larger areas with more users by reducing the number of central offices (COs), the so-called concept of node consolidation [12]) makes operators face increased complexity from the relationship between infrastructure and technology. A certain technology might be an excellent solution for a certain point in time in Greenfield, but might limit the ability to gradually migrate to the proper next generation approach from the current deployed infrastructure and technology. This optimization problem—network migration over time—demands a technical as well as economic analysis.

A number of techno-economic studies have been performed on different types of optical access networks in order to estimate the required investments. Initial studies considered Greenfield scenarios and evaluated capital expenditures (CAPEX) to install and start operating a network [13, 14]. However, these studies disregarded operational expenditures (OPEX), such as service provisioning and failure management, which have the same importance as CAPEX, as proved in [15]. Furthermore, most operators are already operating access networks, and, hence, techno-economic studies should consider not only Greenfield scenarios but also Brownfield scenarios. Some studies have addressed the operation situation covering both CAPEX and OPEX aspects for time-division multiplexing passive optical networks (TDM PONs) [16, 17] and next generation optical access (NGOA) networks [18]. However, study of the migration process and the cost involved had been basically addressed. In [19] a time-step migration planning from a Greenfield or asymmetric digital subscriber line (ADSL) network toward a traditional GPON or active optical network (AON) was presented, but this model still lacks consideration of NGOA as well as the different roles of providers. In [20] a migration cost evaluation of core networks was solved using meta heuristics, but it does not include the intricacies of economic modelling. In [21], different options that cable operators have in the migration of their networks were presented. It is a comprehensive methodology in understanding the basic principles of the cable network market with an in-depth analysis of existing players, technology deployments, and demand in terms of existing take rate. Several migration paths from/toward different technology options have been analyzed, but they lack a long-term perspective for fiber and backhaul technologies (e.g., the NG-PON2 strategy [1]) and overall cost analysis (e.g., covering both OPEX and CAPEX). For that purpose, using our proposed methodology, we compare different Next Generation Optical Access Technologies taking into account greenfield and brownfield scenarios in different types of areas, which has been summarized in our Paper **J6**. Furthermore, possible migration options for brownfield scenarios have been proposed and compared based on the existing architecture: **J9, J7** for passive optical networks such as GPON and **J3, J1** for active optical networks.

Access networks have been the last segment of the network to be considered to be protected due to the lower impact of failures compared to core and aggregation networks. It is shown that fiber access networks without any protection are characterized by poor reliability performance [22]. This fact has been realized already in late 90's and the standard PON protection architectures have been defined by ITU-T [23] around two decades ago. These standard PON protection schemes are referred to as Type A, B, C and D. In Type A only the Feeder Fiber (FF) is redundant. Type B protection duplicates the shared part of the PON, i.e., FF and optical interfaces (i.e., PON LT) at the Optical Line Terminal (OLT). In Type B the primary optical interface at OLT is normally working while the second one is used as a cold standby. Type C represents 1+1 dedicated end-to-end path protection with full duplication of the PON resources. In Type C both the primary and secondary interfaces are normally working (hot standby), which allows very fast recovery time. Type D protection specifies the independent duplication of Feeder and Distribution fibers and thus, it enables network provider to offer differentiated reliability level for the users. It is obvious that adding redundant components and systems can improve network reliability performance, but it may not be a practical solution for the cost sensitive access networks. Therefore, both system deployment cost (related to CAPEX) and network management cost (related to OPEX) should be minimized. For instance, some protection schemes, e.g., [24, 25], try to maximize the sharing rate of the existing infrastructure by using duct/cable for the working fibers in the other PONs as part of the protection path. Meanwhile, several schemes, e.g., [26, 27], utilize wireless solutions which have much lower deployment cost to offer protection links for feeder and/or distribution segments. This work proposes a set of metrics to compare different protection schemes (existing and new proposed ones as in **J11** and **J12**) as shown in papers **J8, J5**.

Some of the previous protection schemes can be applied to hybrid TDM/WDM PONs, which is an architecture for Hybrid Passive Optical Converged Access Networks. However, currently proposed protection architectures [28, 29], assume the use of Loss-of-Signal (LOS) of upstream transmissions from ONUs to indicate equipment/fiber failure. Using LOS at the Main Central Office (MCO) may potentially be unsuitable in networks that implement sleep/doze mode operation. As the access segment was shown to be the dominant contributor to the overall power consumption of optical networks [2], power-saving operations have been introduced in access networks to reduce the power consumption of the ONUs [30]. During idle periods where no upstream data needs to be transmitted, sleep/doze capable transceivers at the end node can be powered down. If the LOS of upstream transmissions is used at the MCO to detect faults, erroneous triggering of false LOS alarm and subsequently erroneous protection switching will occur during these idle transmission. So new protection schemes compatible with energy saving approaches have been proposed and evaluated in **J4** and **J2**.

### 1.1.2 Core networks

Currently, most transport wavelength-division multiplexing (WDM) networks operate statically (i.e., lightpaths are established semi-permanently). Although the high capacity of these lightpaths is underutilized (10–25 percent [31]), the ever increasing Internet traffic (annual growing rates of 35–50 percent [31]) and the emerging worldwide deployment of fiber to the x (FTTx) and 5G networks can mean that such high capacity might not be enough to meet the quality of service requirements of massive multimedia applications. Most of the proposed network upgrades or migration, have analyzed the cost without taking into account that during a migration process some network components can be reutilized by the new network solution. Additionally, most works have focused on either CAPEX (not the increase of CAPEX with respect the existing solution) or OPEX, but not both simultaneously. The authors in [32] quantified the number of wavelengths required in static and dynamic networks. Results showed a lower wavelength requirement from dynamic operation, but only at low traffic loads or if wavelength conversion is provided. The authors in [33] evaluate the CAPEX of a static WDM network for transparent and opaque nodes. Transparent networks were shown to require lower CAPEX than opaque ones. However, OPEX and migration analysis were still not considered. OPEX was initially considered in [34, 35] showing again significant savings of transparent networks. In **J10**, CAPEX and OPEX are compared for static and dynamic optical networks aiming at upgrading their capacity for the first time.

### 1.1.3 Virtualization

The term of virtualization is being used in a wide spectrum of areas from software, devices, resources and even operators. In this work two aspects of virtualization have been considered:

### Virtual operators

With the introduction of virtualization, the business models of operators have become more complex. The first telecom operators were providing specific services (initially radio, voice and television) by installing any required infrastructure at the national level (e.g., Deutsche Telecom in Germany, Telefonica in Spain). These operators were covering all aspects from physical infrastructure, network equipment, service providing, etc. and hence, they are usually referred as integrated operators [36]. With the evolution of services (e.g., video conferencing, video and music streaming, 3D television, e-health) and technologies, the telecom scenario has drastically changed: from analog to digital transmission, from customers receiving content to also producing them, from single/dedicated service network to converged networks. This evolution has encouraged a migration from integrated operators to dedicated operators with different business objectives, as depicted in Figure 1.1. For example, there can be a Physical Network Operator (NO) giving access to their physical infrastructure to a Communication Operator, who at the same time gives access to different Service providers (SP) [36, 37].

Virtualization has increased the flexibility of business models even more by increasing net-

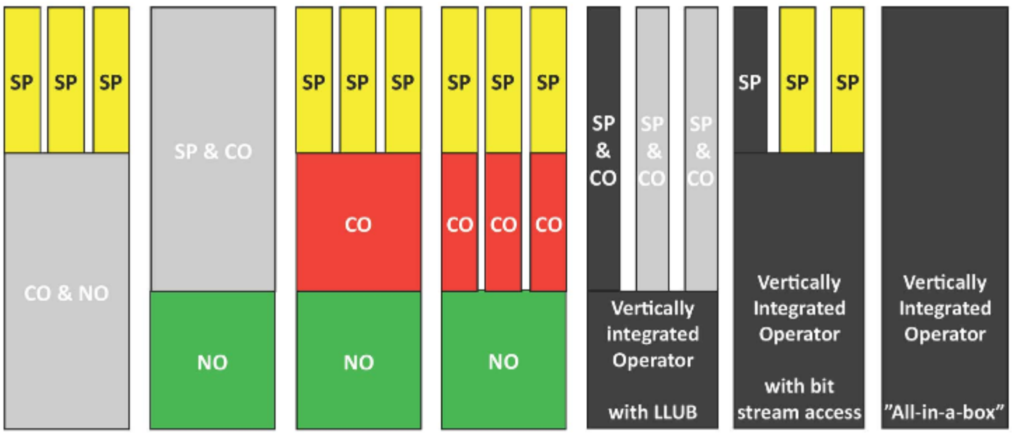


Figure 1.1: Overview of different business models considering Network Operators (NO), Communication Operators (CO), Service Providers (SP). LLUB stands for local loop unbundling as possibility to give access to the physical infrastructure.

work flexibility, resource differentiation and the support of open source. Hence, nowadays there are Virtual Network Operators which are able to provide management services and resell network services from other SPs without owning any telecommunication infrastructure. This is particularly interesting from new communication players aiming to get into the game without requiring an initial significant investment. Due to the high expenditures associated to the implementation of Radio Access Networks, special interest has been focused on Mobile Virtual Network Operators (MVNO) [38]. Previous research in the MVNO area has investigated MVNO classifications, e.g., according to network components owned [38] or business strategies [39]. Existing work has also tackled generic MVNO challenges, e.g., measuring MVNO performance depending on the host-Mobile Network Operator (MNO) in real deployments [40]. The authors in [40] identify ten MVNO problems and suggests a solution through acquiring certain network components. However, the common assumption was that all the MVNOs target the same market, i.e., Human-to-Human communications, and thus have the same requirements as existing MNOs. For the automotive case, the requirements are different. For example, the cars have much longer lifetimes compared to mobile phones. Hence, the technology investments made by the Automotive Manufacturers (AMs) and the dependencies on the host-MNO have a long-term impact. The urgent need for long-term solutions and thus independency make the AM consider entering the telecommunication market.

The research in automotive communications focuses on choosing the appropriate technology for the manifold of automotive services with very different requirements under the constraint of very high mobility, e.g., [41]. Although the state-of-the-art vehicular technology is considered to be 802.11p, its poor scalability, limited radio range and QoS issues have leveraged LTE as prospective technology for supporting vehicular communication [42]. A common assumption in automotive communication research is that the connectivity is ubiquitous and through a dedicated network, where the Quality of Service (QoS) is determined by the AMs. In reality, unfortunately it is not so.

We have taken a first step towards identifying the automotive requirements and the challenges of different MVNO solutions **C15**. The current work provides a deeper insight into the technological aspects of the LTE-based automotive MVNOs. Furthermore, we have looked into a long-term investment plan aiming at achieving the total independency. Thus the AMs can be sure that, if they implement a solution based on some specific feature of a specific technology, this feature will be available for as long as they need it.

### Software Defined Networking and Network Function Virtualization

Two new paradigms have been recently proposed to increase network flexibility and efficiency: Software Defined Networking and Network Function Virtualization.

- Software Defined Networking (SDN) proposes the separation of control and data plane so that common forwarding components can be used and logically centralized controlled by an SDN controller. The SDN controller has a global view of the network and based on the current state of the network in terms of e.g., link utilization, is able to make better routing decisions [43]. In this way, SDN enables more efficient network control and management. In paper **C2** we give an overview of existing approaches to increase the reliability of SDN networks in data and control plane.

  Since most of the approaches to provide data plane reliability can be also applied to SDN, our interest focuses on the reliability increase of the control plane. High availability and low control plane latency are necessary to guarantee the data plane performance, which is especially important for mission critical applications [44].

  Deciding where to place the controllers in a network is known as Controller Placement Problem (CPP). Heller et al. analysed in [45] the impact of the controller placement on the average and worst case latencies of the control plane. Apart from control plane latency, other metrics have been defined, e.g., latency in case of a failure, inter-controller latency and load balancing between the controllers [46]. Several authors developed efficient heuristic algorithms to find Pareto optimal solutions for different combinations of control plane performance metrics [47, 48]. Resilience aspects of the control plane have been studied extensively. Joint optimization of control plane latency and reliability was studied in [49, 50], the impact of the controller placement on the fault tolerance of the control plane was analysed in [51], while [52] also provides an optimal list of backup controllers.

However, since none of the proposed papers considers planning of the protection control paths in advance, we propose in **C3** two alternatives to increase the control plane reliability:

- Disjoint Control Paths (RCP-DCP): Every node must be connected to its assigned controller over two disjoint paths.
- Different Controller Replicas (RCP-DCR): Every node must be connected to two different controllers over two disjoint paths.

The proposed schemes are able to increase significantly the control plane reliability while adding very limited overhead ot the average control path length.

- Network Function Virtualization (NFV) applies the concept of virtualization to network functions so that they can be deployed as modular software components on the commodity hardware, instead of specialized hardware boxes. These network functions (e.g Network Address Translation, firewall, Intrusion Detection System) can be chained to provide services. The network function placement is very flexible since the software instances can be installed at any commodity hardware with enough spare capacity. Although some studies have evaluated the delay introduced by the virtualization of network functions [53, 54, 55], little effort has been devoted to the impact to the service availability in the context of NFV.

  We propose in **C1**, two function placement strategies that minimize the service deployment cost for the operator, without compromising the quality of service promised in the Service Level Agreements (SLAs). It has been shown that guaranteeing both delay and availability requires only a limited increase of used network resources. The work in this area is being extended.

## 1.2 Main contributions

The main findings on this work can be summarized as follows:

- New techno-economic methodology for next generation optical access networks, including yearly planning given a penetration rate. Application of the methodology to several next generation optical access architectures able to cope with long reach (i.e. node consolidation) as well as large client count (more than 1000 users per feeder fiber) and more than 300 Mbps per user.
- Proposal of migration steps towards NGOA networks so that service interruption is minimized.
- Novel techno-economic methodology of the migration towards next generation optical access network. This methodology allows evaluating the impact of the migration starting time and duration. The methodology has been applied to different migration alternatives for passive and active optical networks.
- Application of the methodology to geographic area models to achieve a more realistic network dimensioning. Particular attention is devoted to Hybrid PON as it is able to cope with large delivered bandwidth as well as it supports cascading of remote nodes and reuse of existing Optical Distribution Network.
- Proposal of a new optical core node architecture and the cost analysis of different node architectures that allows the required increase of capacity.
- Proposal of new protection schemes for next generation optical access networks. The proposed schemes have been techno-economically compared with other existing schemes. The work proposes a complete set of metrics to achieve a fair and comprehensive comparison.
  - 1:1 protection schemes based on received power
  - new protection schemes compatible with power saving modes

- Optimal placement of personnel/equipment to minimize costs:
  - Placement of technicians to minimize the failure reparation cost and penalties in a core network.
  - Placement of remote nodes to minimize the cost of required infrastructure and consumed power of a next generation optical access network.
  - Placement of controllers to minimize the cost of a resilient SDN control plane.
  - Placement of network functions to minimize the cost of the required hardware and software.

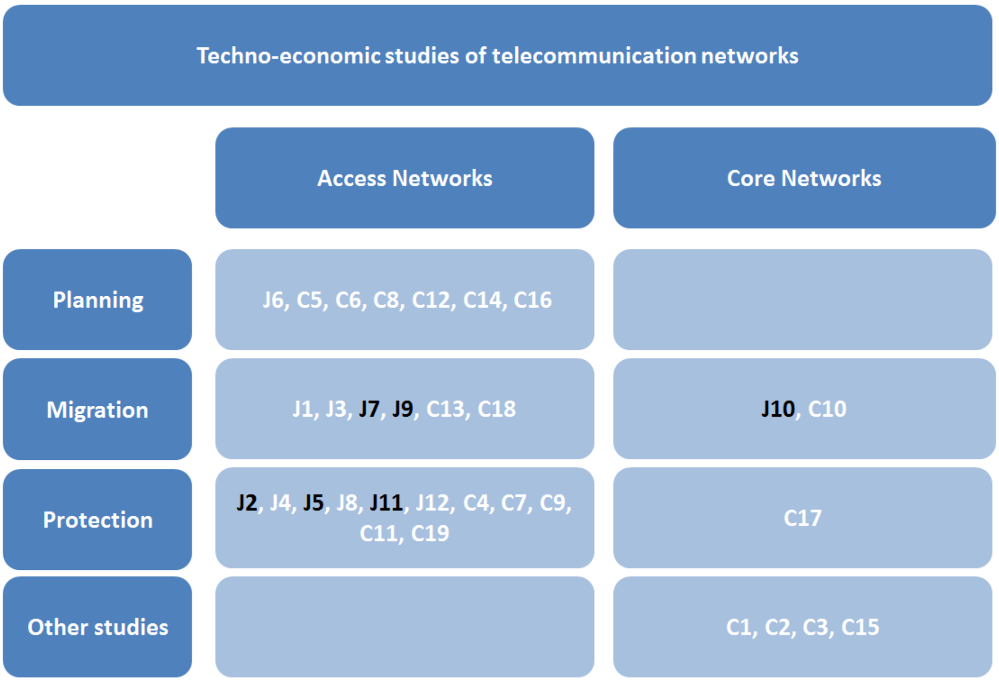


Figure 1.2: Publications overview in terms of network domain and targeted assessment

## 1.3 Publications

The result of this work has been disseminated in several papers, which are listed in the following subsections. The overview of the papers in relation to the addressed area is depicted in Figure 1.2. The papers highlighted in the Figure in bold have been included in full text in Section 5.

### 1.3.1 Journal papers

**[J1]** K. Wang, **C. Mas Machuca**, L. Wosinska, P. J. Urban, , A. Gavler, K. Brunnström, J. Chen, *A Techno-Economic Analysis of Active Optical Network Migration Towards the Next Generation Optical Access* , OSA Journal of Optical Communications and Networking, Accepted for publication, 2017.

**[J2]** E. Grigoreva, E. Wong, M. Furdek, L. Wosinska, **C. Mas Machuca**, *Energy Consumption and Reliability Performance of Survivable Passive Optical Converged Networks: Public ITS Case Study*, OSA Journal of Optical Communications and Networking, Accepted for publication, 2017.

**[J3]** K. Wang, A. Gavler, **C. Mas Machuca**, L. Wosinska, K. Brunnström, and J. Chen, *Migration Strategies for FTTx Solutions based on Active Optical Networks* , IEEE Communications Magazine, Vol. 54, Issue 2, pp. 78-85, February 2016.

**[J4]** E. Wong, **C. Mas Machuca**, L. Wosinska, *Survivable Hybrid Passive Optical Converged Network (HPCAN) Architectures Based on Reflective Monitoring*, IEEE/OSA Journal of Lightwave Technology, Vol. 34, Issue 18, pp. 4317-4328, 2016.

**[J5]** **C. Mas Machuca**, L. Wosinska, J. Chen, *Assessment methodology of protection schemes for next generation optical access networks*, Optical Fiber Technology, Vol. 26, Part A, pp. 82-93, December 2015.

**[J6]** M. Forzati, A. Bianchi, J. Chen, K. Grobe, B. Lannoo, **C. Mas Machuca**, J. Point, B. Skubic, S. Verbrugge, E. Weis, L. Wosinska, D. Breuer, *Next Generation Optical Access Seamless Evolution*, OSA Journal of Optical Communications and Networking, Vol. 7, 2015.

**[J7]** R. Romero Reyes, R. Zhao, **C. Mas Machuca**, *Advanced Dynamic Migration Planning Towards FTTH*, IEEE Communications Magazine, Vol. 52, Issue 1, pp. 77-83, February 2014.

**[J8]** M. Mahloo, A. Dixit, J. Chen, **C. Mas Machuca**, B. Lanoo, D. Colle, L. Wosinska, *Towards Reliable Hybrid WDM/TDM Passive Optical Networks*, IEEE Communications Magazine, Vol. 52, Issue 2, pp. S14-S23, February 2014.

**[J9]** **C. Mas Machuca**, M. Kind, K. Wang, K. Casier, M. Mahloo, J. Chen, *Methodology for A Cost Evaluation of Migration towards NGOA Networks*, Journal of Optical Communications and Networking , Vol. 5, no. 12, pp. 1456-1466, December 2013.

**[J10]** A. Leiva, **C. Mas Machuca**, A. Beghelli, R. Olivares, *Migration Cost Analysis for Upgrading WDM Networks*, IEEE Communications Magazine, Vol. 51, Issue 11, pp. 87-93, November 2013.

**[J11]** **C. Mas Machuca**, J. Chen, L. Wosinska, *Total Cost Reduction Achieved by Offering Protection in PON Architectures*, Telecommunication Systems journal, Vol. 54, no. 2, pp. 129-135, October 2013.

**[J12]** M. Mahloo, **C. Mas Machuca**, J. Chen, L. Wosinska, *Protection cost evaluation of WDM-based Next Generation Optical Access Networks*, Optical Switching and Networking Journal, Vol. 10, Issue 1, pp. 89-99, January 2013.

### 1.3.2 Conference papers

**[C1]** P. Stojsavljevic, M. Condoluci, **C. Mas Machuca**, T. Mahmoodi, W. Kellerer, *QoS-driven Function Placement Reducing Expenditures in NFV Deployments*, IEEE International Conference on Communications (ICC), Paris, France, May 2017

**[C2]** **C. Mas Machuca**, S. Secci, P. Stojsavljevic, F. Kuipers, A. Gouglidis, D. Hutchison, S. Jouet, D. Pezaros, A. Elmokashfi, P. Heegaard, S. Ristov, M. Gusev, *Technology-related Disasters: A Survey towards Disaster-resilient Software Defined Networks*, 8th

International Workshop on Resilient Networks Design and Modeling, 2016, Halmstad, Sweden, September 2016.

**[C3]** P. Stojsavljevic, **C. Mas Machuca**, W. Kellerer, *Controller Placement Strategies for a Resilient SDN Control Plane*, Reliable Networks Design and Modeling (RNDM), 2016 8th International Workshop on, Halmstadt, Sweden, September 2016.

**[C4]** **C. Mas Machuca**, E. Wong, M. Furdek, L. Wosinska, *Energy Consumption and Reliability Performance of Survivable Hybrid Passive Optical Converged Networks*, Photonic Networks and Devices, Advanced Photonics 2016 Congress, Vancouver, Canada, July 2016.

**[C5]** E. Grigoreva, **C. Mas Machuca**, W. Kellerer, *Optical Backhaul Network Planning for DSRC-based Public Intelligent Transportation System: A Case Study*, IEEE International Conference on Transparent Optical Networks (ICTON), Trento, Italy, July 2016.

**[C6]** B. Kanj, **C. Mas Machuca**, K. Grobe, *Comparison of Wavelength-Routed and Wavelength-Split WDM-PON in Mobile x-Haul in dense urban areas*, ITG-Fachtagung Photonische Netze 2016 , Leipzig, Germany, May 2016.

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**[C11]** A. Munoz Diaz, **C. Mas Machuca**, *Impact of protection to converged access networks planning in rural areas*, Progress In Electromagnetics Research Symposium (PIERS), Prague, Czech Republic, July 2015.

**[C12]** A. Munoz Diaz, **C. Mas Machuca**, *Are Converged Access Networks suitable in rural areas?*, IEEE International Conference on Transparent Optical Networks (ICTON), Budapest, Hungary, July 2015.

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# Chapter 2

# Methodology

This chapter gives an overview of the methodology for a techno-economic evaluation. This methodology is the basis for the methodologies proposed in this work, which are described more in detail in Chapter 3. Although the methodology depends on the objective of the evaluation, four different general modules can be identified, as depicted in Figure 2.1.

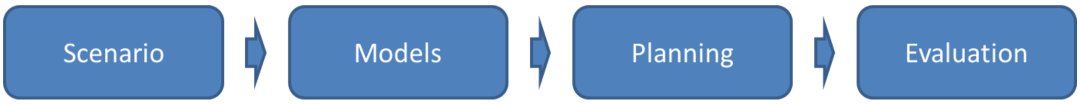



Figure 2.1: Methodology for a techno-economic evaluation

The following sections describe each of these modules in detail. Section 2.1 presents the information required to define the scenario. Section 2.2 gives an overview of different models that could be used for cost, and the information required to model network architectures and components. Section 2.3 introduces several dimensioning and planning problems and finally, Section 2.4 summarizes different economic related metrics that can be used to perform the techno-economic assessment.

## 2.1 Scenario

The first step to perform a techno-economic study is to define the target of the study, which includes the following information:

- Domain: The domain of the study can be defined as core, aggregation, access, etc. A study may embrace more than one domain: e.g., in order to analyse the impact of node consolidation [56], access and aggregation domains should be jointly studied.
- Area: For some studies the domain is not enough and more detailed information of the area has to be defined. For example, in access networks, it is important to specify the user density, which is closely related to the area type, i.e. dense urban, urban, rural. In other domains, the area related information may not only be associated to the user or terminal density but also to distances and area sizes.
- Technology: The technology or set of technologies that are going to be evaluated should be defined. In core and aggregation networks, the most used technology is optical, which actually can be based on fixed or flexible grid. The range of technologies in access networks is much wider and can be combined at the so-called converged access networks.
- Architecture: This category refers to aspects related to the network architecture such as topology/ies, energy savings, resilience aspects, etc. Each technology will have to be modelled (e.g., as proposed in Section 2.2.2).
- Services: Some studies have to take into account the offered services so that the requirements (e.g., QoS) can be guaranteed by considering them during the planning phase. Furthermore, the associated revenues can be considered in the final techno-economic assessment.
- Time dependence: In order to evaluate the impact of time in the techno-economic assessment, any information on the time dependence is required for parameters such as number and/or location of users, services per user/node, variation of parameters

such as ageing of components, etc. This time dependence is important in order to do a reliable cost efficient planning (Section 2.3).

- Depending on the study, other information may be required. For example, the starting time of the network implementation, network upgrade or migration to another technology, the allowed duration of such implementation or migration, the expected penetration and/or churn curve per type of client or increase of traffic.

## 2.2 Models

Different models may be required depending on the study. This section is first giving a summary of different models that can be used to model cost. Then, an overview of the information that is required to model network architectures and models is provided.

### 2.2.1 Cost models

One of the pillars of any techno-economic analysis is the evaluation of the Total Cost of Ownership (TCO). TCO embraces three cost categories: Capital Expenditures (CAPEX), Implementation Expenditures (IMPEX) and Operational Expenditures (OPEX).

**CAPEX** considers the upfront cost for the network infrastructure including all the equipment and cabling required to interconnect the equipment. CAPEX encompasses the cost of the equipment to set up the network as well as the equipment that should be bought to replace the initial equipment after its end-of life.

**IMPEX** considers all the installation and configuration costs of the equipment and the cabling. In case of optical cabling, the cost of trenching, installing (mini) ducts and blowing fibre should also be considered.

**OPEX** is related to all the cost associated to the operation of the network, that is, the cost of keeping the network up and running: power consumption, maintenance and failure reparation costs, service related costs for establishing/modify/tear-down, leasing on line/capacity/floor space, penalties for non-accomplished SLAs, etc.

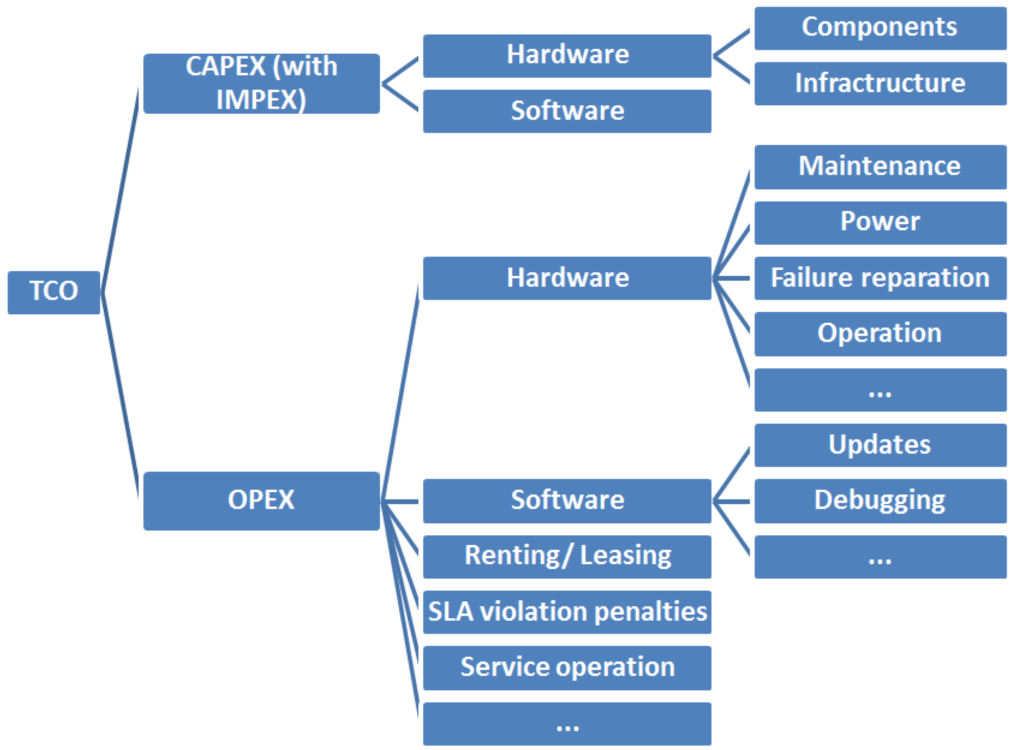



Figure 2.2: Overview of cost classification

One characteristic that distinguishes CAPEX from OPEX and IMPEX is that CAPEX is subject to depreciation, that is, its cost can be allocated over the useful life of the network (in particular to each equipment or component). For example, the cost of a router ∼40k$ with a lifetime of 5 years, the operator may consider a depreciation expense of ∼8k$ in each year. Obviously, the amount can vary depending on the depreciation method (e.g., straight line or double declining balance) and the assumptions (e.g., salvage value), which are outside the scope of this work.

It has to be mentioned that most of the studies consider IMPEX as part of CAPEX and hence, the TCO comparison is based on CAPEX and OPEX analyses.

Regardless on the cost classification, different cost models can be considered:

- Dimensioning model: This is the basic cost model that assigns a cost to a component based on its characteristics. These costs are mainly (i) the investment costs, i.e. CAPEX; (ii) the power cost, which can be derived on the power consumed by this component as well as by the A/C required; (iii) the floor space cost, which can be derived on the floor space required by this component and for any extra associated equipment.

- Proportional model: This model considers a cost as proportion of another cost, which usually is larger and dominant.
  For example, the maintenance cost of a component $MC$ could be modelled as a percentage of the investment cost, that is, $MC = \alpha CAPEX$ [57].
  The critical points of this model are: to find the right proportion parameter $\alpha$ since it may depend on the technology, the country, etc.; the lack of detailed information on the cost itself such that its dependencies, possible time evolution, etc.

- Driver based model: This model is based on the cost drivers identified by the cost dependences. Given the cost drivers, an analytical expression of the cost can be derived.
  For example, the maintenance cost can be modelled as dependent on the number of expected maintenance per year $n$ and the number of required technicians $tech$ with a wage $wage$ and time required for each maintenance $T$. The analytical expression of the cost in function of the cost drivers is $MC = n * tech * T * wage$.

- Dedicated models: These models go more into detail by considering other parameters such as probabilities of occurrence.

  – Process based models: Some operational costs that follow a repetitive execution of tasks, can be modelled as a process. Let us consider a flowchart modelling approach where a process can be modelled as a set of interconnected tasks and conditional split gateways. Each of the tasks has an assigned cost (e.g., based on the required time and/or personnel).

Let us consider again the example of the maintenance cost of a component. This cost can be modelled as a process depicted in Figure 2.3, which contains the following tasks: "Go to location", "Perform required tasks" and based on the output on whether the maintenance has been successful or not, the process ends (if it has been successful) or it performs "Extra task" aiming at completing the maintenance. In this case, each of the tasks has an assigned cost which is denoted as $C_A, C_B$ and $C_C$ respectively and the output of the gateway is "Yes" with probability $p_Y$ and "No" with probability $p_N = 1 - p_Y$.

The maintenance cost can be then be calculated using the following expression:

$$MC = C_A + C_B + p_Y p_N (C_C + 2C_C p_N + 3C_C p_N^2 + ...) = C_A + C_B + C_C \frac{p_N}{1 - p_N} \quad (2.1)$$

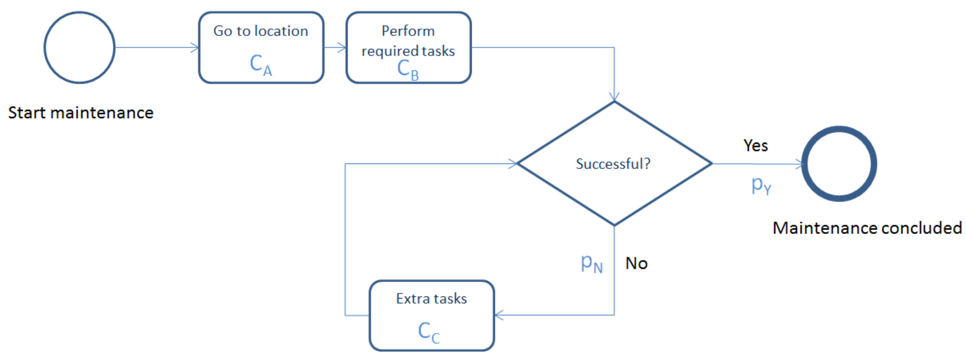



Figure 2.3: Example of maintenance process cost model

– Markov Chain models: Markov Chains can be also used to model the costs. In this case, the cost is modelled by a Markov Chain of a defined set of states $i$ of cardinality $N$, a transition matrix $P[i, j]$ and the visit to a defined state $i$ has an assigned cost $c_i$. The cost can be calculated for an unlimited period of time iff the Markov Chain is irreducible, that is, if and only if it is possible to go from any state $i$ to any state $j$ in one or more steps. In that case, the cost is independent of the initial state and can be calculated as

$$Cost = \sum_{j=1}^{N} \widehat{\pi}_j c_j \quad (2.2)$$

where $\widehat{\pi}_j$ are the occupancy distribution of each state and can be calculated knowing that

$$\sum_{j=1}^{N} \widehat{\pi}_j = 1 \tag{2.3}$$

$$\widehat{\pi}_j = \sum_{i=1}^{N} \widehat{\pi}_i P_{ij} \tag{2.4}$$

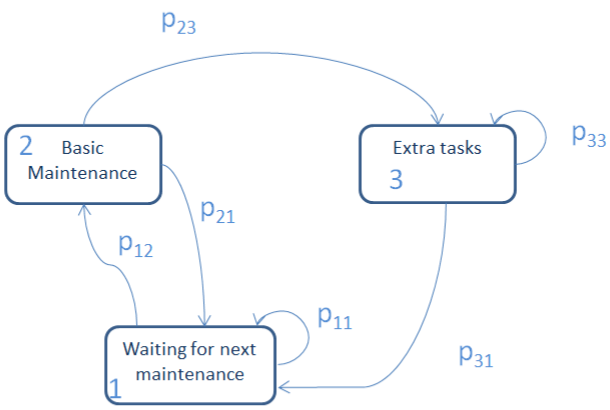



Figure 2.4: Example of maintenance Markov Chain cost model

Let us consider the maintenance cost example. The Markov Chain that could be associated to this cost is shown in Figure 2.4. The transition matrix is as follows:

$$P[i,j] = \begin{bmatrix} p_{11} & p_{12} & 0 \\ p_{21} & 0 & p_{23} \\ p_{31} & 0 & p_{33} \end{bmatrix}$$

and as property of the Markov Chain the sum of each row is 1,i.e., $p_{11} + p_{12} = 1$, $p_{21} + p_{23} = 1$ and $p_{31} + p_{33} = 1$.

Let us apply the expressions 2.3 and 2.4 as follows:

$$\widehat{\pi}_1 = p_{11}\widehat{\pi}_1 + p_{21}\widehat{\pi}_2 + p_{31}\widehat{\pi}_3 \tag{2.5}$$

$$\widehat{\pi}_2 = p_{12}\widehat{\pi}_1 \quad (2.6)$$

$$\widehat{\pi}_3 = p_{23}\widehat{\pi}_2 + p_{33}\widehat{\pi}_3 \quad (2.7)$$

$$\widehat{\pi}_1 + \widehat{\pi}_2 + \widehat{\pi}_3 = 1 \quad (2.8)$$

Once the occupancy distribution of each state is calculated, the cost can be expressed as

$$MC = C_1\widehat{\pi}_1 + C_2\widehat{\pi}_2 + C_3\widehat{\pi}_3 \quad (2.9)$$

### 2.2.2 Architecture model

The network architecture that has to be evaluated should be modelled at the component level and according to the dimensioning and planning tool. Aspects that should be considered are:

- Components: The most important information to define an architecture is the components that make it up. Components can be defined at different levels of detail depending on the considered component model and the associated and available information. An example for a protected optical backhaul with two different modeling levels is shown in Figure 2.5. Further details are given at the Component model section (Section 2.2.3).
- Connection between components: Once the network components are defined, the next step is to give details on how these components are interconnected. Depending on the architecture, the interconnection can be done either using wireless connections (e.g., mobile, microwave) or wired connections (e.g., fiber, copper). The selected technology will define connection constraints as for example, which is the maximum distance between the two interconnected components. Moreover, the costs will depend not only on the technology but on the used technique. For example, techniques that can be used to install optical cables are trenching (fully buried and dedicated

infrastructure), aerial (using poles), reusing existing ducts (replacing copper by flowing fiber), etc.

Another important parameter to define the connection between components is the connectivity ratio, that is, how many components can be connected to one given component. This is important specially in access networks where the splitting ratio of the remote node (RN) determines the minimum number of required RNs.

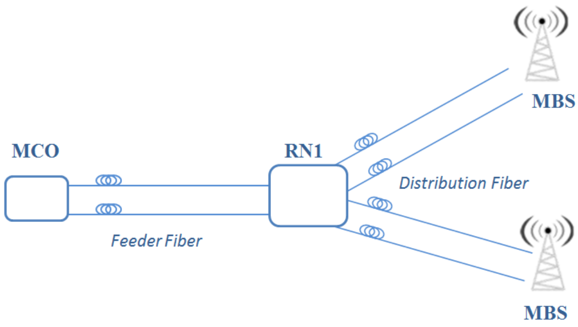
- Protection: In case the architecture is protected, the model should include how the protection is considered, that is, which components are duplicated, when are they used (e.g., 1+1 or 1:1), etc. For example, in the architecture shown in Figure 2.5(b), it can be observed that components that are duplicated are both fiber segments as well as the wavelength router at the RN. The duplicated fiber will be used only in case of failure, once the optical switch (OSW) commutes to the protection fiber.

### 2.2.3 Component model

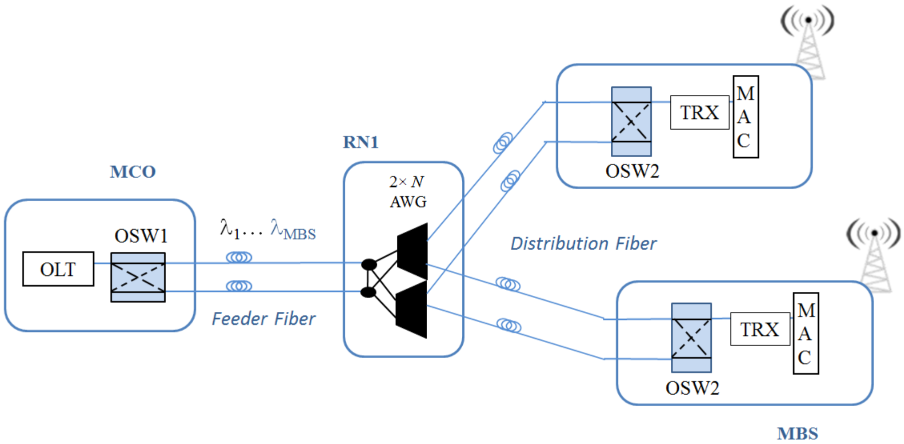
The component model defines the level of detail of the network architecture as well as the characteristics associated to the component. The selection of the model will be done based on the available information and the objective of the techno-economic analysis.

Let us consider the remote node of the previous optical networks as an example. One high level component model, as in Figure 2.5(a), considers the RN as an interconnection component that distributes the signal of the MCO to the different MBS. However, at this level, this RN can host a power splitter, a wavelength router, an Ethernet switch, etc. For dimensioning purposes, a more detailed component is required (e.g., Figure 2.5(b)). In this case, it is clear the equipment that should be placed at the RN as well as the splitting ratio (*2xN* in this case).

However, this information may not be enough. Other required information important for planning are:




(a)




(b)

Figure 2.5: Example of (a) simple and (b) more detailed protected access network model interconnecting the Main Central Office (MCO) with several Macro Base Stations (MBS) with a single Remote Node (RN)

- Location: The cost (not only CAPEX but also OPEX) and the technical requirements of a component depend significantly on the location. Most of the components of a core and aggregation network are placed in basements of buildings owned by the operators. However, components of access networks are mostly in other locations (e.g., cabinet, antenna, basement of building own by private persons). For example, some access network components may required strict temperature and humidity ranges and hence should be in a protected places. Other components that require frequent maintenance should be placed in a location with easy access. Another aspect if whether the component requires power supply and/or A/C to keep the temperature stable.

- Specifications: Each network component is characterized by the technical specifications given by the manufacturer in the such as size, consumed power, floor space, failure rate, interfaces, insertion losses, capacity, etc. All these specifications should be checked by the operator to be compliant with their requirements given the planned location and use in the architecture. Furthermore, the operator should take into account possible variations of some parameters (e.g., the failure rate may vary in different conditions and hence, components may have to be replaced earlier in harsh environments).

- Cost: The cost of a component depends on different aspects such the maturity of the component, the volume of the expected purchase, the manufacturer market competition, etc. All these aspects will define the cost of the component. It has to be mentioned that for the roll-out of a new network or use of a new technology, operators ask for Request for Proposals (RfP) or Request for Quotation (RfQ) so that manufacturers offer the detailed proposal or quotation of the solution. The quotation does not only include the cost of the components, but other costs like the required software, the expected updates of the software, the required maintenance, the operational processes that the manufacturer can take care of, etc.

## 2.3 Network Dimensioning and Planning

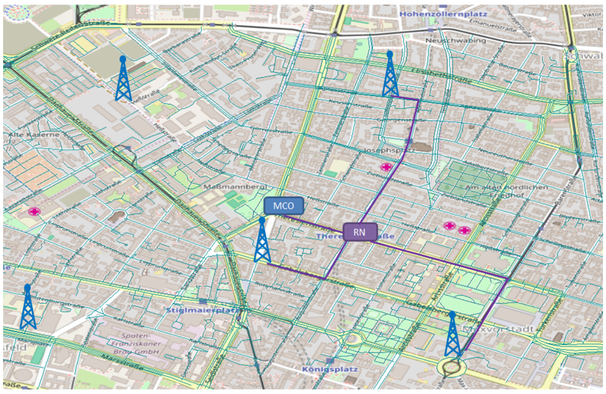
Let us first define planning and what is the difference with dimensioning since these two concepts are often confused in literature.

Network dimensioning is the process to evaluate how many network components (hardware, software, links, etc.) are required in order to offer the required connectivity/services to a given number of end points/users. Network planning takes the time dependency into account by evaluating the number and type of network components required per year

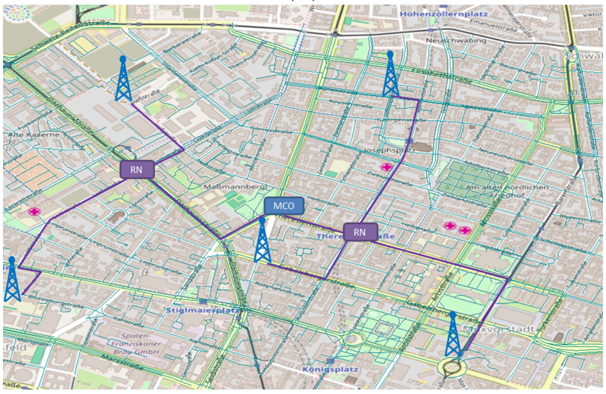
given some time aspects such as for example, the expected penetration rate and the life time of the components.
Different techniques can be used in order to find the best dimensioning or planning solution. In general the problem for an operator is to find the solution that minimizes costs and/or maximize benefits given a set of requirements and constraints. However, the objective problem can change depending on the target of the techno-economic assessment.
Let us consider as example, the case of a network operator that wants to offer mobile access to the users of a certain area with a protected backhaul (as the one depicted in Figure 2.5(b)). The operator will initially dimension the network, that is, it will compute how many components are required to cover the area; i.e., mainly, how many MBS and RN are needed and where they should be placed, how much fiber and cable (and its size) should be purchased and which is the cable layout to evaluate the required digging. The second step is to plan the network roll-out, that is, organize the implementation of the network considering the time dependence (i.e. the pace for the solution roll-out). Planning should consider the expected customer changes, service demand variations, etc. in order to allocate implementation steps to a given time frame. Keeping the same example, an operator may start installing and connecting the MBS at the areas of highest user concentration (e.g., Figure 2.6(a)) encouraged by the high expected revenues, it may continue with the MBS in less dense areas aiming at increasing the coverage (Figure 2.6(b)) and at the end, the operator may install and connect the protection fibers (Figure 2.6(c)) intending to increase the connection availability.

The dimensioning and planning problem can be implemented using different techniques. In this work two techniques have been mainly used:

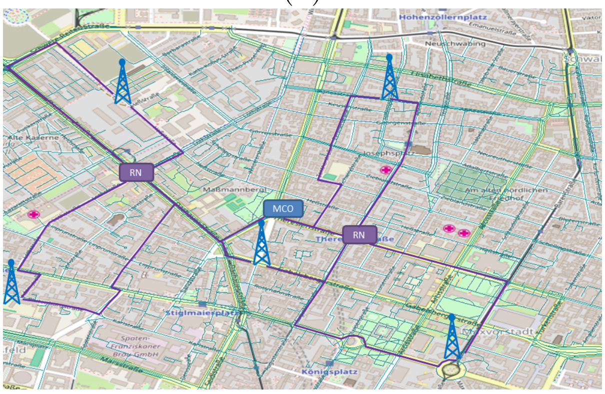
- Heuristics. This methodology aims at finding a solution which may not be optimal with a reasonable computational time. In most of the studies, due to the large solution space, this methodology is the preferred one. Furthermore, it is also justified by the fact that operators take more parameters into account than the technical related ones (e.g. available real state, company type).




(a)




(b)




(c)

Figure 2.6: Planning example of a protected backhaul of five Macro Base Stations (MBS) with two Remote Node (RN) to be connected to the main central office (MCO)

Heuristics have been applied to next generation access network planning, network migration, as well as to evaluate protection schemes in access networks.Let us summarize the two main approaches considered in this work.

The tool used at the OASE project ([58]) was an extension of the TONIC frame-tool ([59]) based on the geometric model of an area. The data of different areas is obtained from the average of each type of area in the whole Germany. The new version of the tool allowed performing the network dimensioning and planning of several new Next Generation Optical access architectures. Furthermore, the tool could be used to assess the migration costs based on the proposed methodology.

The second main heuristic tool was developed using ArcGIS which uses real network information available at openstreetmap.org (e.g. the area shown in Figure 2.6). This project allows creation and provision of free geographic data anywhere in the world and hence, it is possible to download the database associated to any selected area and which contains information such as streets, buildings, crossroads, transport lines, etc. Following the methodology proposed in [60], we can plan different types of architectures, topologies, etc.

- Optimization using Linear programming. This methodology is characterized by expressing the objective function that should be minimized or maximized as a linear function of decision variables (i.e. all decision variables have power of 1 and do not multiply nor divide other variables). The problem is solved given a set of parameters that define the problem as well as a set of constraint giving the relation between parameters and decision variables.

  Linear programming has been applied to solve optimal hardware and infrastructure placement of converged access networks as well as to the optimal hardware and technical personnel in core networks.

## 2.4 Evaluation Criteria

Techno-economic analysis is mainly used by operators and providers to evaluate the economic feasibility of a technical solution (protection scheme, technology, service, etc.). This analysis is mainly based on the cost modelling presented in Section 2.2.1 but it can be extended to include other financial aspects.

First, this section presents the most common parameters that are used by operators. Let us consider as example an operator facing the possibility to upgrade its copper access network with an optical access network in a rural area (depicted in Figure 2.7). This area close to Schönberg, covers around 150 $km^2$ and has 933 buildings. This section concludes with an overview of other analysis required for a complete techno-economic assessment.

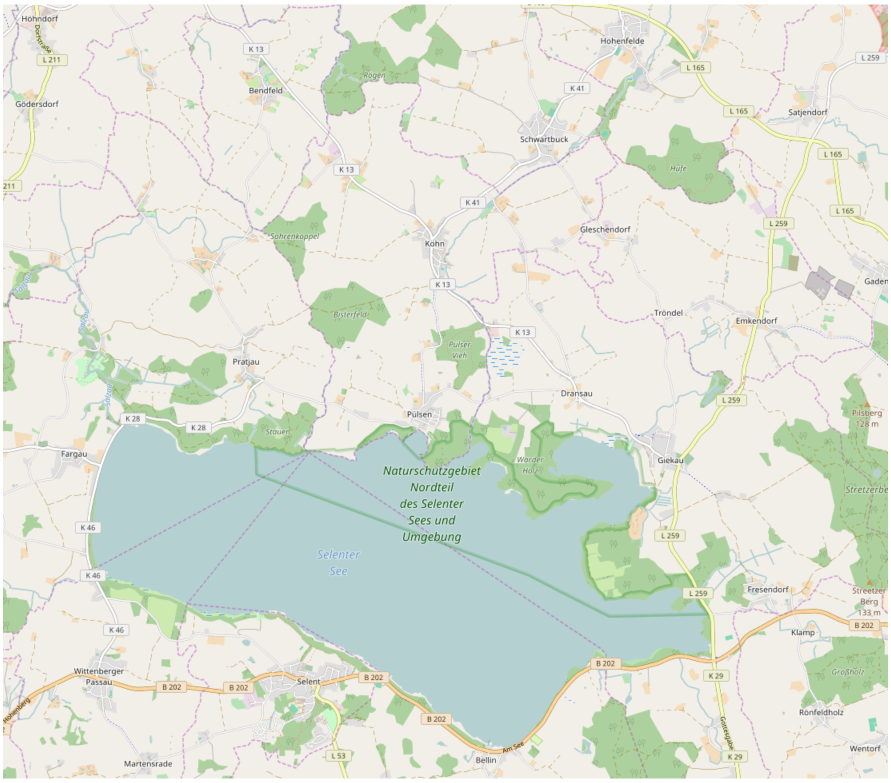



Figure 2.7: Rural area in Germany with less than 10 buildings/$km^2$

### 2.4.1 Cost

Using the cost models presented in Section 2.2.1, the cost of a particular technical solution can be computed. There are different ways to evaluate the cost:

- Total Cost of Ownership (TCO) is the total cost over the expected lifetime of the solution, that is, for how long the solution will be or is planned to be operational. The lifetime not only depends on the lifetime of the components (it can vary from few years for the components to several decades for optical cables [61, 62]) but on the business plans and marketing studies of the operator.
  The TCO can be expressed as
$$TCO = \sum_{t=1}^{T}(CAPEX_t + OPEX_t) \tag{2.10}$$
  where $CAPEX_t$ and $OPEX_t$ are the CAPEX and OPEX of year $t$ respectively. The CAPEX of the first year includes all the initial investment, whereas the CAPEX of the following years include the cost of the components that have to be purchased for their replacement (due to their end-of life or to failure).
  Considering our optical access network example, and a conservative penetration rate as given shown in Figure 2.8, the TCO for 20 years has been depicted in Figure 2.9. It can be observed, that in 2026, all buildings should be connected and hence, no further cost on equipment and fiber roll-out is expected. However, maintenance, sales and power consumptions costs are expected until 2036.

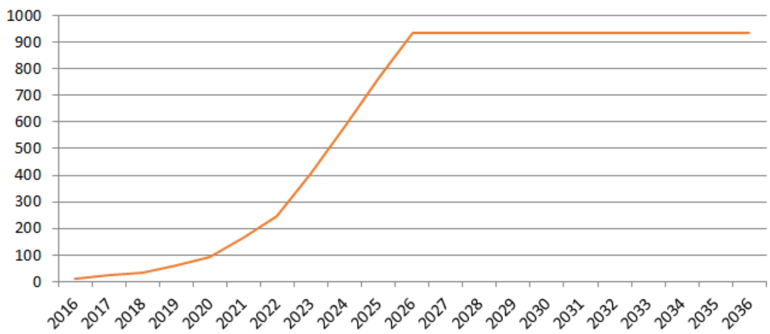



Figure 2.8: Passed buildings per year

- Cost per user is commonly used by operators in order to compare the investments for a user and the revenues. Let us compare as example the cost of Fiber To The Home solutions in dense urban and rural areas [22], as shown in Figure 2.10. Three solutions

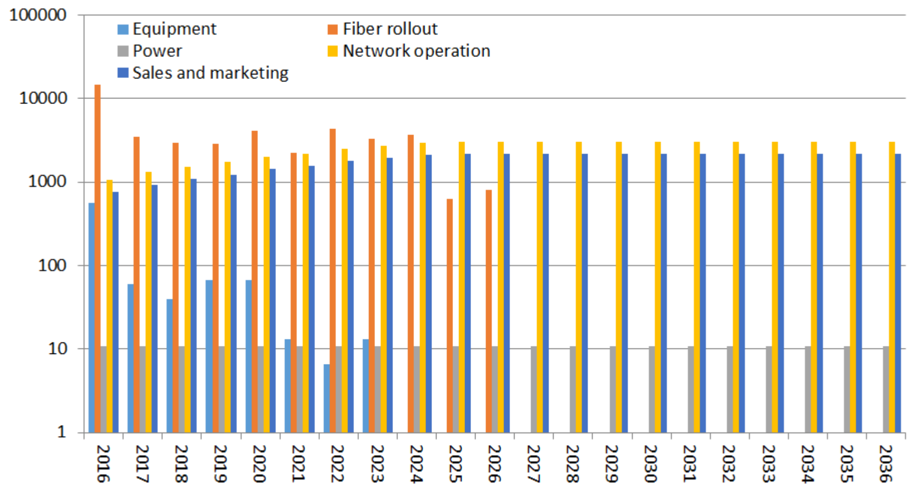



Figure 2.9: Cost evolution in Cost Units per year

have been compared: Point to Point (P2P) connection of users to central office (CO), Active Optical Networks (AON) that uses an Ethernet switch at the remote node (RN) to interconnect several users to the CO, and Passive Optical Networks (PON) that instead of the active switch uses a passive component (e.g., power splitter) at the RN. The investment required in dense urban areas is much higher than in rural areas. However, the cost per user in dense urban areas is much lower and offers higher benefits than in rural areas, what encourages this deployment in such areas.

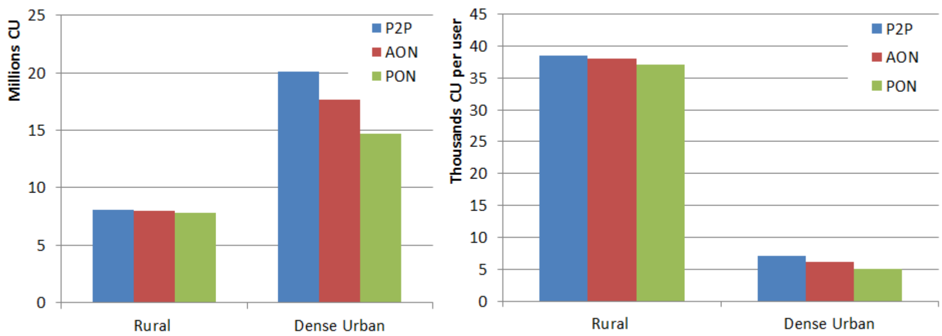



Figure 2.10: Cost comparison of different Fiber To The Home solutions in rural and dense urban areas as total cost in cost units-CU (left) and cost units per user (right)

- Other metrics such as cost per $km^2$, cost per Mbps, cost savings with respect an existing or baseline solution, etc. are also frequently used depending on the study.

### 2.4.2 Benefits

In order to evaluate whether a proposed solution is worth or not, the first basic metric is to evaluate the benefits that are expected to be obtained. Benefits can be calculated as the difference of the revenues and the expenses and is also referred as *Profitability*. Revenues can be made out of the offered services, leasing lines, etc. The revenues are given as *Average Revenue Per User* (ARPU) and it depends obviously on the service, required availability, bandwidth, etc. Continuing with our previous example and considering an ARPU of 1,2 CU/month, the benefits of the optical access network can be plot as shown in Figure 2.11. Taxes are computed based on the benefits.

Another used term is *Cash Flow*, which is defined as the difference between cash inflows

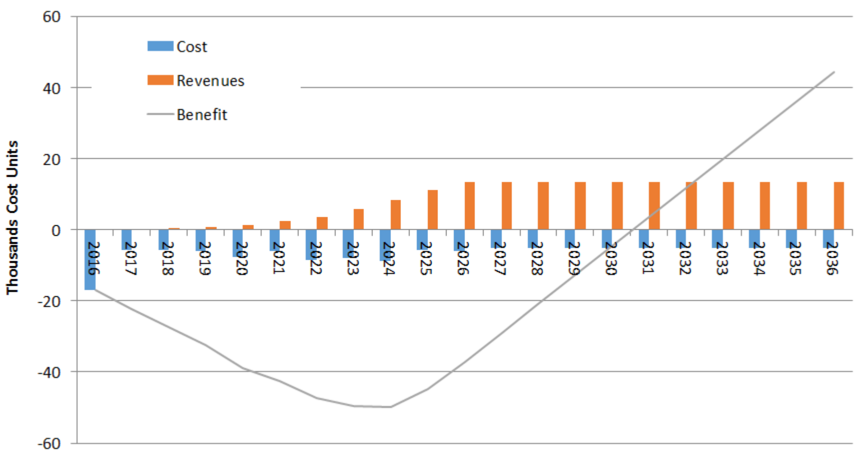



Figure 2.11: Cost, revenues and benefits in Cost Units

and cash outflows of a certain period. Cash flows include in the statement cover payments to suppliers, employees, etc. as well as cost of buying merchandise, revenues from offered services, etc. A particular type of cash flow is the Operating Cash Flow, which is the difference between the revenues (cash inflows) and the operational costs (operational outflows) without considering CAPEX. Both Cash flow and Benefits have to be reported

by operators and any business in general. They differ since some cash flows may not be recorded as revenues or expenses at the time of the transactions.
Figure 2.11 also shows the *Payback period*, which can be defined as the time required to recover the cost of the investment. This figure shows that after 15 years, the investment is recovered.
Another approach to evaluate benefits is the *Return of Investment* (ROI), which is defined at the ratio of the benefits with respect the costs. The higher the ROI, the better is the solution. Based on our access network example, in 2036 we expect 44353 CU of benefits but the costs have been 137792 CU, resulting in a ROI of 32%, that is, for every 100 CU invested in 2016, we could expect a benefit of 132 CU. However, this should not be the only metric, but rather be combined with Net Present Value and the discounted payback time.

### 2.4.3 Net Present Value

So far, the impact of time in the value of money (i.e. the value of 1000 € in 2020 is not the value of having 1000 € today) has been disregarded. Since the value of money depends on time, the parameters presented in the previous section should be adapted take into account this effect. The time dependence is usually considered using the *discount rate*, which is the parameter that models the time value of money and the risk of future cash flows: the higher discount rate, the greater the uncertainty and also the lower the present cash flow.
The expression to calculate the present value PV (i.e. in 2016) of an amount F in year T (denoted as $F_T$)is

$$PV = \frac{F_T}{(1+r)^{T-2016}} \tag{2.11}$$

For example, 1000 € in 2020 with a discount rate of 10% corresponds to 683 € today.
Let us consider the particular example of an optical access network.
The Net Present Value (NPV) is the difference between the present value of cash inflows

and the present value of cash outflows. The expression of the NPV is

$$NPV = \sum_{t=1}^{T} F_t(1+r)^{t-2016} - I_0 \tag{2.12}$$

where $F_t$ is the net cash flow during period $t$, $I_0$ is the initial investment, $r$ the discount rate and $T$ the total number of time periods (e.g., years). A positive NPV indicates that the project may be worth since it seems profitable.

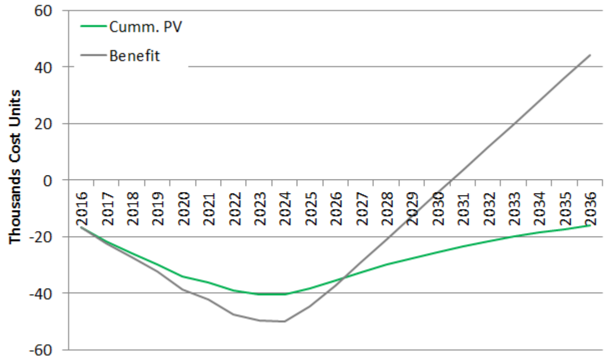



Figure 2.12: Comparison of benefits and cumulative Present Values

Using once again our optical access example with a discount rate of 10%, the NPV is -16083 CU, which implies that this project will not add value to the operator, but rather to reduce it and hence, the operator may discard this project. However, this seems to be contradictory of what it was shown in Figure 2.11. The reason is that NPV takes into account the discount rate and if we compare the benefits with the accumulated present values as in Figure 2.12, it can be observed the impact of the discount rate that relatives the impact of the revenues on the last years of the operational time. In other words, we can compute the *Discounted Payback time* based on the accumulated PV which in this case exceeds the operational time of the network.

### 2.4.4 Further analyses

Techno-economic analyses are not only based on the evaluation of the presented metrics but also on other analyses. As it has been already mentioned, the metrics are based on some input which can be variable, difficult to be estimated and depending on future uncertainties (social, political, market, etc.). Hence, some further analyses are often and always welcome to be performed.

- Sensitivity analysis: This type of analysis allows to evaluate the shift of the resulting metrics given a variation of the inputs (usually given as range or a probability density function). On interesting metric is the NPV and sensitivity analysis will identify in which cases the NPV is positive and how possible would be to get a negative NPV. Several tools are available to perform such analysis which can be at a first step classified as single or global analysis depending on whether one or several input parameters are varied [63].

- Risk analysis: This analysis targets not only to identify which are the risk of a particular project (e.g. negative NPV) but also to propose measures to mitigate their impact and occurrence. The identification of risks is based partially on sensitivity analysis [64, 65].

- Game theory: The telecom area has become more plural and competitive since the first vertical integrated operators which were operating at one country without competition [58]. The large number of providers and the different available technologies makes hard to estimate the expected number of customers. This number is in general given based on adoption and churn rates. In order to evaluate the impact of competition and offered service fees, game theory is used to model the fact that the customers of one provider depends on their own rules (in our case offered service fee based on how much the services costs) but also on the competitor rules (e.g., if the competitor decreases the fee, the provider may decrease its own fee as well in order to reduce the exodus of customers). Some studies on this area have been published but are outside the scope of this work [66, 67, 68, 69].

## 2.5 Summary

This chapter has presented an overview of the generic methodology to perform techno-economic assessment. This methodology includes the four basic steps: scenario definition, models, dimensioning and planning and finally the evaluation. Special attention has been given to the different cost models and the different metrics and studies that are required for the final evaluation.

The presented general methodology was the reference to the methodology developed to evaluate new architectures for access and core networks (e.g our paper **J6**). Furthermore, it has been extended to be able to evaluate also migration scenarios (e.g our paper **J7, J10**) or protection schemes (**J2, J4, J5, J8**).

Next chapter gives an overview of main contributions on this area.

# Chapter 3

# Case Studies

The techno-economic studies included in this work cover different network domains (in this case classified as access or core networks) and different aspects: dimensioning/planning, migration and protection. The overview of topics and the publications have been depicted in Figure 3.1.

It can be observed that most of the effort has been devoted to access networks. The reason is that after the last upgrades of core networks, access solutions are now forced to a fast evolution to cope with the always increasing of bandwidth driven by the raise of users, terminals and services. However, this evolution does not only imply larger bandwidth but also higher connection availability.

The studies have been classified as *dimensioning/planning*, *migration* or *protection* depending on the main contribution of the paper.

## 3.1 Dimensioning and planning

- [**J6**] M. Forzati, A. Bianchi, J. Chen, K. Grobe, B. Lannoo, **C. Mas Machuca**, J. Point, B. Skubic, S. Verbrugge, E. Weis, L. Wosinska, D. Breuer, *Next Generation Optical Access Seamless Evolution*, OSA Journal of Optical Communications and

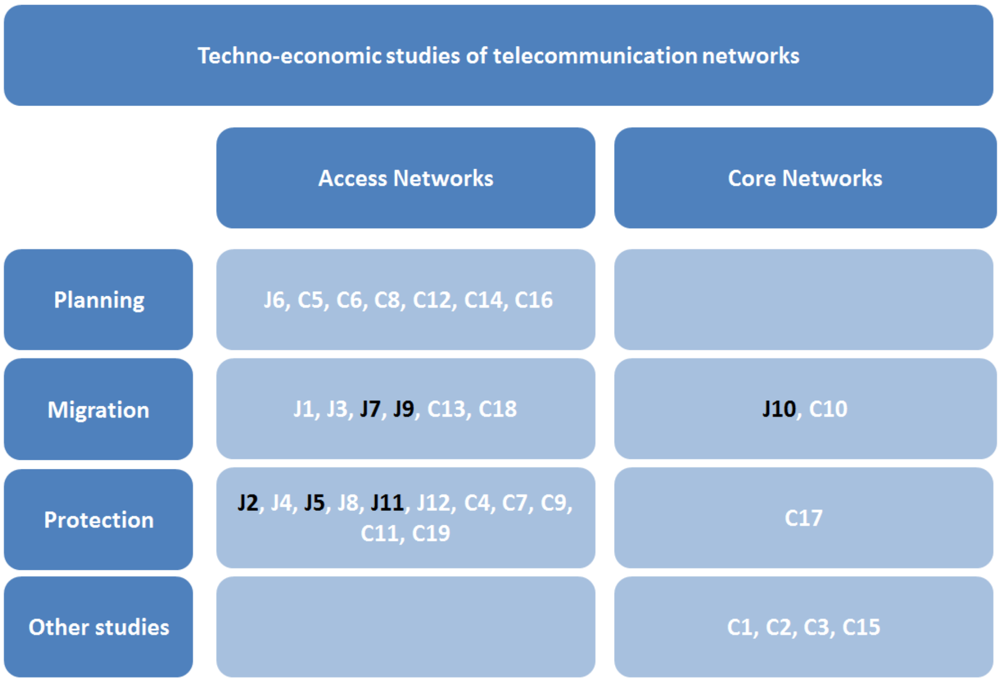



Figure 3.1: Publications overview in terms of network domain and targeted assessment

Networking, Vol. 7, 2015

Increasing bandwidth demand drives the need for next-generation optical access (NGOA) networks that can meet future end-user service requirements. This paper gives an overview of different NGOA solutions, the enabling optical access network technologies, architecture principles, and related economics and business models. NGOA requirements (including peak and sustainable data rate, reach, cost, node consolidation, and open access) are proposed, and the different solutions are compared against such requirements in different scenarios (in terms of population density and system migration). Unsurprisingly, it is found that different solutions are best suited for different scenarios. The conclusions drawn from such findings allowed to formulate recommendations in terms of technology, strategy, and policy. The technical recommendations, which are the ones related to this habilitation, are summarized Figure 3.2.

Due to a pure technical or even architectural assessment of the different proposed

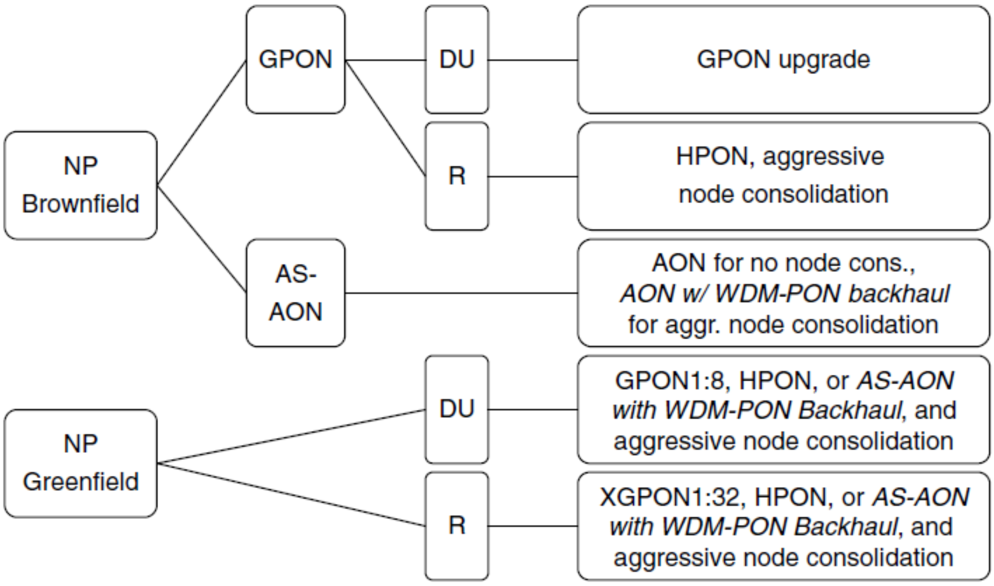



Figure 3.2: NGOA proposed solutions [J6] where NP stands for Network Provider, and DU and R stand for Dense Urban and Rural areas respectively.

NGOA concepts, it is not possible to single out a main system contender for NGOA. The best architecture depends on the type of area, on the existing solution in the area, if any, on the existing competition, etc. An overview of the recommendations is depicted in 3.2. From a pure technology perspective, the maturity level of the different technologies and associated system concepts has also been addressed to establish a technology roadmap. The proposed roadmap is in line with the current focus of the FSAN: a so-called TWDM approach, which is a hybrid WDM/TDM-PON approach with a limited number of wavelengths of between 4 to 10 channels.

## 3.2 Migration

- **[J1]** K. Wang, **C. Mas Machuca**, L. Wosinska, P. J. Urban, , A. Gavler, K. Brunnström, J. Chen, *A Techno-Economic Analysis of Active Optical Network Migration Towards the Next Generation Optical Access*, OSA Journal of Optical Communications and Networking, Accepted for publication, 2017

Active Optical Network (AON) has been one of the most deployed fiber access solutions in Europe. However, with the increasing traffic demand, the capacity of the existing AONs is becoming insufficient. For the legacy AONs, there are two major variants of architectures, namely point-to-point and active star. Considering the different characteristics of these two AON architectures, this paper proposes and analyzes several migration paths towards Next Generation Optical Access (NGOA) networks offering a minimum 300Mbit/s sustainable bit rate and 1Gbit/s peak bit rate to every end-customer. Furthermore, this paper provides detailed descriptions of the network cost modeling and the processes for AON migration. The Total Cost of Ownership (TCO) for the proposed migration paths are evaluated taking into account different migration starting times, customer penetration, node consolidation and business roles in the fiber access networks. The migration from AON to NGOA can be economically feasible. The results indicate that a network provider plays a key business role and is responsible for the major part of TCO for AON migration. Moreover, performing node consolidation during AON migration can be beneficial from the cost point of view, especially in rural areas.

- **[J3]** K. Wang, A. Gavler, **C. Mas Machuca**, L. Wosinska, K. Brunnström, and J. Chen, *Migration Strategies for FTTx Solutions based on Active Optical Networks* , IEEE Communications Magazine, Vol. 54, Issue 2, pp. 78-85, February 2016

  Active Optical Network (AON), one of the most deployed fiber access solutions in Europe, is facing the need to be upgraded in order to satisfy the ever growing bandwidth demand driven by new applications and services. This paper presents different migration strategies from the data and control plane perspectives from existing AON deployments. One example towards Time and Wavelength Division Multiplexing (TWDM) Passive Optical Network (PON) is shown in Figure 3.3. The paper also considers topology migrations towards mesh and ring topologies since they offer better resilience and support traffic locality. The different strategies are evaluated with respect to the key elements of both CAPEX and OPEX. The proposed migration strategies have both pros and cons depending on their features. They can be adopted either individually or combined. Operators/providers may choose the migration strategies which fit best to both their current network characteristics and future service/network planning.

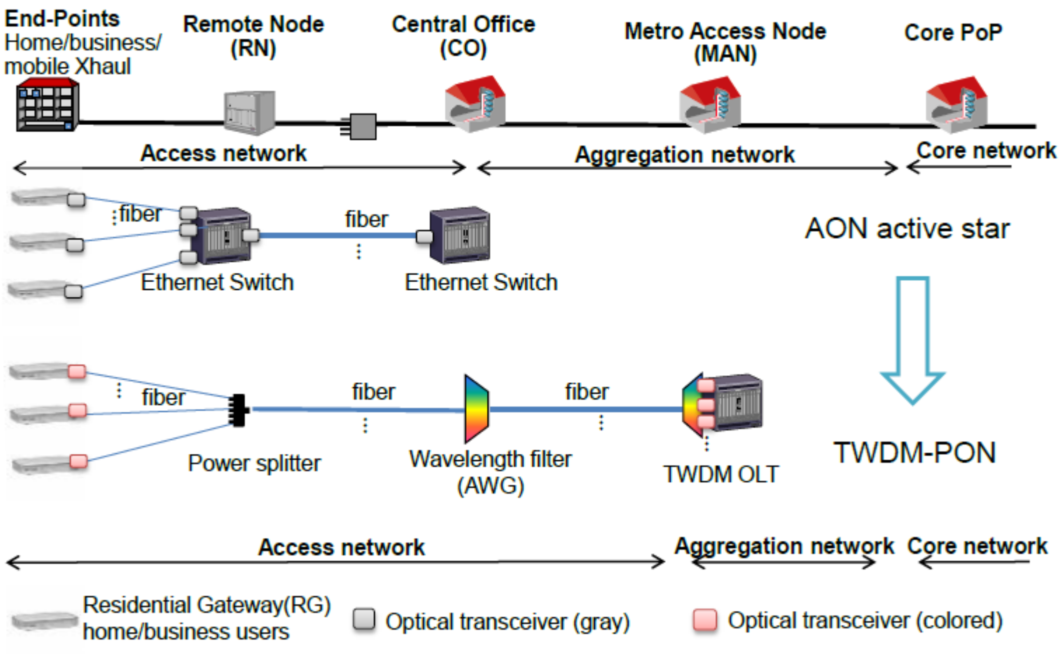



Figure 3.3: Migration from AON active star to TWDM-PON with node consolidation [J3]

- [**J7**] R. Romero Reyes, R. Zhao, **C. Mas Machuca**, *Advanced Dynamic Migration Planning Towards FTTH*, IEEE Communications Magazine, Vol. 52, Issue 1, pp. 77-83, February 2014.
  This work proposes a migration methodology towards FTTH taking into account the required investments, realistic demand forecasts and expected revenues. This stepwise methodology, depicted in Figure 3.4 delivers for a particular area and expected migration time, the best migration path to FTTH in terms of costs and profits. The methodology is applied to the particular case of the Bogota area, which illustrates that migration is not always feasible. Although profitability can be achieved by

increasing revenues and/or decreasing the TCO, we show that migration could be possible, if instead of profit, the objective is to achieve coverage without losses. Hence, profitable users can subsidize unprofitable areas. The analysis shows that any migration strategy has to be aware not only of the technical, but also the economic constraints of the problem to be solved.

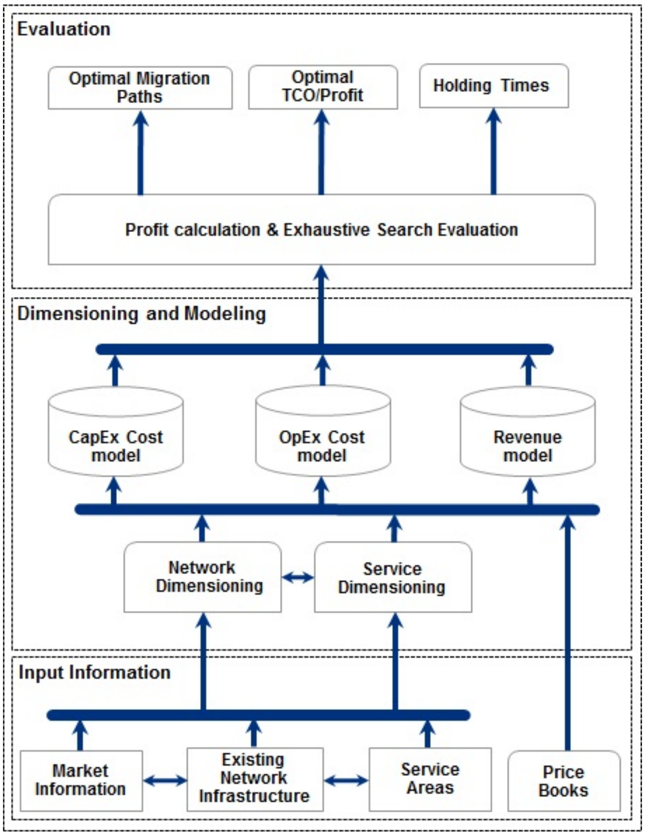



Figure 3.4: Techno-Economic framework for dynamic migration planning [J7]

- [J9] **C. Mas Machuca**, M. Kind, K. Wang, K. Casier, M. Mahloo, J. Chen, *Methodology for A Cost Evaluation of Migration towards NGOA Networks*, Journal of Optical Communications and Networking , Vol. 5, no. 12, pp. 1456-1466, December 2013.
  Evolution of optical access networks promises to bring higher bandwidth to more customers. However, this evolution towards the so-called Next Generation Optical

Access (NGOA) networks also introduces additional challenges that operators and/or vendors have to address: How to properly estimate and compare different NGOA architectures and their evolutionary paths in terms of their economics. Calculating the Total Cost of Ownership (TCO) for NGOA networks is a very complex target as it needs to involve a good knowledge of the technology, the existing network infrastructure and any migration-related process. In this paper a complete methodology is presented for evaluating the TCO of the migration towards a NGOA network (the considered costs are depicted in Figure 3.5). It contains a detailed description of which key aspects have to be considered (e.g., penetration curves as the ones presented in Figure 3.6), which process they affect and how they are translated into costs in a logical manner. Finally the paper presents an example showing the power of this methodology for the estimation of the migration scenario from GPON to TWDM PON solution. Together with GPON upgrading approach, the total four alternatives have been compared, in terms of average cost per user per year, as well as the yearly cost evolution. The average cost comparison has specified the average CAPEX and OPEX parameters for each alternative which allows the different players in telecom area to identify the key cost factors and drivers. Both operators and vendors can also utilize this approach to get useful economic background of their future investments and potential sales.

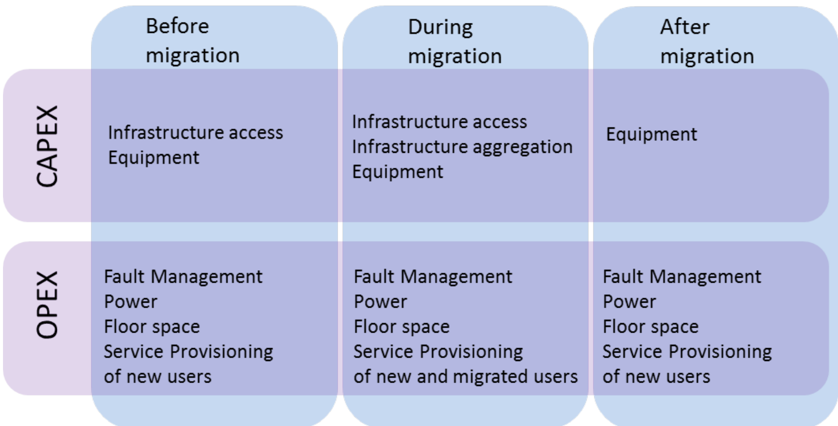



Figure 3.5: Different TCO considered at each migration phase [J9]

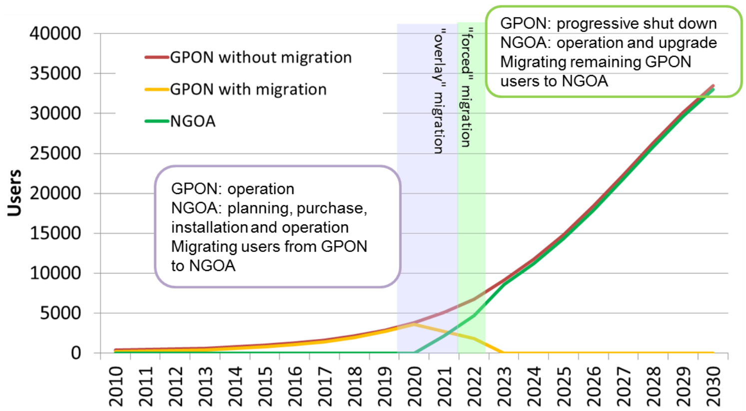



Figure 3.6: Example of penetration curve and the migrated users from existing GPON towards NGOA in 2020 and considered cost categories [J9]

- **[J10]** A. Leiva, **C. Mas Machuca**, A. Beghelli, R. Olivares, *Migration Cost Analysis for Upgrading WDM Networks*, IEEE Communications Magazine, Vol. 51, Issue 11, pp. 87-93, November 2013.

  This paper presents a generic step-by-step methodology for evaluating the total cost of migrating from a capacity-exhausted WDM network to different upgraded alternatives. The presented methodology is the first effort to provide a generic evaluation framework (allowing the evaluation of scenarios with different traffic growth rates, optical technologies, network architectures, and resource allocation algorithms) that considers both capital and operational expenditures of the upgraded alternatives to then identify the lowest-cost option. Previous works have just evaluated specific scenarios or only CapEx or OpEx (not both). As a way of illustration, the proposed methodology was applied to compare the migration cost of two upgrading scenarios using static or dynamic WDM operation with the node architectures shown in Figure 3.7. The methodology allowed identifying the lowest cost alternative, categorizing the key cost factors of CapEx and OpEx, and evaluating its impact on the migration cost. Surprisingly, results for the study case presented show that migrating to an automatically provisioned network does not necessarily lead to cost savings.

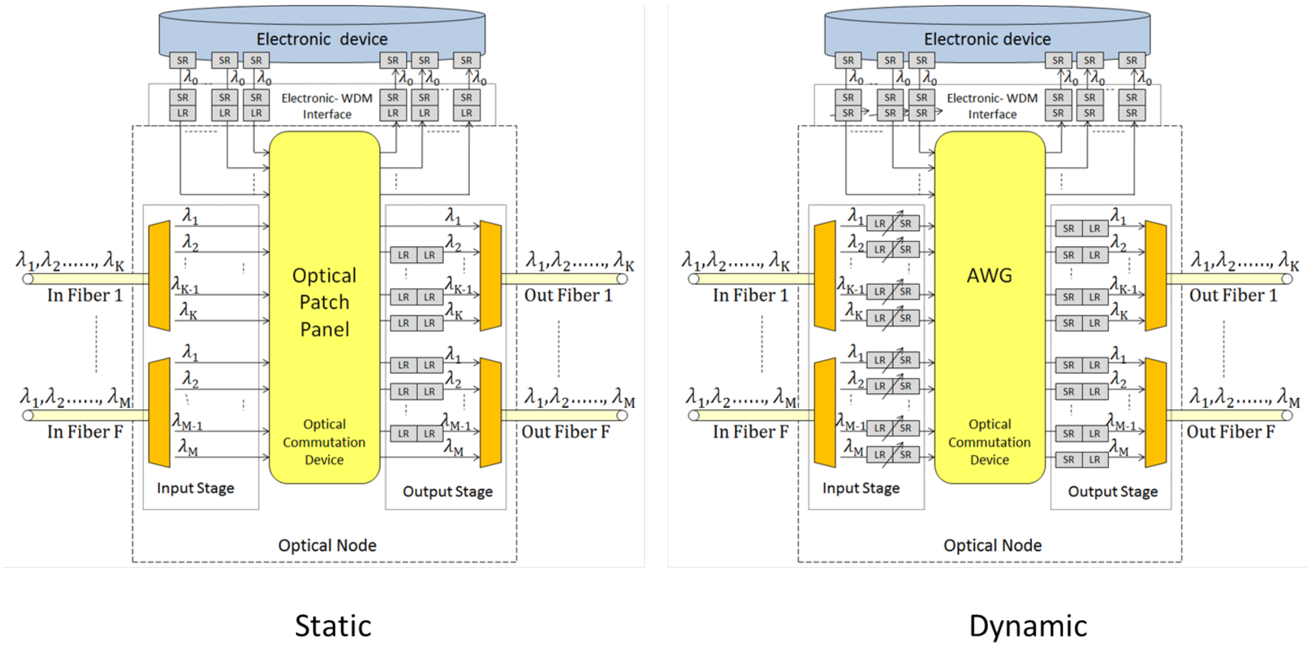



Figure 3.7: Core node architectures [J10]

## 3.3 Protection

- **[J2]** E. Grigoreva, E. Wong, M. Furdek, L. Wosinska, **C. Mas Machuca**, *Energy Consumption and Reliability Performance of Survivable Passive Optical Converged Networks: Public ITS Case Study*, OSA Journal of Optical Communications and Networking, Accepted for publication, 2017.

  Access networks are evolving fast by increasing their capacity and coverage area, coping with a larger number of users and variety of terminals. Operators aim at keeping high network performance and quality of service but limiting their capital and operational expenditures by e.g., minimizing investments and energy consumption using power saving at the network components. To address these challenges this paper evaluates energy consumption, connection availability and failure detection time of three protection schemes applicable for converged access networks: Disjoint Fiber Protection, Energy-Efficient Disjoint Fiber Protection, and Reflective Disjoint Fiber Protection. The schemes are assessed by a case study considering public Intelligent

Transport System (ITS). The studied ITS deploys a Dedicated Short Range Communications (DSRC) Radio Access Network connected to the service server through a protected passive access network. Comparison with unprotected architecture shows that the Reflective Disjoint Fiber Protection offers low energy consumption and high connection availability, while it significantly reduces the failure detection time and hence, the connection interruption time.

- **[J4]** E. Wong, **C. Mas Machuca**, L. Wosinska, *Survivable Hybrid Passive Optical Converged Network (HPCAN) Architectures Based on Reflective Monitoring*, IEEE/OSA Journal of Lightwave Technology, Vol. 34, Issue 18, pp. 4317-4328, 2016. This paper presents four survivable architectures that are compliant with the Hybrid Passive Optical Converged Access Networks (HPCAN) specifications which are able to support high client count with different bandwidth requirements, long network spans, high traffic and finally cover the need of rapid fault detection and subsequent restoration of services to users. These proposed architectures do not need to rely on upstream transmissions for Loss-Of-Signal (LOS) activation, thereby making them suitable for use with sleep/doze mode transceivers for power-saving. In networks that implement sleep/doze upstream transceivers, the transition into sleep/doze mode would result in no upstream signal transmission. If using conventional LOS activation rather than our proposed architectures to indicate equipment/fiber failure in the network, the absence of upstream transmission would result in erroneous triggering of false LOS alarm and subsequently unnecessary protection switching. The four survivable HPCAN architectures, one of these is depicted in Figure 3.8, are compared against an unprotected HPCAN using illustrative examples of three different population densities, namely covering dense urban, urban, and rural areas, and three different deployment scenarios, namely brownfield, duct reuse, and greenfield. The evaluation based on the methodology proposed in **[J5]**, compares connection availability, failure-impact-factor, yearly network energy consumption, and total network cost. Results from this study provide guidance for the choice of the best survivable

HPCAN architecture to serve each of the three considered area densities under each of the three deployment scenarios. The R-$\mu$WP architecture offers the best solution in duct reuse and greenfield deployments. Though incurring an incremental network energy consumption of up to 8% as compared to the unprotected HPCAN, the R-$\mu$WP delivers high connection availability with zero failure impact factor at the lowest total network cost for all area densities considered. For the brownfield scenario, R-DMBSP offers the best solution, providing high connection availability, low FIF, whilst incurring the lowest total network cost and incremental network energy irrespective of area density.

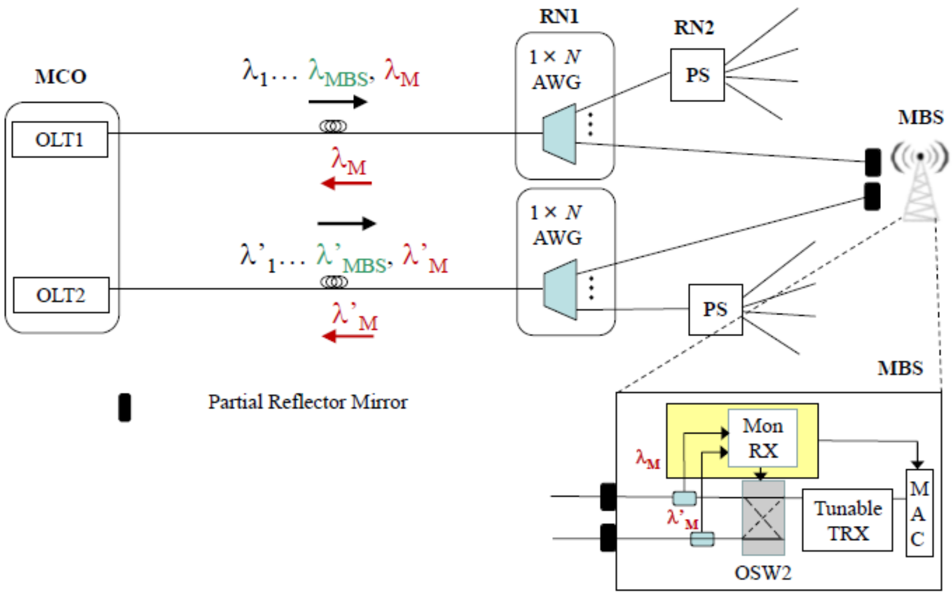



Figure 3.8: Reflective Disjoint MBS DF Protection (R-DMBSP) architecture [J4]

- **[J5] C. Mas Machuca**, L. Wosinska, J. Chen, *Assessment methodology of protection schemes for next generation optical access networks*, Optical Fiber Technology, Vol. 26, Part A, pp. 82-93, December 2015.

  This work proposes an assessment methodology that can be used to compare different protection schemes and help to identify the best suitable solution for a given scenario. The assessment criteria includes some reliability measures such as Failure

Impact Factor (FIF) and connection availability, as well as cost parameters such as the investment required in greenfield and brownfield scenarios and the increase in power consumption compared to the unprotected network. The proposed criteria have been used to compare seven representative protection schemes shown in literature, which differ mainly in the number of protected network elements and the technology used for protection (fiber, wireless, etc.). The considered protection schemes have been applied to a hybrid wavelength division multiplexing/time division multiplexing Passive Optical Network (Hybrid PON) architecture in an urban area. It has been shown that it is difficult to identify the absolute best scheme with respect to all the considered criteria. However, depending on the requirements from the operator regarding the targeted reliability performance in the network, an appropriate protection scheme can be recommended for either a greenfield or a brownfield scenario.

- **[J8]** M. Mahloo, A. Dixit, J. Chen, **C. Mas Machuca**, B. Lanoo, D. Colle, L. Wosinska, *Towards Reliable Hybrid WDM/TDM Passive Optical Networks*, IEEE Communications Magazine, Vol. 52, Issue 2, pp. S14-S23, February 2014.
  This paper looks into the migration of existing unprotected access networks towards protected networks. This study is triggered by the increasing request of high service reliability as well as the failure impact of a single failure in converged access networks with larger client count. Different degrees of resilience are proposed depending on the user profiles (partial and full protection for residential and business access, respectively as shown in Figure 3.9).
  The study showed that providing protection up to the first remote node with very low extra investment and significant improvement in resilience, especially failure impact is reduced more than 10 times compared to the unprotected case. Furthermore, providing full protection by investing less than twice of the CAPEX of an unprotected network, leads to a considerable improvement in the connection availability of the enterprises. The cost per user requiring full protection will reduce as the density of

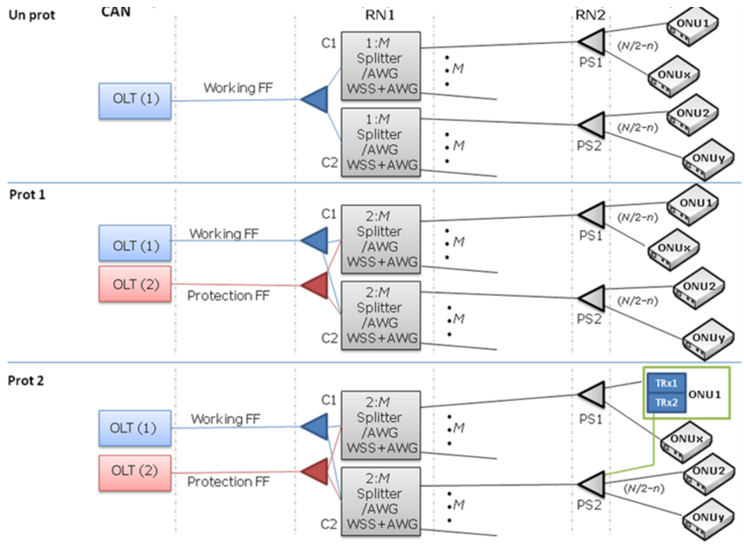



Figure 3.9: Protection upgrades paths from the unprotected scenario (Unprot) through the partial protection (Prot1) to the full protection of business users (Prot2) [J8].

protected users increases due to the higher possibility to share infrastructure. Considering future protection in the planning, allows operators to significantly reduce the CAPEX.

- [J11] **C. Mas Machuca**, J. Chen, L. Wosinska, *Total Cost Reduction Achieved by Offering Protection in PON Architectures*, Telecommunication Systems journal, Vol. 54, no. 2, pp. 129-135, October 2013.

  Protection of access networks has been always considered to be too expensive. This work proposes a new way to provide protection in TDM and WDM PONs for three different type of areas: sparse, sparse/dense and dense areas. An efficient network planning is able to provide protection with very low extra investment. It is shown that in this way the total cost per user can be effectively reduced due to the savings in terms of penalty costs related to the connection unavailability. The cost benefits have been shown to be crucial for business users but it is expected to also concern the residential users in the near future. The proposed way to deploy working/protection FFs and DFs can be compatible with next generation PON.

- **[J12]** M. Mahloo, **C. Mas Machuca**, J. Chen, L. Wosinska, *Protection cost evaluation of WDM-based Next Generation Optical Access Networks*, Optical Switching and Networking Journal, Vol. 10, Issue 1, pp. 89-99, January 2013.

  New technologies and advanced network devices make it possible to move towards high capacity access networks able to satisfy the growing traffic demand. Wavelength division multiplexing (WDM) is considered as one of the promising technologies for the next generation access networks since it offers higher bandwidth and longer reach compared to the current technologies (such as time division multiplexing (TDM) based networks). However, the migration to a new technology is typically based on an overall techno-economic study which should assure the network operator that the new implementation is cost effective and profitable while able to provide the required services to the users. Another important aspect in the access network design is the network reliability performance, which can be improved by providing a certain level of protection for equipment and/or infrastructure with high failure impact ratio in order to prevent a big number of the users being affected by a single failure. The cost of protection should be carefully evaluated since providing the backup resources may be too expensive for a network operator.

  In this paper, we investigate the capital and operational expenditures for two next generation optical access (NGOA) networks based on the WDM technology in dense urban areas. Three scenarios with different splitting ratios are studied for each technology, with and without protection. The aim of this work is to investigate the impact of providing protection on the total cost of NGOA networks. The results show that in the dense urban areas the fibers and digging costs are highly shared among the end users but still vary according to the splitting ratios for different scenarios and the fiber layout. It also can be seen that with a proper fiber layout design, minor extra investment for protection of NGOA networks can make a significant saving on failure related operational cost and that operational expenditures depend significantly on the fiber layout.

## 3.4 Virtualization

- **[C15] C. Mas Machuca**, T. Krauss, A. Basta, E. Grigoreva, W. Kellerer, *Alternatives for the automotive industry to become an MVNO*, 16th International Conference on Transparent Optical Networks, Graz, Austria, July 2014.
  Mobile services are evolving rapidly, moving from their conventional mobile voice to a wider portfolio such as Internet access, entertainment, health, and also location-based services. A wide range of on-board mobile services with very different requirements is also offered by automotive manufacturers. They rely on Mobile Network Operators (MNOs) to offer the expected connectivity and QoS in markets worldwide. However, this solution is inflexible, offers limited network control, is highly dependent on the MNO coverage, and can incur costly roaming fees. These disadvantages can be overcome by the automotive manufacturer when owning a set of the mobile network components, which is referred in this paper as becoming a Mobile Virtual Network Operator (MVNO). This approach is expected to allow the automotive manufacturers to increase potentially their network control, the coverage (e.g., by being more flexible to connect to different MNOs), and reduce connectivity costs. This paper proposes two different MVNO models, Subscriber MVNO and Full MVNO. It has been shown that the Subscriber MVNO is able to have access to the user subscriber data at low cost. On the other hand, at a higher cost, the Full MVNO is also able to push the MVNO's own downlink policies as well as to have its own roaming agreements. As this paper represents a first approach towards MVNO modeling for AMs, further work will be devoted to a deeper comparison of MVNO models.

- **[C3]** P. Stojsavljevic, **C. Mas Machuca**, W. Kellerer, *Controller Placement Strategies for a Resilient SDN Control Plane*, Reliable Networks Design and Modeling (RNDM), 2016 8th International Workshop on, Halmstadt, Sweden, September 2016.
  Software Defined Networking (SDN) offers efficient network control and management by introducing a logically centralized control plane. However, outsourcing of the con-

trol plane intelligence to an SDN controller requires reliable switch to controller connection. This paper presents two strategies to address the Reliable Controller Placement (RCP) problem, which aims at protecting the control plane against failures and providing seamless failover mechanism by exploiting the principles of resilient routing. The first approach considers that switches have to be connected to a controller over two Disjoint Control Paths (RCP-DCP). The second approach considers that switches have to be connected to two Different Controller Replicas (RCP-DCR) over two disjoint paths. Both approaches are finding working and protection control paths of minimum length to enable fast and efficient failover. In this paper, the two models have been compared with respect to the unprotected scenario, in terms of control path length, expected control path loss in different failure scenarios and average control plane availability. The results show that both models RCP-DCP and RCP-DCR improve significantly the resilience of the control plane, while adding very limited penalty to the average control path length. If link failures are the dominating failures, both RCP-DCP and RCP-DCR offer similar performance and the best strategy depends on the topological characteristics and the number of the controllers in the network. RCP-DCR provides additional protection against controller failures and it shows better performance when node failures are dominating or are comparable to link failures.

- **[C2] C. Mas Machuca** et al. *Technology-related Disasters: A Survey towards Disaster-resilient Software Defined Networks*, 8th International Workshop on Resilient Networks Design and Modeling, 2016, Halmstad, Sweden, September 2016.

  Resilience against disaster scenarios is essential to network operators, not only because of the potential economic impact of a disaster but also because communication networks form the basis of crisis management. COST RECODIS aims at studying measures, rules, techniques and prediction mechanisms for different disaster scenarios. This paper gives an overview of different solutions in the context of technology-related disasters. After a general overview, the paper focuses on resilient Software

Defined Networks (SDN).

- **[C1]** P. Stojsavljevic, M. Condoluci, **C. Mas Machuca**, T. Mahmoodi, W. Kellerer, *QoS-driven Function Placement Reducing Expenditures in NFV Deployments*, IEEE International Conference on Communications (ICC), Paris, France, May 2017
Network Function Virtualization (NFV) applies the concept of virtualization to network functions so that they can be deployed as modular software components on the commodity hardware, instead of specialized hardware boxes. These network functions (e.g Network Address Translation, firewall, Intrusion Detection System) can be chained to provide services. Network operators offer different services to their users and their expected requirements are specified in Service Level Agreements (SLAs) which include for example the maximum tolerated delay or the minimum availability. However, the most of the existing solutions focus on delay related requirements, neglecting the importance of the service availability.
This work presents mechanisms to place virtualized network functions so that support service differentiation in terms of delay and availability while minimizing the associated costs. We present two solutions: an ILP formulation and an efficient heuristic to obtain near optimal solution. Considering a national core network as our case study, we show that the proposed virtual function placement solutions are able to guarantee both delay and availability requirements, and imply only a limited increase of used network resources. Finally, we show that the solving time of the proposed heuristic scales well with the size of the problem.

# Chapter 4

# Conclusions and further directions

Techno-economic studies are crucial for any telecom player in order to take decisions on their networks, components, services, etc. This work has proposed different methodologies to evaluate the viability of new solutions in access and core networks, to identify best migration path and time, as well as to optimize solutions (e.g., best locations for equipment, best fiber layout, best technicians locations) to reduce costs. These methodologies have been applied to address different studies such as next generation optical access networks, dynamic optical core networks and SDN and NFV.
Actual research is being performed on the following areas:

- Converged access planning for Intelligent Transport Systems (ITS) and fixed users using different wireless and wired technologies.
  Different types of end points with various requirements in terms of bandwidth, delay and connection availability are being considered.

- Include optimization techniques to the ArcGIS network planning to find optimal network layout. The tool is further extended to combine different technologies (e.g., optical fiber and mobile).

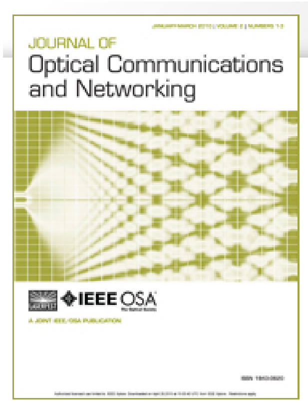
- Extend planning and protection schemes to 5G scenarios which include a large number of end points with high bandwidth and reliability requirements.

- Adapt the planing methodology to SDN/NFV networks e.g., proposing cost and component models.
- Propose cost models for SDN/NFV and data centers. Use the proposed cost models to optimize their planning by minimizing cost as well as guaranteeing the requirements in terms of bandwidth and availability.

# Chapter 5

# Most Relevant Papers

## 5.1 Paper J2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# Energy Consumption and Reliability Performance of Survivable Passive Optical Converged Networks: Public ITS Case Study

E. Grigoreva, E. Wong, M. Furdek, L. Wosinska and C. Mas Machuca

***Abstract*— Access networks are evolving fast by increasing their capacity and coverage area, coping with a larger number of users and variety of terminals. Operators aim at keeping high network performance and quality of service but limiting their capital and operational expenditures by e.g., minimizing investments and energy consumption using power saving at the network components. To address these challenges this paper evaluates energy consumption, connection availability and failure detection time of three protection schemes applicable for converged access networks: Disjoint Fiber Protection, Energy-Efficient Disjoint Fiber Protection, and Reflective Disjoint Fiber Protection. The schemes are assessed by a case study considering public Intelligent Transport System (ITS). The studied ITS deploys a Dedicated Short Range Communications (DSRC) Radio Access Network connected to the service server through a protected passive access network. Comparison with unprotected architecture shows that the Reflective Disjoint Fiber Protection offers low energy consumption and high connection availability, while it significantly reduces the failure detection time and hence, the connection interruption time.**

***Index Terms*— Next generation optical access (NGOA), energy consumption, failure location**

## I. Introduction

Access networks are rapidly evolving to accommodate larger and more diverse types of terminals, services, bandwidth demands and higher reliability requirements. Further, advancements in the underlying technology are allowing for a decrease of components costs (e.g., colorless Optical Network Units (ONUs) [1]) and an increase of the passive reach. Consequently, operators are considering the migration of existing access networks (e.g., combining optical fiber and copper or using GPON) to new architectures in order to support potential new requirements (e.g. higher bandwidth, higher availability) but at limited cost.

One possible approach considered by operators is to deploy Hybrid Passive Optical Networks (HPONs) in their network domain. This architecture, as shown in Fig. 1, combines Wavelength Division Multiplexing (WDM) using wavelength demultiplexers such as Array Waveguides (AWG) with Time Division Multiplexing (TDM) based on Power Splitters (PS). Such HPON architecture offers several advantages:

- Similar to GPON with Dynamic Bandwidth Allocation (DBA) but coping with higher bandwidth range (MBS get a full wavelength), HPON supports terminals with different bandwidth requirements, whereby terminals with lower bandwidth requirements, e.g., residential users, are connected to the PS whereas terminals with higher bandwidth requirements, e.g., Macro Base Stations (MBS), are connected directly to the AWGs.
- It can reuse any existing Optical Distribution Network (ODN) already deployed by the operator. For example, the HPON can reuse the ODN and the power splitter of an already deployed Gigabit Passive Optical Network (GPON).
- It allows greater maximum reach and hence, supports node consolidation with a reduced number of central offices. Node consolidation offers cost reductions through a lower number of active components, lower power consumption, less floor space, etc. [2].
- HPON can support a large client count which in turn depends on the splitting ratio of the AWG and the PS. Some possible examples as outlined in [3] combine AWGs of 40 and 80 wavelengths with 1:32 power splitters which results in more than 1200 and 2500 terminals, respectively.

HPON can serve as the underlying architecture to support converged access networks [4], whereby the same architecture can be used to interconnect different types of terminals (residential users, business users, MBSs, small cells, *etc.* based on their bandwidth requirements. To date, operators deploy different networks for different types of access clients, e.g., MBS and residential user are connected to different access networks. Having independent networks can be costly to install, deploy and maintain.

As noted earlier, aside from bandwidth, reliability performance is also increasingly important in the deployment of future access networks. The diversity of services and terminals could lead to higher connection availability requirements than that currently offered by existing unprotected access networks. One important concern of network operators is to find a compromise between the investments required to offer protected access and the expected increase of revenues from customers (i.e., how much are the customers willing to pay for increased network reliability performance. Different solutions have been proposed for HPON architectures, aiming to reduce the required investments [5], energy consumption and failure detection time [6].

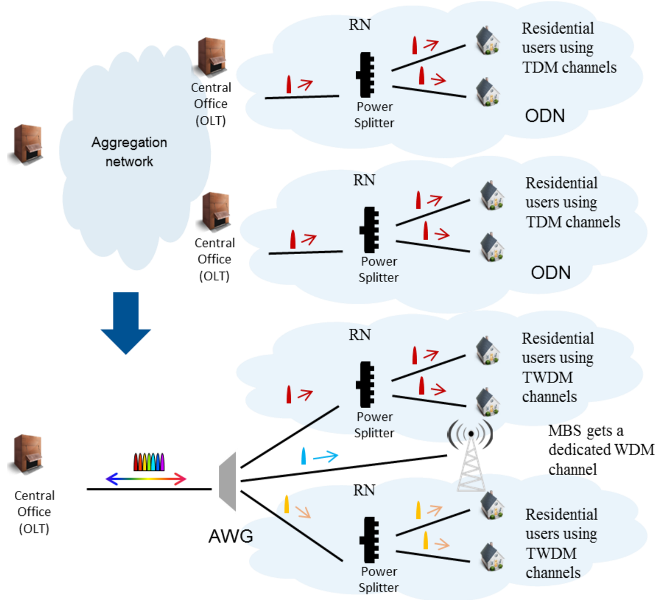


Fig. 1 Example of migration of a conventional power splitting access network (top of the figure) towards a Hybrid Passive Optical Network (HPON) solution (bottom of the figure)

The vast majority of optical access network studies are focused on telecom operators and their case studies to interconnect cabinets, MBSs, buildings, etc. In contrast, in this paper, we consider a different case study: Intelligent Transportation System (ITS). ITS was introduced in the early nineties and can be defined as a system in which information and communication technologies are applied to improve safety, transport efficiency, and provide information and entertainment. Unlike conventional communication systems, an ITS requires high reliability and low failure detection time for the road safety applications. Conversely, it is imperative that the survivability performance of any deployed ITS is critically studied. Generally, ITS is not bound to a specific technology [7]. The most prospective ITS technologies are Long Term Evolution (LTE) and IEEE 802.11p or Dedicated Short Range Communications (DSRC) [8]. To date, only some of the ITS services are realized with most of them yet to be implemented, especially those relating to safety applications. For the intended implementations in some countries like in USA [9], DSRC was chosen as the main technology for ITS realization.

In this paper, we apply HPON protection schemes to the ITS infrastructure based on the DSRC Radio Access Network (RAN). To narrow the scope of ITS, we explore the applicability of three HPON protection schemes to on-ground public transport, such as the bus, tram and trolleybus lines.

The focus of our case study lies in the backhaul infrastructure provisioning for DSRC-based RAN. Fig. 2 presents the scenario under investigation. The backhaul connects DSRC base stations or Road Side Units (RSUs) to the Service Server (SS) for centralized processing and control. As the maximal data rate supported by DSRC RSUs is only up to 54Mbps [10], GPON can be used for the backhaul.

In our setup, Service Server (SS) is collocated with the OLT, at the central office. The fiber between the OLT and Power Splitter (PS) is referred to as Feeder Fiber (FF). The fiber between PS and ONU is Last Mile Fiber (LMF). All ONUs are collocated with the respective RSUs.

The tree topology of the network with no redundant links makes the ITS vulnerable to link cuts which, depending on the particular location of the cut, may leave a great number of RSUs unconnected and jeopardizing the effectiveness of the ITS. In order to ensure connectivity in the presence of link cuts, a protection scheme must be deployed, taking into consideration various trade-offs between the different schemes.

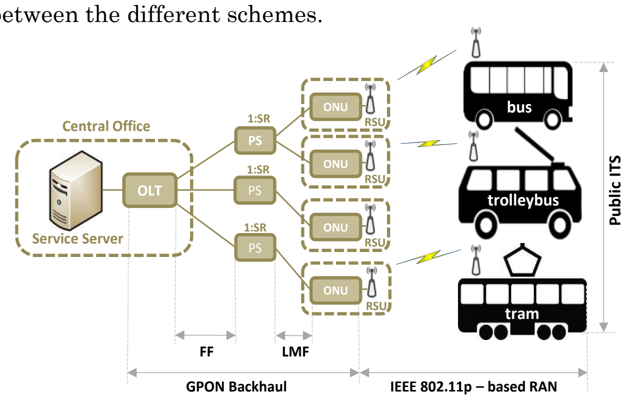


Fig. 2 Communication Network Infrastructure for public ITS with DSRC-based RAN and GPON backhaul

This paper aims at comparing power consumption, connection availability and failure detection times of three different protection schemes for HPON architectures, applied to a particular case study of ITS. The details of these three protection schemes are presented in Section II. In Section III, the ITS case study and the considered network including the user activity, network planning, and evaluation methodology, are described. Evaluation results are then presented in Section IV. Finally, the main conclusions are drawn and summarized in Section V.

## II. Protection Schemes

Due to the high bandwidth and connection availability required by RSUs, this paper aims at comparing different solutions to provide protection to RSUs. Note that each RSU is collocated with its corresponding ONU. In that respect, three HPON protection alternatives proposed in [6] are presented here and compared against the unprotected HPON architecture (refer to Fig. 1) in terms of energy consumption, connection availability and failure detection time. The architectures are termed: (a) disjoint fiber protection HPON (denoted as P-Active); (b) energy-efficient disjoint fiber protection HPON (denoted as P-A&S); and (c) reflective disjoint fiber protection HPON (denoted as RP). Note that in the descriptions of the studied architectures, a two stage network with two Remote Nodes (RNs) is considered to reflect practical deployment scenarios where RN1 implements the wavelength de/multiplexing function and RN2 implements the power splitting function. Also note that, in order to achieve protection and survivability, active components are added only to CO and RSUs, leaving the optical distribution network completely passive to allow reuse of legacy TDM-PONs for HPON deployments. The three protected HPON architectures considered in this work are described as follows.

### A. *Disjoint Fiber Protection (P-Active)*

The disjoint fiber protection HPON architecture (denoted as P-Active) is a protection scheme whereby both the Feeder Fiber (FF) and Last Mile Fiber (LMF) of each ONU are protected. As illustrated in Fig. 3, this architecture provides 1:1 protection where each RSU is connected to the CO via a disjoint FF *and* a disjoint DF. Here, the standard definition of disjointness is considered whereby disjoint fibers are those located in different geographically separated ducts. In contrast to the unprotected HPON architecture, redundant and additional components/ equipment are deployed at the CO, RN, and ONU to achieve protection. At the CO and ONU, an additional optical switch denoted as OSW1 and OSW2 in the figure, respectively, is implemented for protection switching. At RN1, two 1×2 couplers and two 2×N AWGs are deployed.

Under normal operating conditions, OSW1 and OSW2 are in BAR state with upstream and downstream traffic traversing the primary FF and the primary DF. When a failure (primary FF, primary DF, 1×2 coupler, or AWG) occurs, a Loss of Signal (LOS) is detected at the CO and the RSU, which triggers OSW1 and OSW2 to change to the CROSS state and shift the traversing signals onto the disjoint protection paths.

### B. *Energy-Efficient Disjoint Fiber Protection (P-A&S)*

The Energy-efficient Disjoint Fiber Protection scheme (denoted as P-A&S) has the same architecture as the P-Active architecture but as alluded to by its name, this protection HPON architecture achieves high energy-efficiency due to the sleep state capability of its ONUs (integrated with RSUs in this study) [11]. In this architecture, ONUs can transition between an active and a sleep state where the latter supports powering down transceivers to save energy when no data is to be transmitted/received, i.e. during quiet period. The drawback of this scheme is that failures that occur during the quiet period will be detected only when the ONU transitions back to the active state. Hence, the outage duration and, consequently, the penalty on operators will be larger than in P-Active albeit P-A&S is more energy-efficient.

Another drawback of the P-A&S architecture is that the SS, which relies on LOS of upstream transmissions to detect failures in the network, may erroneously trigger protection switching of OSW1 when all ONUs are in a sleep state. Loss-of-Signal is commonly used in conventional networks to detect the occurrence of an equipment/fiber failure and to trigger protection switching of the affected traffic onto the backup path. A LOS alarm will be activated at the headend if an incoming signal has no transitions over a period of 175±75 contiguous pulse intervals (ITU-T G.775 [12]). Using the absence of incoming transmissions to detect failures and trigger LOS alarm is therefore ineffective in P-A&S since (a) ONUs in sleep state have zero output power and may erroneously set off the LOS alarm at the CO and (b) an ONU in sleep state cannot continuously monitor the network until it transitions out of the sleep state to reinstate LOS monitoring.

### C. *Reflective Disjoint Fiber Protection (RP)*

The Reflective Disjoint Fiber Protection (denoted as RP) addresses the limitations of the P-A&S by employing an out-of-band continuous wave monitoring signal, $\lambda_M$ [6]. Here, $\lambda_M$ is spaced an integer multiple of the AWG's free spectral range away from the ONU's downstream and upstream wavelength channels. Such wavelength assignment allows $\lambda_M$ to be detected at and reflected from the ONU.

The RP architecture, depicted in Fig. 4, achieves the energy efficiency of the P-A&S scheme by allowing sleep state in quiet periods, while it also enables fast failure detection. Compared to an unprotected HPON, this architecture requires additional equipment to facilitate protection. This includes an optical switch (OSW1), two WDM filters, and a monitoring module at the CO; two 1×3 couplers and two 2×N AWGs at RN1; and two WDM filters, an optical switch (OSW2), and a monitoring receiver (MON RX) at each ONU. Under normal working conditions, $\lambda_M$ is launched into the ODN and a fraction of the optical power of $\lambda_M$ is reflected at the AWG. The reflected $\lambda_M$ is then detected back at the monitoring module at the CO.

In the event of a working path failure, the reflected $\lambda_M$ is absent at the OLT thereby triggering the transition of OSW1 into CROSS state. Also, the absence of $\lambda_M$ at the ONU triggers the transition of OSW2 into CROSS state and traffic is sent through the protection LMF. This RP architecture does not rely on upstream transmissions to trigger LOS alarm. Consequently, failures can be continuously monitored during quiet period when ONUs are in the sleep state.

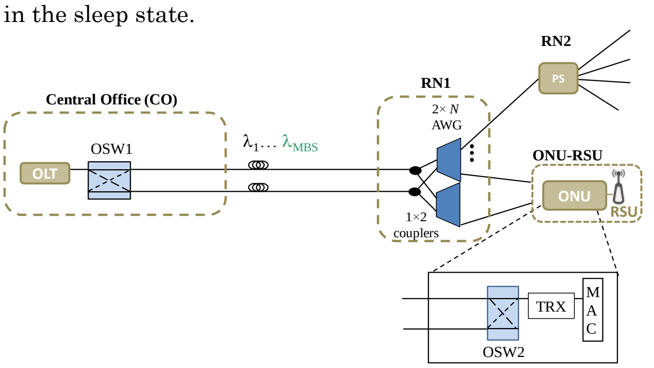


Fig. 3 Disjoint Fiber Protection (P-Active) and Energy-Efficient Disjoint Fiber Protection (P-A&S) HPON architecture

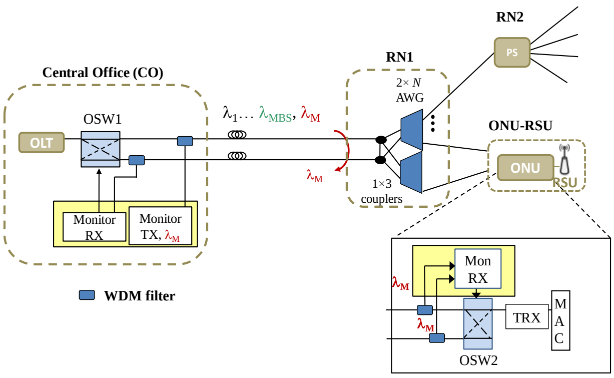


Fig. 4 Reflective Disjoint Fiber Protection (RP) HPON architecture

## III. Public ITS Case Study

A first comparative study of energy consumption, connection availability, failure detection time and restoration time in the presence of failure was carried out in [13], considering residential users and LTE MBS for different areas given average traffic models available in literature. In this paper, we consider a real case study of a public ITS aiming at providing services for buses, trams and trolleybus in the central area in Munich (Germany) of approximately 7 km².

ITS research normally focuses on the technology applicability, while neglecting the infrastructure implications, e.g., [10]. The implications, on network planning, protection and power consumption are significant. The public ITS network is more sparse than FTTB, requires higher reliability, but at the same time can be less bandwidth-demanding compared to residential users. As ITS is planned for implementation, for example USA has decided on DSRC-based ITS implementation [14], it is crucial to understand the aforementioned factors that differ from conventional networks.

In this section, we introduce the case study methodology. We define the scenario, user activity patterns and explain network planning concepts. Finally, we present the parameters and equations for power and availability calculations.

## A. *User RSU Activity Description*

An advantage of focusing on public ITS is the availability of information regarding the activity times of public transport. Fig. 2 illustrates the used case study scenario, which we use in this work evaluation. This scenario was first introduced in [15]. The RSU and thus the ONU placement is fixed, that is, the placement is based on offering coverage along all considered routed ITS, e.g. day and night busses. In our study, based on DSRC radio access, the inter-station distance between the RSUs is 500m due to communication range limitations of DSRC [16]. Such placement results in 38 RSUs and corresponding ONUs.

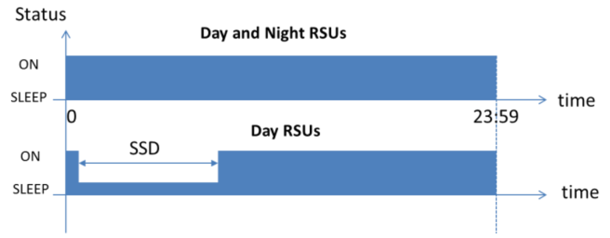


Fig. 5 Sleep Slot Duration (SSD) for public ITS

For the RSUs that are active only during the day, we predetermine its sleep duration by considering the time slot when all RSUs are not used, that is, the time when no transport (i.e., no buses, trams nor trolleybus) circulate through the area covered by the RSU. Fig. 5 illustrates the physical meaning of SSD. As timetables are different for working days, weekends and holidays, we consider a minimal and a maximal SSD. Table I provides details of the two groups of RSUs, day RSUs and day and night RSUs. The minimal SSD and RSU allocation to day or day and night was obtained from route timetables[1] that are publically available [17]. The maximal SSD was arbitrarily chosen for comparison purposes. This value can be seen as an upper bound for the sensitivity analysis or a maximum time, representing weekend, holiday, other city and other timetable differences.

TABLE I
RSU ACTIVITIES BASED ON ON-GROUND PUBLIC TRANSPORT ACTIVITY

| Day RSUs, id | | Day and Night RSUs, id |
|---|---|---|
| *3,4,12,13,16,17, 19, 20, 25, 26, 27, 28, 29, 30, 31, 33, 35, 36* | | *1, 2, 5, 6, 7, 8, 9, 10, 11, 14, 15, 18, 21, 22, 23, 24, 32, 37, 38* |
| *Min. SSD* | *Max. SSD* | *Always active* |
| *3h10m* | *12h* | |

## B. *Network planning*

Once a set of RSUs and their activities are defined, we first need to plan the network, i.e., define the interconnections between the RSUs (ONUs), PSs and CO. In our case study, network planning consists of two parts: RSU clustering and fiber routing. RSU clustering can be done *independently* from the user activity pattern, i.e., based solely on geographic position with the objective to minimize the overall fiber length. This option is referred to as "*ind*". Alternatively, the RSUs can be grouped *depending* on the activity pattern, i.e., clustering the day RSUs and the day and night RSUs into separate clusters. In this case, it is possible to put some OLT ports to sleep if all RSUs (and ONUs) belonging to the PS connected to an OLT port are put to sleep. This approach is referred to as "dep" and it has potential to save more energy.

We further explore two RSU clustering scenarios: greenfield and brownfield. In *greenfield* scenario there is no prior infrastructure available. We investigate this setting using PSs with different Splitting Ratios (SR): 8, 16 and 32 considering an 80% port use (the remaining unused 20% of ports are kept for redundancy or future use [5]). In *brownfield* scenario there is an existing GPON infrastructure for FTTB with SR = 32 and 80% port use. This leaves us with seven ports at the PS that are free for ITS implementation.

For fiber routing, we use the shortest path algorithm in street metric, thus yielding a geographical planning approach. The maps used for our case study are Open Street Maps [18]. Routing scripts and all the geography related processing was performed using ArcGIS [19].

## C. *Power and Connection Availability*

In this subsection, we describe the methodology used in evaluating the power and connection availability of the three protection HPON architectures. We present the yearly power consumption for the active components of the GPON backhaul network. We use graphical representation of Reliability Block Diagrams (RBDs) to describe equations for connection availability. All calculations are carried out for the four cases of HPONs: unprotected (UP), P-Active, P-A&S and RP.

TABLE II
GPON COMPONENT PARAMETERS [21]

| Element | | Power, W | | Availability | |
|---|---|---|---|---|---|
| Active Components | | | | | |
| *OLT* per port[1] | active | 13 | $P_{OLTport}^{active}$ | 0.9999638 | $a_{OLT}$ |
| | sleep[2] | 3.9 | $P_{OLTport}^{sleep}$ | | |
| *ONU* | active | 5 | $P_{ONU}^{active}$ | 0.999961 | $a_{ONU}$ |
| | sleep | 0.75 | $P_{ONU}^{sleep}$ | | |
| *OS* | | 1 | $P_{OS}$ | 0.999994 | $a_{OS}$ |
| *TxMon* | | 1 | $P_{TX\_mon}$ | (0.9999994) [3] | |
| *RxMon* | | 1 | $P_{RX\_mon}$ | (0.9999994) [3] | |
| Passive Components | | | | | |
| PS | | - | - | 0.999999 | $a_{PS}$ |
| Coupler | | - | - | 0.9999993 | $a_c$ |
| *WDM filter* | | - | - | 0.999994 | $a_f$ |
| *Fiber per km* | | - | - | 0.9999857 | $a_{km}$ |

[1] Derived from [13] for SR = 32.
[2] Based on [23]
[3] The value is stated for completeness. See Eqn. 1-3.

Table II summarizes the GPON component parameters. Although GPON is a passive network, the transceivers in the CO and ONU are active and thus consume energy. At the CO, each OLT port can transition to sleep mode if all connected ONUs are in the sleep mode.

A port in sleep mode consumes only 30% of the power consumed in the active state [23]. Here the Layer 2 optical equipment, i.e., switching, is excluded from power consumption calculations. It is important to point out that the values were obtained by only considering the physical layer OLT power consumption. For the protection case, further active elements are added, for example Optical Switches (OSs), monitoring transmitters (TxMons) and receiver (RxMons).

*Power.* First, we define power consumption for the unprotected and P-Active protection architectures. The active components in this case are never put to sleep. The total energy consumption per year can be then calculated as:

$$P^{UP} = (P_{OLT_{port}}^{active} \cdot N_{PS} + P_{ONU}^{active} \cdot N_{ONU}) \cdot 24 \cdot \frac{365}{1000} \quad (1),$$

$$P^{P-Active} = \left(P^{UP} + P_{OS} \cdot (N_{PS} + N_{ONU})\right) \cdot 24 \cdot \frac{365}{1000} \quad (2),$$

where $N_{PS}$ and $N_{ONU}$ are the numbers of PSs and ONUs, respectively. Further, we adopt the notation of $N_{element}$ to denote the number of any network element.

In the unprotected case, the active components are the OLT ports and ONUs, as represented by Eqn. 1. For the P-Active protection case, Eqn. 2, we add one OS for the OLT and an OS per ONU to provide protection. Thus, consumed energy is determined by the number of PSs and ONUs.

In P-A&S and RP, equipment can be put to sleep to save power. An ONU can transition to sleep outside activity hours. In our case, the RSUs and their corresponding ONUs that are active during the day can be put to sleep during SSD. However, an OLT port can be put to sleep only if all the ONUs connected to the same PS are in sleep mode. If during assignment of ONUs to PSs, we do not take into account user activity patterns, the OLT ports will, in most of the cases, not be transitioned to sleep. The power consumption for P-A&S are described as follows:

$$P_{ind}^{P-A\&S} = (P_{(24-T_{SSD})}^{ind(P-A\&S)} + P_{T_{SSD}}^{ind(P-A\&S)} + P_{24}^{ind(P-A\&S)}) \cdot \cdot \frac{365}{1000}, \quad (3)$$

whereby the three terms on the Right Hand Side (RHS) represent the power consumption of the network components that are active during the various intervals of the day. The first term represents power consumption in the time interval $(24 - T_{SSD})$, in which all ONUs are active (day):

$$P_{(24-T_{SSD})}^{ind(P-A\&S)} = P_{ONU}^{active} \cdot N_{ONU} \cdot (24 - T_{SSD}). \quad (4)$$

The second term represents power consumption of the $T_{SSD}$, i.e., sleep time (SSD) or night, in which the day ONUs are in a sleep mode and only the night ONUs are active:

$$P_{T_{SSD}}^{ind(P-A\&S)} = \left(P_{ONU}^{sleep} \cdot N_{ONU}^{day} + P_{ONU}^{active} \cdot N_{ONU}^{night}\right) \cdot T_{SSD} \quad (5)$$

Finally, the last term of the RHS represents power consumption of the OS and OLT ports that are always active:

$$P_{24}^{ind(P-A\&S)} = ((N_{PS} + N_{ONU}) \cdot P_{OS} + P_{OLT_{port}}^{active} \cdot N_{PS}) \cdot 24 \quad (6)$$

For RP, the general equation of its power consumption is the same as (3) but with the additional power contributions from active monitoring components. Hence:

$$P_{24}^{ind(RP)} = ((N_{PS} + N_{ONU}) \cdot P_{OS} + (P_{TX\_mon} + P_{RX_{mon}}) \cdot \cdot N_{PS}^{day} + P_{RX\_mon} \cdot N_{ONU}^{day} + P_{OLT_{port}}^{active} \cdot N_{PS}) \cdot 24 \quad (7)$$

As discussed in Section III.B, RSUs can be grouped *depending (dep)* on the activity pattern. In this case, some OLT ports can be transitioned to sleep mode during the $T_{SSD}$. The number of such ports corresponds to the number of PSs, for which all connected ONUs can be simultaneously transferred to the sleep mode. In our case, all day ONUs can be put to sleep during $T_{SSD}$. Power consumption in $T_{SSD}$. interval is then composed of active and sleep parts. The active part is due to active (always-on) ONUs and their corresponding OLT ports. The sleep part, respectively, is due to day ONUs and their corresponding OLT ports:

$$P_{T_{SSD}}^{dep(P-A\&S)} = \left(P_{ONU}^{active} \cdot N_{ONU}^{night} + P_{OLT_{port}}^{active} \cdot N_{PS}^{night} + + P_{ONU}^{sleep} \cdot N_{ONU}^{day} + P_{OLT_{port}}^{sleep} \cdot N_{PS}^{day}\right) \cdot T_{SSD} \quad (8)$$

During the time $(24 - T_{SSD})$, all the ONUs and thus OLT-ports are active. The power consumption in the time interval $24 - T_{SSD}$ can be calculated as:

$$P_{(24-T_{SSD})}^{dep(P-A\&S)} = \left(P_{OLT_{port}}^{active} \cdot N_{PS} + P_{ONU}^{active} \cdot N_{ONU}\right) \cdot \cdot (24 - T_{SSD}). \quad (9)$$

Finally, OSs are active 24h:

$$P_{24}^{dep(P-A\&S)} = P_{OS} \cdot (N_{PS} + N_{ONU}) \cdot 24. \quad (10)$$

RP power consumption differs from the P-A&S only in the 24h power component due to the presence of the monitoring system and is given by:

$$P_{24}^{dep(RP)} = \left(P_{OS} \cdot \left(N_{PS} + N_{ONU}^{day}\right) + (P_{TX_{mon}} + P_{RX_{mon}}) \cdot \cdot N_{PS}^{day} + P_{RX_{mon}} \cdot N_{ONU}^{day}\right) \cdot 24. \quad (11)$$

*Connection availability* is defined as the probability that a connection is in an operable state at a random point of time. The commonly used availability model is graphically illustrated by Reliability Block Diagram (RBD) [20], where blocks represent components which are connected in series and in parallel from a reliability point of view. The availability of each component $i$ is denoted by $a_i$, see Table II. The calculation takes into account the average fiber length. We define average FF availability as $a_{FF} = a_{km}{}^{l_{FF}}$, where $l_{FF}$ is the average FF length in km. We define LMF availability, $a_{LMF}$, in the same way. Protection elements are labelled following the working path notation, but with a dash, e.g., $a_{FF'}$.

The RBD for the UnProtected (UP) architecture is shown in Fig. 6. The RBD consists of the blocks representing OLT, FF, PS, LMF and ONU connected in series and hence, the availability, denoted by $a_{con}^{UP}$, can be computed as the product of their availabilities (Eqn. 12).

$$a_{con}^{UP} = a_{OLT} \cdot a_{FF} \cdot a_{PS} \cdot a_{LMF} \cdot a_{ONU} \quad (12)$$

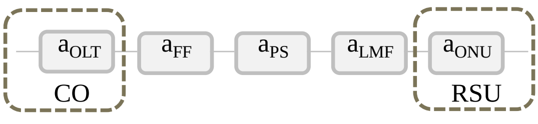


Fig. 6 RBD of the UnProtected (UP) architecture

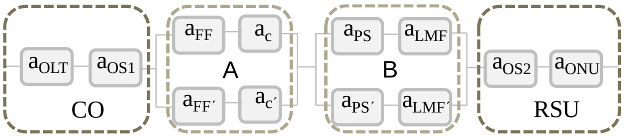


Fig. 7 RBD of the P-Active or P-A&S architectures

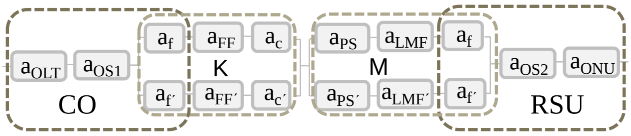


Fig. 8 RBD of the RP architecture

Having the same network components, P-Active and P-A&S feature the same RBDs, shown in Fig. 7, and availability calculation, expressed by Eqn. 13, as the network components are the same. Here $a_c$ stands for the availability of the coupler.

$$a_{con} = a_{OLT} \cdot a_{OS1} \cdot a_A \cdot a_B \cdot a_{OS2} \cdot a_{ONU} \tag{13}$$
$$a_A = 1 - (1 - a_{FF} \cdot a_c)(1 - a_{FF'} \cdot a_{c'})$$
$$a_B = 1 - (1 - a_{PS} \cdot a_{LMF})(1 - a_{PS'} \cdot a_{LMF'})$$

For the RP architecture, we have additional filter components ($a_f$) that influence connection availability model, as shown in Fig. 8. The RP connection availability can be calculated as follows:

$$a_{con} = a_{OLT} \cdot a_{OS1} \cdot a_K \cdot a_M \cdot a_{OS2} \cdot a_{ONU}, \tag{14}$$
$$a_K = 1 - (1 - a_f \cdot a_{FF} \cdot a_c)(1 - a_{f'} \cdot a_{FF'} \cdot a_{c'}),$$
$$a_M = 1 - (1 - a_{PS} \cdot a_{LMF} \cdot a_f)(1 - a_{PS'} \cdot a_{LMF'} \cdot a_{f'}).$$

## IV. Case Study Results

In this section, we present the case study results on the power consumption and connection availability for the greenfield and brownfield case. We also show a sensitivity analysis of the power consumption to the proportion of the day and night ONUs.

Power consumption figures in this Section show independent and dependent clustering with minimum and maximum SSD. For example, notation "ind_ssd3.1" would stand for the results for independent clustering with SSD = 3.1 hours. For the brownfield scenario, additional notation of "+b" is used, it means that in this case residential users were taken into account, i.e., existing FTTB network.

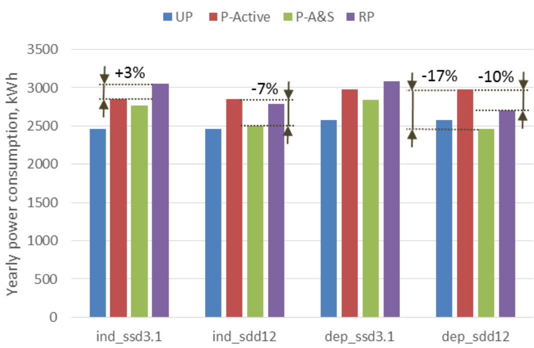


Fig. 9 Yearly network power consumption, SR=8

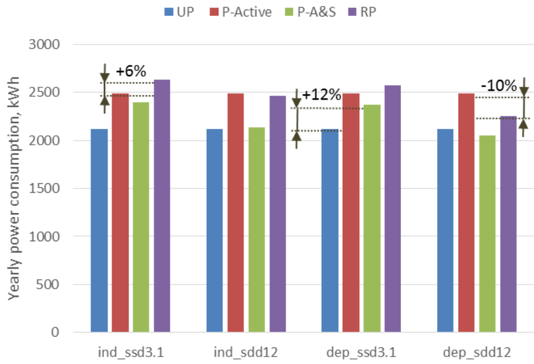


Fig. 10 Yearly network power consumption, SR=16

Figs. 9 and 10 depict power consumption per year for SR = 8 and SR = 16, respectively, showing the outcomes arising from the independent and dependent ONU (or equivalently RSU) grouping for two different sleep slot duration values. The power consumption is the lowest for the unprotected case (UP) as it has the lowest number of active components, i.e., only OLT ports and ONUs. In the case of independent RSU clustering, there are in total seven PSs with SR = 8. For the activity pattern case- dependent clustering, there are four clusters for day ONUs and four clusters for day and night ONUs. This leads to a total of eight PSs, one more than the independent clustering. It can be observed that the power consumed by the additional active equipment due to an extra cluster, and thus by the extra OLT port, is compensated by the energy saving of the P-A&S and RP schemes.

For P-Active there are several additional active components such as OSs that are always active. Consequently, changing SSD does not impact the power consumption. As for P-A&S, activity information of the public ITS is exploited to place some of the active components into sleep mode during SSD. Unsurprisingly, power consumption of P-A&S is reduced by up to 7% compared to P-Active, where savings are higher for longer SSD. The number of PSs derives the number of additional active elements, and the SSD has to be long enough to compensate for the increase in the power consumption. For example, with SR = 8 dependent clustering results in more clusters, i.e., PSs, and SSD = 3.1 hours results in more power consumption than in the independent case, while SSD = 12 hours, in lower power consumption of the dependent clustering.

Finally, the power consumption of the RP architecture fluctuates around the P-Active values. Specifically, with $SSD_{min}$ it is 3% higher and with $SSD_{max}$ it is 10% lower. This small additional power consumption is attributed to the additional monitoring components but this is in exchange for significantly improved failure detection times.

TABLE III
FAILURE DETECTION AND RESTORATION TIMES

| [ms] | UP | P-Active | P-A&S | RP |
|---|---|---|---|---|
| Detection | 3.5 | 3.5 | 3.5 | 0.000524 |
| Restoration | 14400000[1] | 10.5[2] | 10.5[2] | 10.5[2] |

[1] This value represents a four hour reparation time [26], including the traveling time to the failure site, testing and independent of the number of required technicians.

[2] Switching time to the protection path.

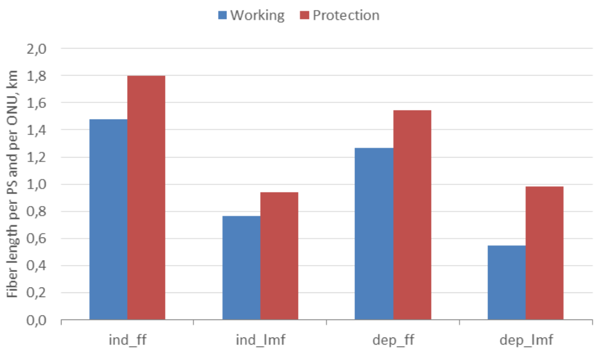


Fig. 9 Fiber length with independent and dependent clustering, normalized to the number of PSs for FF and ONUs for LMF. SR=16

Fig. 10 shows that with the same amount of PSs (number of clusters) the activity pattern dependent ONU clustering results in the same power consumption levels for UP and P-Active. As for P-A&S, the additional components result in up to 12% additional power consumption compared to the unprotected case. As for the RP architecture, its yearly power consumption shows similar fluctuations as in the previous case. One important deployment consideration when deciding upon whether to plan for independent or dependent clustering is that the former requires longer fiber, as shown in Fig. 11. Here, we compare the fiber length of independent and dependent clustering, normalized to the number of PSs for FF and ONUs for LMF. How much additional fiber is required in the dependent clustering over the independent clustering depends on the topology connectivity and ONU (RSU) density. In our case, the topology is well connected, but the ONU density is low (compared to a typical FTTB scenario). The total additional fiber length is only about 11%.

Fig.12 illustrates connection availability. From the unprotected case (UP), we can clearly see the impact of clustering and thus fiber lengths. That is the connection availability for the dependent clustering is always lower than that for an independent one. As expected, all protection schemes improve connection availability, leveraging the difference between clustering and SRs. Most importantly, the results indicate the similar reliability performance of the protection schemes. Consequently, the decisive performance metric then comes down to the failure detection time.


Fig. 12 Connection availability for the greenfield scenario

For ITS safety applications, which is the primary goal of most implementations, low failure detection time is a crucial metric. For example, for pre-crash sensing warning, the maximum latency should be as low as 50ms, and a standard safety application latency is bounded by 100ms [18]. In the case of a failure, the detection and restoration time shall be as low as possible.

Table III summarizes the failure detection and restoration times for all the protection architectures and compares their values to the unprotected architecture [21], [22]. So the RP architecture is able to provide the lowest failure detection time, thus minimizing the delay due to the failure.

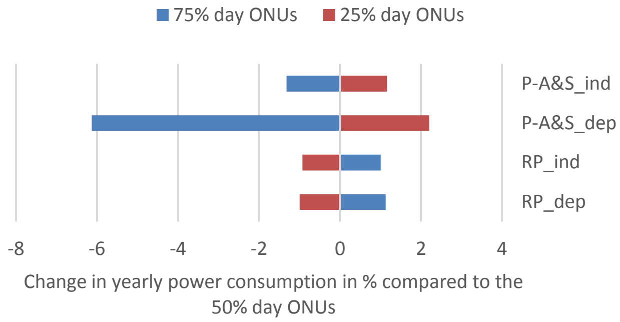


Fig. 13 Yearly power consumption sensitivity analysis, SR =16. We compare 50% of day ONU with an increase and decrease by 25% showing the difference between power consumption with min SSD

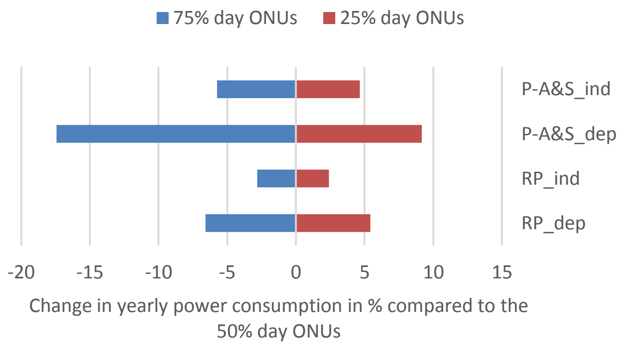


Fig. 14 Yearly power consumption sensitivity analysis, SR =16. We compare 50% of day ONU with an increase and decrease by 25% showing the difference between power consumption with max SSD

Finally, Figs. 13 and 14 show the sensitivity analysis of the yearly power consumption for different portions of day-only ONUs (increased or decreased by 25%) with minimal SSD = 3h10m (Fig. 12) and maximal SSD = 12h (Fig. 13). P-A&S shows the same trends for both values of SSD. Power consumption has an inverse relation with the number of day ONUs. The more day ONUs there are, the more can be put to sleep. As there are no additional active components, compared to the P-Active, this directly results in power consumption decrease. As for the RP, it can be observed in Fig. 13 that an increase in the number of day ONUs results in power increase. This effect is due to the addition of active monitoring components and the gain from the sleep mode being insufficient to compensate for the power consumption increase. Fig.14 shows the opposite case, when the chosen SSD is adequate, and hence the reduction in power consumption from sleeping ONUs outweighs the additional power consumption from additional active monitoring components.

## B. *Brownfield*

The main particularity of the brownfield scenario is that there is existing infrastructure, e.g., FTTB that should be exploited for ITS deployment. As it has already been mentioned, when planning a network, 20% of the RN ports are left for future use. In this brownfield scenario, any of the available 20% of the ports can be used to interconnect the RSU ONUs with the SS at the OLT.

In a brownfield case study, we assume an existing FTTB GPON network for 4877 buildings, clustered with SR = 32 and 80% port use. This leaves us with seven free ports per installed PS. The FF in this case is already installed for the FTTB. For the ITS backhaul, we reuse this GPON network and cluster the ONUs to already available PSs. This clustering, as in the greenfield, is done either independently from or dependently on user activity patterns. In activity-dependent clustering, we first cluster the RSUs that are active only during the day and connect them to the closest PS, which was already placed according to the FTTB planning. The PSs to which the day ONUs are connected, with no more ports available, are then excluded from the possible PSs for the day and night RSUs in the second stage. In the greenfield scenario, there was no need for PS exclusion as all PSs are newly placed, depending on the network needs.

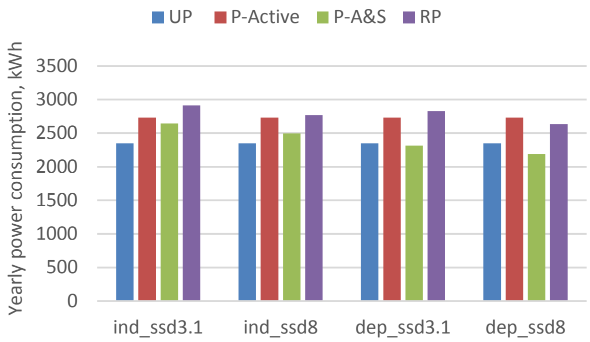


Fig. 10 Yearly power consumption of the ITS optical backhaul network

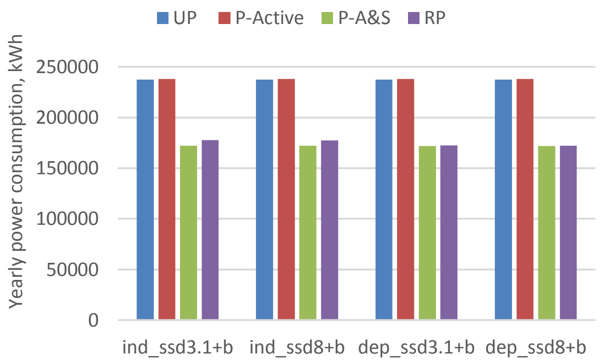


Fig. 11 Yearly power consumption of the total GPON network, including ITS optical backhaul and FTTB

Figs. 15 and 16 show the yearly power consumption for the two cases: only optical ITS backhaul (Fig. 15) and the entire GPON with the FTTB (Fig. 16). These two cases show the difference in the impact of protection on power consumption, depending on the ratio of protected elements to the unprotected.

Fig. 15 shows that yearly power consumption of the ITS backhaul only in the brownfield scenario is similar to the greenfield scenario with SR = 8 and port use of the spare ports (20% of the FTTB), which results in six ONUs per PS. Thus, for the independent clustering there are in total seven PSs and for dependent – eight. In the brownfield case, there can be seven ports used per PS, which results in six PSs in the independent and dependent clustering. To a great extent, the number of PSs defines the number of active elements, and hence the power consumption of the brownfield scenario is less than that of the greenfield scenario with SR = 8. However, it is higher than that of the greenfield scenario with SR = 16 or 32.

Note that the max SSD in this case is determined not only by the public transport activity pattern, but also by the FTTB users. As it was shown in [1], the maximum SSD for residential users (FTTB) is eight hours. For the brownfield scenario the maximal SSD thus is eight hours as the OLT port can be put to sleep only if all the corresponding ONUs are also in sleep mode.

Fig. 16 depicts the total power consumption by the GPON network, including that of the ITS backhaul and the buildings. We observe that in this case, the trends are similar to the results in [13]. In a hybrid optical network case, presented in [13], only the Macro Base Stations (MBSs) are protected. The majority of the ONUs, i.e., buildings, stay unprotected. This leads to a moderate increase in power consumption due to the active elements used for protection. In the optical backhaul for ITS case all the users, i.e., ONUs located at RSUs have to be protected. Thus, already the always active protection case features significantly higher power consumption compared to the unprotected case.

Generally, protection of all the ONUs results in greater sensitivity to SSD and clustering method. This sensitivity can be seen in Fig. 15, where the P-Active results in significant increase in yearly power consumption compared to the unprotected architecture. Moreover, RP scheme can result in more power consumption as P-Active due to additional active equipment, when the SSD is not adequate. In Fig. 16, there is no such obvious dependency. If we take into account the number of buildings in the total GPON network, i.e., 4877 ONUs, an increase in the power consumption due to protecting ITS ONUs (RSUs), i.e., 38 ONUs, is marginal, about 0.2% compared to the unprotected. Therefore, also for the P-A&S and RP there is no significant difference in power consumption compared to each other and unprotected case.

Fig. 17 summarizes the FF lengths per PS and LMF lengths per ONU for working and protection paths. The FF in this case is reused from the FTTB dark fiber and is presented for completeness. The difference in total fiber length between the results of activity-independent and dependent clustering is 19%. Activity-dependent clustering allows a reduction in power consumption by 3% at a cost of increased fiber length by 11%.

Finally, connection availability of the optical ITS backhaul for the brownfield scenario is illustrated in Fig. 18. We observe that, as in the greenfield scenario, protection increases the connection availability to four nines independent of clustering, i.e., fiber length. Furthermore, P-A&S and RP with dependent clustering allow power consumption reduction.


Fig. 12 Fiber lengths for working and protection FF per PS and LMF per ONU (optical ITS backhaul)

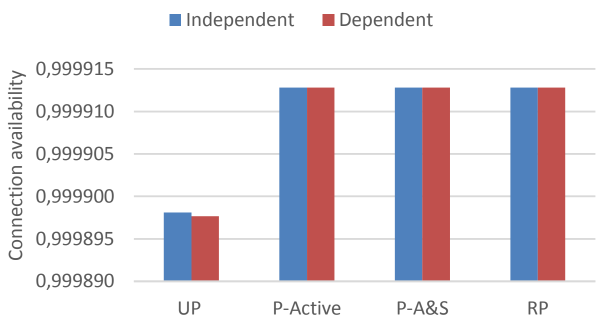


Fig. 13 Connection availability of the brownfield scenario

The choice of the protection scheme depends on the foreseen scenario and its metrics. For public ITS, the two most important deployment criteria are connection availability and failure detection time. From this perspective, in both greenfield and brownfield scenarios, the RP scheme is the most suitable due to its low failure detection time, see Table III in Greenfield scenario.

# V. Conclusion

This paper compares three survivable architectures to protect optical access networks. The architectures differ mainly on the failure detection mechanism. The comparison is based on the evaluation of the power consumption, the failure detection time, the required fiber length as well as connection availability. The three architectures are compared to the unprotected solution and applied to a realistic ITS case study in which the required DSRC RSUs need to be interconnected with a centralized Service Server. The study compares a greenfield and a brownfield deployment scenario and investigates the impact of different splitting ratios, user grouping approaches, and Sleep Slot Durations to the performance of the considered architectures. Through detailed comparisons, the results show that the Reflective Disjoint Fiber Protection architecture offers the most appropriate solution for ITS deployment. This architecture provides fast failure detection even in sleep mode-enabled settings whilst maintaining a low yearly power consumption and providing more than four nines connection availability.

# VI. Acknowledgement

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## 5.2 Paper J5

# Assessment methodology of protection schemes for next generation optical access networks

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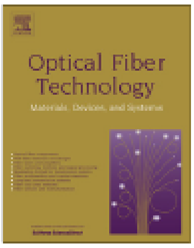

# Assessment methodology of protection schemes for next generation optical access networks

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## ABSTRACT

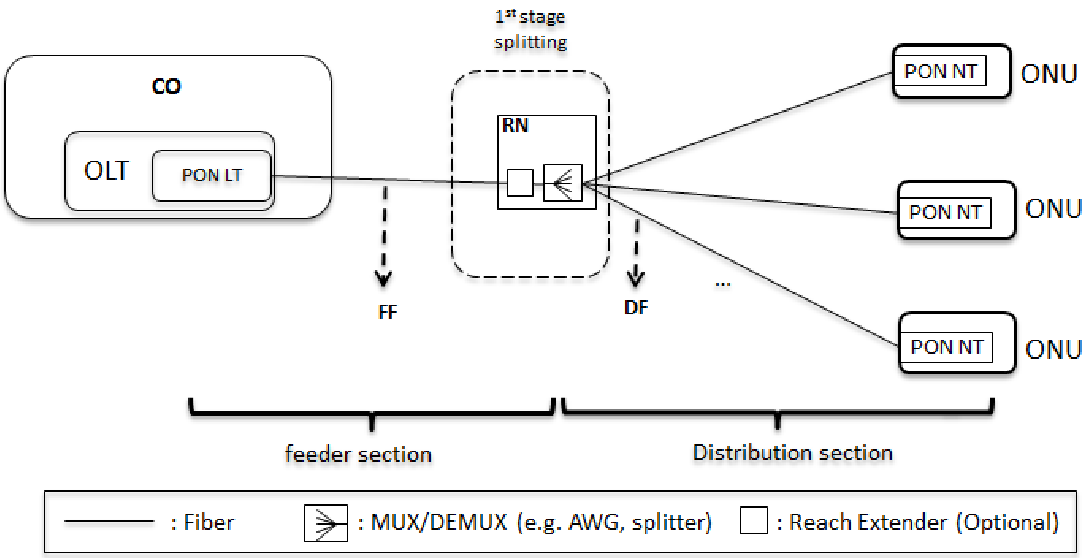
Optical access networks are evolving towards next generation solutions offering much higher bandwidth per end point. Moreover, the uninterrupted access to the network services is becoming crucial and therefore operators are now considering protecting their access networks. However, the cost factor is still very important due to the relatively low cost sharing in access segment. For this purpose, this paper proposes an assessment methodology that can be used to compare different protection schemes and help to identify the suitable solution for a given scenario. The assessment criteria includes some reliability measures such as Failure Impact Factor (FIF) and connection availability, as well as cost parameters such as the investment required in greenfield and brownfield scenarios and the increase in power consumption compared to the unprotected network. The proposed criteria have been used to compare 7 representative protection schemes shown in literature, which differ mainly in the number of protected network elements and the technology used for protection (fiber, wireless, etc.). The considered protection schemes have been applied to a hybrid wavelength division multiplexing/time division multiplexing Passive Optical Network (Hybrid PON) architecture in an urban area. It has been shown that it is difficult to identify the absolute best scheme with respect to all the considered criteria. However, depending on the requirements from the operator regarding the targeted reliability performance in the network, an appropriate protection scheme can be recommended for either a greenfield or a brownfield scenario.

**Keywords**: Protection, optical access networks, reliability, cost, power consumption.

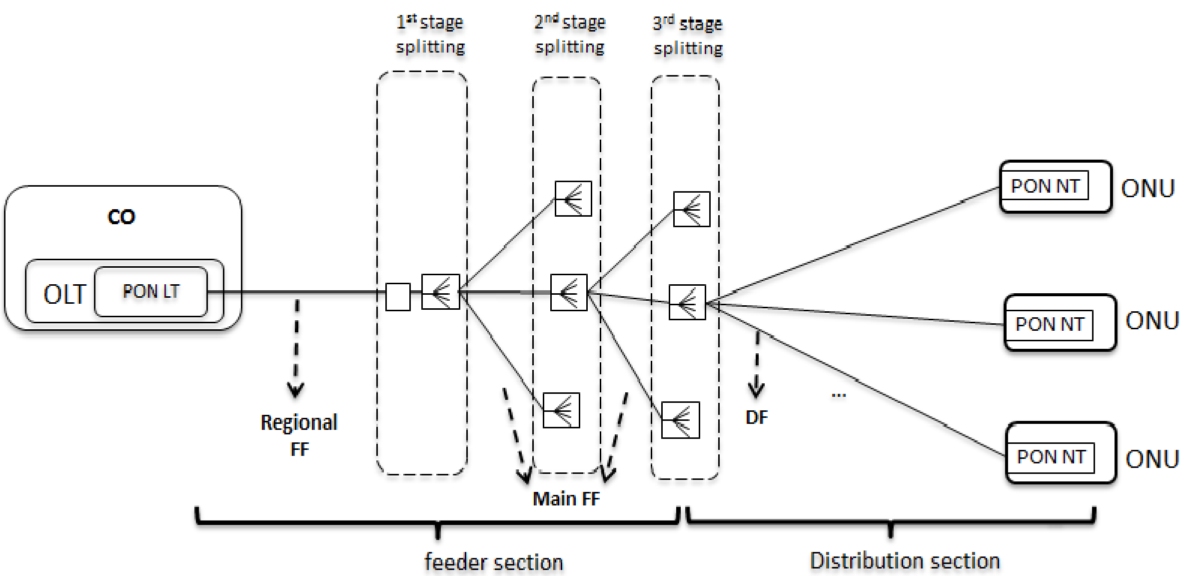
## I. INTRODUCTION

The continuous increase of bandwidth required by users is challenging access network operators to provide a sustained bitrate of 300Mbps per user in 2020 [1]. In order to cope with this problem operators having copper based access networks can increase the capacity of the existing copper infrastructure with new technologies (e.g., G. FAST) To the best of our knowledge, no protection schemes have been implemented in the copper based access networks due to the low capacity, short distances and, consequently, low impact of failures, which do not motivate additional investments to provide protection. However, upgrading the existing copper infrastructure can only be a short term solution. The future proof alternative for operators is to migrate the legacy networks to optical access networks. In some dense urban areas, operators have already deployed optical access networks, mainly Ethernet Passive Optical Networks (EPONs) or Gigabit Passive Optical Networks (GPONs), where 1 or 2.5 Gbps is shared by several tens of users utilizing Time Division Multiplex (TDM). To further increase the access network capacity per user, operators can either decrease the sharing factor or migrate to a new technology, e.g., Next Generation PON2 (NGPON2).

Figure 1 illustrates the basic PON architecture that consists of an Optical Line Terminal (OLT) located at the Central Office (CO), which is interconnected to several Optical Network Units (ONUs) at the end point of the access network through a splitting point, denoted as Remote Node (RN).




(a)




(b)

Figure 1: Basic PON architecture without any protection (a) with single stage of splitting and (b) with multiple stages of splitting (PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; RN: Remote Node)

One CO may accommodate several OLTs and one OLT may include multiple PON Line Terminal (PON LT) cards, (i.e. optical interfaces for sending/receiving optical signals. OLTs can also host some other components (e.g., Optical Switch (OS) for protection purpose, which is described in the later sections). Similarly, ONU includes at least one PON Network Termination (NT) to receive/transmit optical signals and possibly some other components for resiliency purpose. The optical fiber interconnecting the OLT and RN is referred as Feeder Fiber (FF), whereas the one connecting the RN with each ONU is referred as Distribution Fiber (DF). In general, PON architectures can include several splitting stages (see Figure 1(b)), which can increase the flexibility in the fiber plant design to aggregate ONUs (i.e. different splitting stages at the optical distribution network as, e.g., in a GPON 1:32 with two splitting stages of 1:8 and 1:4 respectively). However, these splitting stages can also be related to node consolidation, where several central offices are aggregated into one (so-called main CO), so that the equipment at the remaining central offices can be replaced by a splitting device. In this case, , FF can be divided as Main FF (MFF) between different stages of the RNs and Regional FF (RFF) between the OLT at the main CO and the 1$^{st}$ splitting stage.

Thanks to the recent advances in optical technology, a single PON (e.g. NGPON2) can be used to interconnect different types of end points (ONUs), e.g., residential users, base stations, microcells, business users, etc. Consequently, the reliability performance of future access networks needs to be sufficiently high in order to avoid service interruption for a big number of users. Moreover, the required connection availability may vary among the different types of end users. So far, operators were not interested to invest in protection of access networks due to the high investment and low sharing factor. However, resilience in access network is becoming a critical issue because of the increase of number of users served in a single access network area as well as growing importance of uninterrupted access to the network services.

It is shown that fiber access networks without any protection are characterized by poor reliability performance [2]. This fact has been realized already in late 90’s and the standard PON protection architectures have been defined by ITU-T [3] around two decades ago. These standard PON protection schemes are referred to as Type A, B, C and D. In Type A only the FF is redundant. Type B protection duplicates the shared part of the PON, i.e., FF and optical interfaces (i.e., PON LT) at the OLT. In Type B the primary optical interface at OLT is normally working while the second one is used as a cold standby. Type C represents 1+1 dedicated end-to-end path protection with full duplication of the PON resources. In Type C both the primary and secondary interfaces are normally working (hot standby), which allows very fast recovery time. Type D protection specifies the independent duplication of FF and DFs and thus, it enables network provider to offer differentiated reliability level for the users. It is obvious that adding redundant components and systems can improve network reliability performance, but it may not be a practical solution for the cost sensitive access networks. Therefore, both system deployment cost (related to CAPital EXpenditures CAPEX) and network management cost (related to OPerational EXpenditures OPEX) should be minimized.

Several PON protection schemes have been proposed in literature and the aim of this paper is to use our methodology to compare different aspects of some representative schemes [4-8]. In particular, the tradeoff between reliability performance, investment cost and power consumption is studied. These schemes can be applied to architectures using WDM and TDM technologies unless stated the contrary. Hence, both power splitters and Arrayed Waveguide Gratings (AWGs) can be placed accordingly at the remote nodes. However, since the objective of the paper is to propose the methodology and apply it to these representative schemes, the schemes will not be modified but used as they are proposed in the published papers.

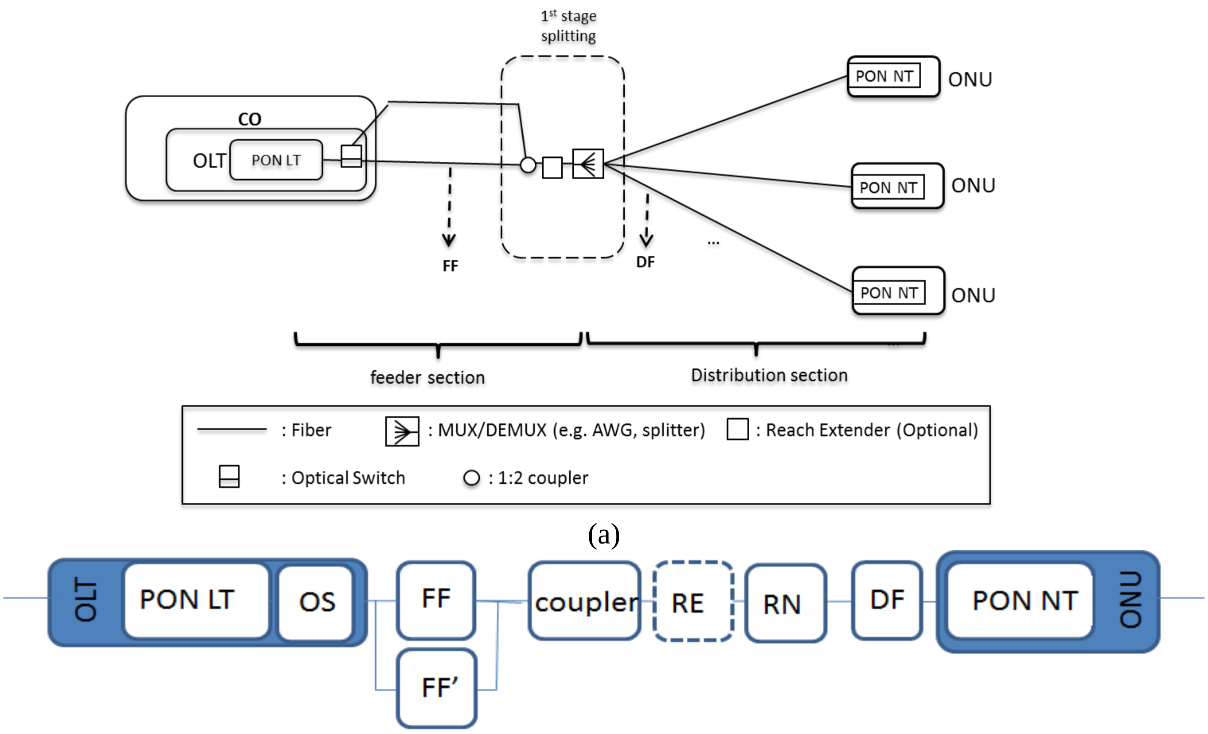
The paper is organized as follows. In Section II the considered protection schemes are presented along with their reliability models in form of reliability block diagrams. In Sections III the assessment criteria are defined while Section IV shows our evaluation results and comparison between the considered protection schemes according to the assessment criteria in a particular scenario. Finally, conclusions are given in Section V.

## II. PROTECTION SCHEMES

PON protection architectures have been widely studied, e.g., in [2-8], in order to increase the reliability performance of access networks. The evolution of PON protection has experienced two phases [2]. The first phase has been initialized in late 90's, in which the key idea for protection is based on adding redundant components and systems, e.g., in [3-4]. It is reflected in the standard PON protection architectures defined by ITU-T [3]. However, improving reliability performance only by duplication of the components and systems is expensive and thus, not always suitable for the cost sensitive access networks. Then, in the second phase of the PON protection evolution the effort has been put on the development of cost-efficient architectures improving the reliability performance with limited cost. For instance, some schemes, e.g., [5, 6], try to maximize the sharing rate of the existing infrastructure by using duct/cable for the working fibers in the other PONs as part of the protection path. Meanwhile, several schemes, e.g., [7, 8], utilize wireless solutions which have much lower deployment cost to offer protection links for feeder and/or distribution segments. Furthermore, some other aspects are also considered recently for PON protection, such as flexibility of protection upgrade, and energy consumption. In this section, several representative PON protection schemes are reviewed as they were originally proposed. However, it should be noted that they are not dedicated to a specific PON technology and hence can be applied to different types (for instance, they can be applied in hybrid WDM/TDM PON, which will be further evaluated in terms of various aspects in Section IV). Besides, one protection scheme can also be combined with the others, e.g., dual homing (connecting two OLTs located at different places) can be used together with 1+1 protection to further enhance the resiliency.

**Scheme I: Feeder fibre protection (Type A in ITU-T G983.1)**

As shown in Figure 2 (a), in Scheme I (i.e., Type A in ITU-T G983.1) only FF is duplicated.



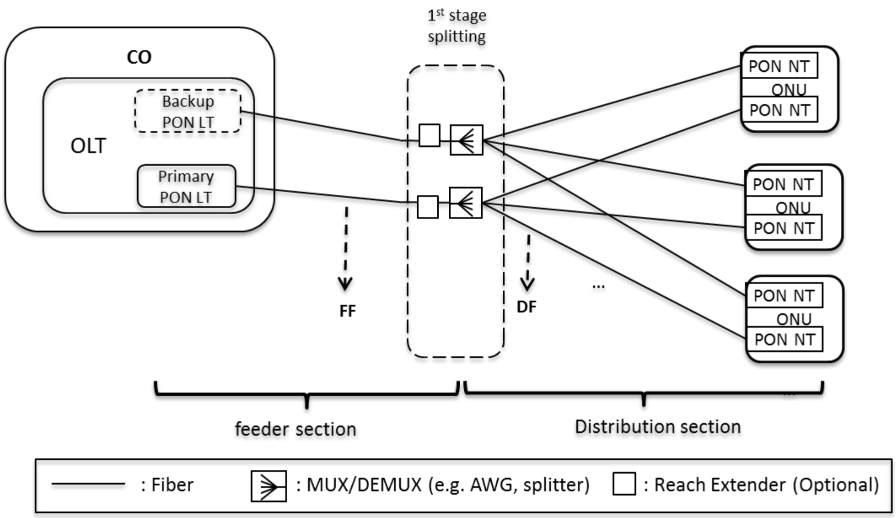

(b)

Figure 2: (a) Scheme I: Feeder fibre protection (Type A in ITU-T G983.1) [3] and (b) RBD (PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; RE Reach Extender; FF: Feeder Fiber; OS: Optical Switch; RN: Remote Node; DF: Distribution Fiber)

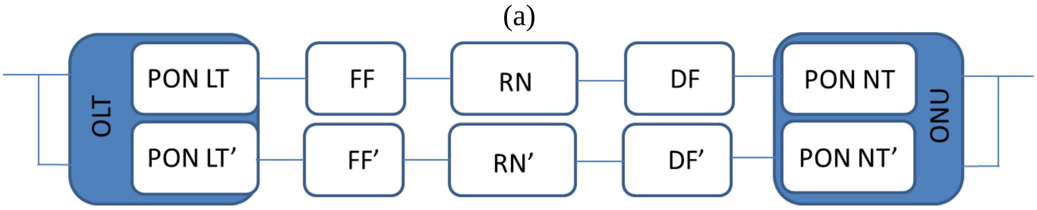
Optical Switch (OS) is needed at the OLT to switch the signal to protection FF in case a failure occurred in the working FF. At the RN, an extra 1:2 coupler is needed to connect both working and protection FFs. Figure 2 (b) shows the Reliability Block Diagram (RBD) for this scheme. RBD is a graphical representation of the system illustrating the relation between system components from the reliability point of view, and is often referred to as its connection availability model. Scheme I is relatively simple. On the other hand, it offers a limited improvement of the reliability performance.

**Scheme II: 1+1 dedicated path protection (Type C in ITU-T G983.1)**

Scheme II (see Figure 3 (a)) represents 1+1 dedicated path protection with full duplication of the PON resources defined as Type C in ITU-T standard [3]. Reach extender is considered as optional. It is used in case long-reach scenario needs to be supported. It is used in case long-reach scenario needs to be supported (e.g., rural areas). Figure 2(b) shows RBD for Scheme I, indicating how to include the reach extender in the reliability model, in case it is used. Full protection can offer very high reliability performance but unfortunately they require duplication of all network resources (and investment cost). 1+1 hot standby requires almost doubled energy consumption. Meanwhile, this scheme has low flexibility in terms of providing differentiated protection, i.e., all the connected users can either have full protection or no protection at all.




(a)




(b)

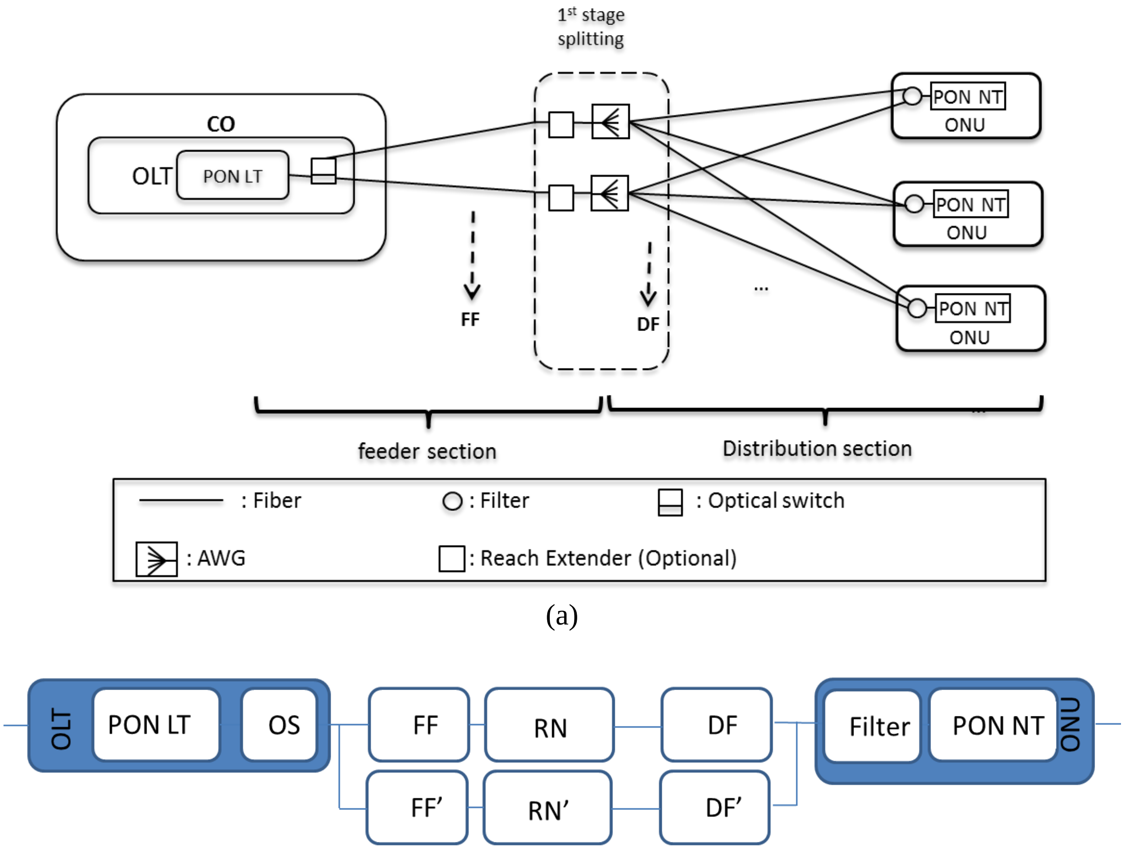
Figure 3: (a) Scheme II: 1+1 hot standby [3] and (b) RBD

(PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; FF: Feeder Fiber; RN: Remote Node; DF: Distribution Fiber)

**Scheme III: Self-survivable WDM PON**

Besides standardized schemes, many other protection schemes based on introducing redundant sections are proposed to increase PON reliability performance. As an example, a centrally-controlled Wavelength Division Multiplexing (WDM) PON architecture has been introduced in [4], where redundant fiber segments (including FF and DF) are required. Therefore, this self-survivable WDM

PON can recover from all types of failures in distribution and feeder fibers as well as remote nodes (see Figure 4). A specific wavelength plan is required in this WDM PON so that working transceivers at both OLT and ONU can be reused for protection purpose. Compared to Scheme II, this scheme has lower reliability performance as the PON LT and PON NTs are not protected, whereas it requires less cost. This scheme also has low flexibility, where the connected users either have full protection or no protection at all.




(a)

(b)

Figure 4: (a) Scheme III: Self-survivable WDM PON [4] and (b) RBD
(PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; FF: Feeder Fiber; OS: Optical Switch; RN: Remote Node; DF: Distribution Fiber)

**Scheme IV: Reliable Hybrid WDM/TDM PON architecture**

Figure 5 shows Scheme IV [5] that can be applied to various types of hybrid Wavelength Division Multiplexing/Time Division Multiplexing (WDM/TDM) PONs. In this scheme, in order to accommodate different user profiles (e.g., residential and business users) in the same network two degrees of resilience are offered: 1) protection up to first remote node, which is shared by all the connected users; and 2) end-to-end protection for the users that would pay extra for high reliability. Besides, the architecture uses the existing duct in distribution section as much as possible. In this way, the additional cost for protection can be minimized. Besides, this scheme can support different stages of splitting points, leading to a flexible fiber plant design. The first stage consists of couplers allowing broadcasting the signal through two disjoint paths towards the ONU.

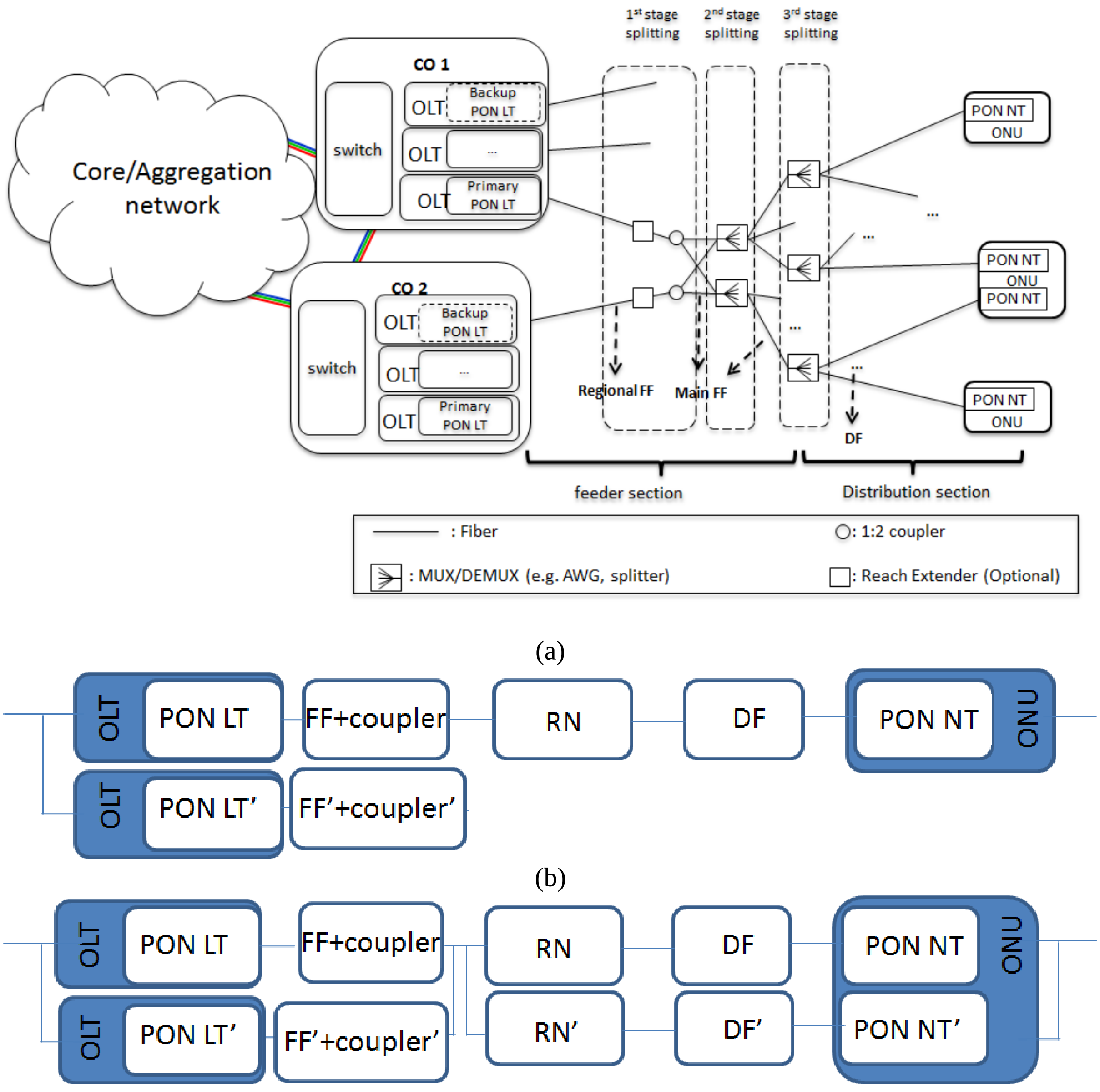



Figure 5: (a) Scheme IV: Reliable Hybrid PON architecture [5], (b) RBD for protection of Feeder Section (FS) and (c) RBD for End-to-End (E2E) protection
(PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; FF: Feeder Fiber; RN: Remote Node; DF: Distribution Fiber)

**Protection of the Feeder Section (FS)**

For hybrid PON architectures, more than thousand end users can be connected to a single OLT through one FF. Consequently, both OLT and FF have high impact on the reliability performance. First, their failure rates are relatively high compared to the equipment at the user side due to the use of complex active components at OLT and long FF. Secondly, they are shared by all the connected end users, which means that a single OLT or FF failure leads to the service interruption for a large amount of users. Therefore, it is significantly important to protect the feeder section of the hybrid PON.

In Scheme IV the 1:M splitting components at the first remote node (i.e., 1st stage splitting) used in the basic (unprotected) PON, are replaced by two 1:2 couplers to connect two feeder fibers towards COs and two parallel distribution networks towards the user end. The RBD for the protection up to the first remote node is shown in Figure 5(b)

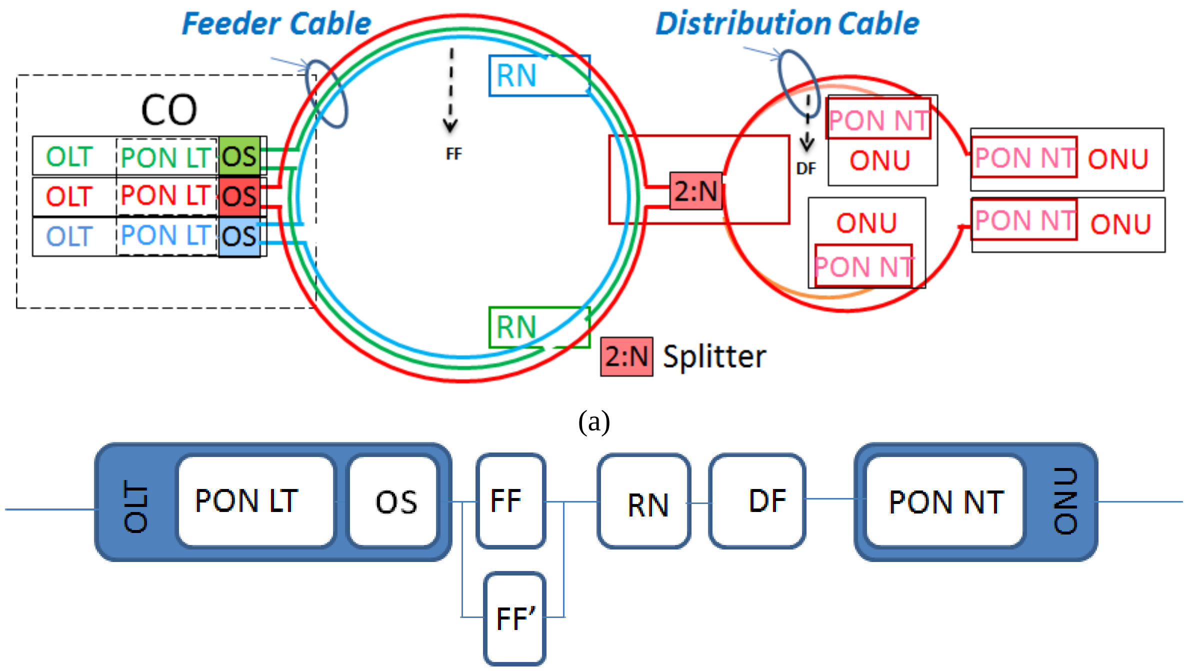
**End-to-End protection (E2E)**

For the users with high reliability requirement (e.g., business customers) the protection of only feeder section (i.e., feeder fibers and OLT) may not be sufficient. To obtain an End-to-End (E2E) protection for such users, duplicated NTs are considered at the ONU side to access both working and protection DFs. To reduce the need of new trenching for the protection, the available ducts are utilized, i.e., the additional fiber should be blown through available ducts wherever possible. Therefore, in this scheme ONU with end-to-end protection is connected to closest neighboring remote node (see example of the ONU in the middle at the right hand side) by a disjoint distribution fiber. This disjoint distribution fiber route may reuse the existing trench in the field. In this way, deployment of extra ducts can be reduced as much as possible. They can potentially also be shared with other business users to further decrease deployment cost. The RBD for the end-to-end protection is shown in Figure 5(c).

Compared to the previous schemes, Scheme IV has obviously higher flexibility, where the type of protection can be provided to the users upon request. Apparently, E2E protection has much higher reliability performance than FS protection, but at the expense of higher cost. Since the existing duct of the other ONU's working DF can be partly used for the protection DF, the additional cost for the user requesting end-to-end protection can be reduced.

**Scheme V: Ring based fibre topology for PON**

In Paper [6] a cost-efficient way to provide protection down to the RN is proposed taking advantage of deployment cost reduction caused by the opportunity of sharing the same duct by both working and protection fibers. The paper takes a TDM PON as an example to explain the idea. The same fiber topology can be also applied to the other types of PONs, e.g., WDM PON and hybrid PON.



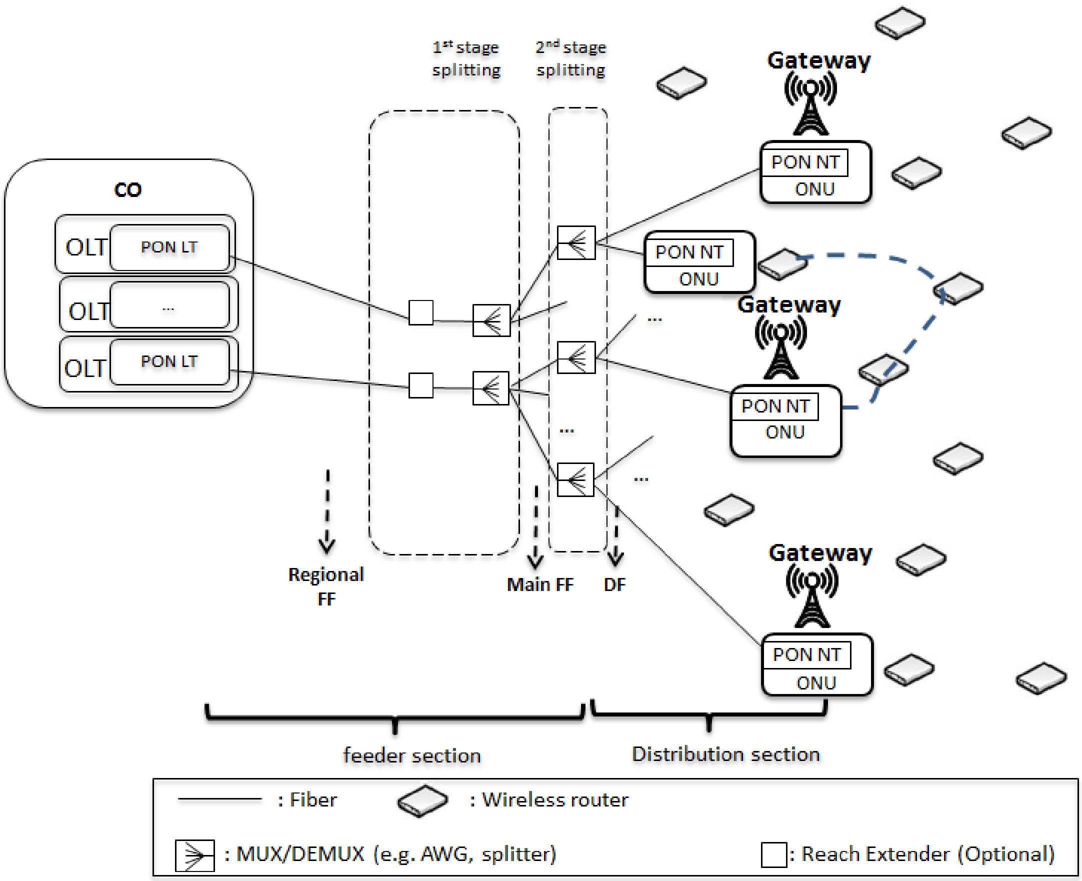

(b)

Figure 6: (a) Scheme V: Ring based fiber topology for PON architecture [6] and (b) RBD (PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; FF: Feeder Fiber; RN: Remote Node; DF: Distribution Fiber; OS: Optical Switch)

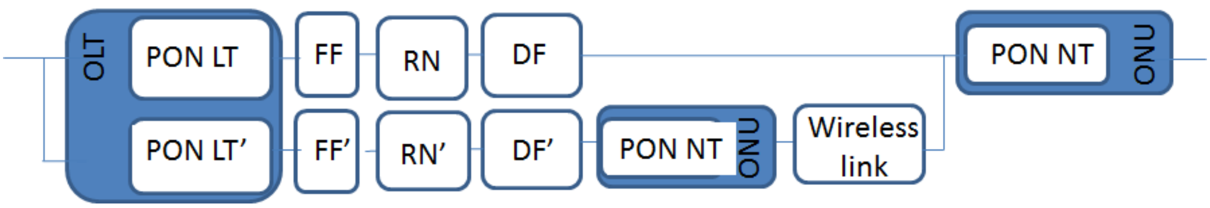
As shown in Figure 6, the proposed fiber topology is ring-and-spur, where a feeder cable ring is shared by several PONs and after splitting point for each PON distribution duct is also ring-based. In this way, the distribution fibers to different ONUs in the same PON still can share the duct as much as possible. In principle, the distribution cable ring could be closed to provide protection as well. It should be noted that to provide protection for distribution part in this scheme, the corresponding ONU should have two fiber interfaces to connect both working and protection DFs, which results in extra cost at the user side. Scheme V puts effort to minimize the fiber infrastructure cost for protection while offering protection for the feeder fibers. Protection up to the first remote node can obviously reduce the failure impact, but for business users the level of connection availability might not be sufficient (hardly achieving 4 nines, i.e., 0.9999).

**Scheme VI: Survivable hybrid wireless-optical broadband access network**

Survivable PON based wireless-optical access network, where the protection is based on routing the signals through the backup ONUs and wireless routers (see Figure 7(a)) is proposed in [7]. In this scheme, the expensive additional fiber deployment for protection can be completely avoided. Instead, wireless path is set up to reroute the traffic in case of fiber cut.




(a)




(b)

Figure 7: (a) Scheme VI: Survivable hybrid-wireless optical access network [7] and (b) RBD (PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; FF: Feeder Fiber; RN: Remote Node; DF: Distribution Fiber)

As both feeder and distribution sections are protected, Scheme VI has high reliability performance. However, the solution still suffers from some disadvantages, i.e., 1) the backup segment requires extremely high spare capacity, particular for a potential failure occurring in feeder section, and 2) the transmission via wireless routers may cause severe delay if multiple hops are involved. To address these two disadvantages, Scheme VII has been proposed in [8].

**Scheme VII: Hybrid fiber and microwave protection**

Scheme VII is a hybrid fiber and microwave protection scheme proposed in [8] (see Figure 8).

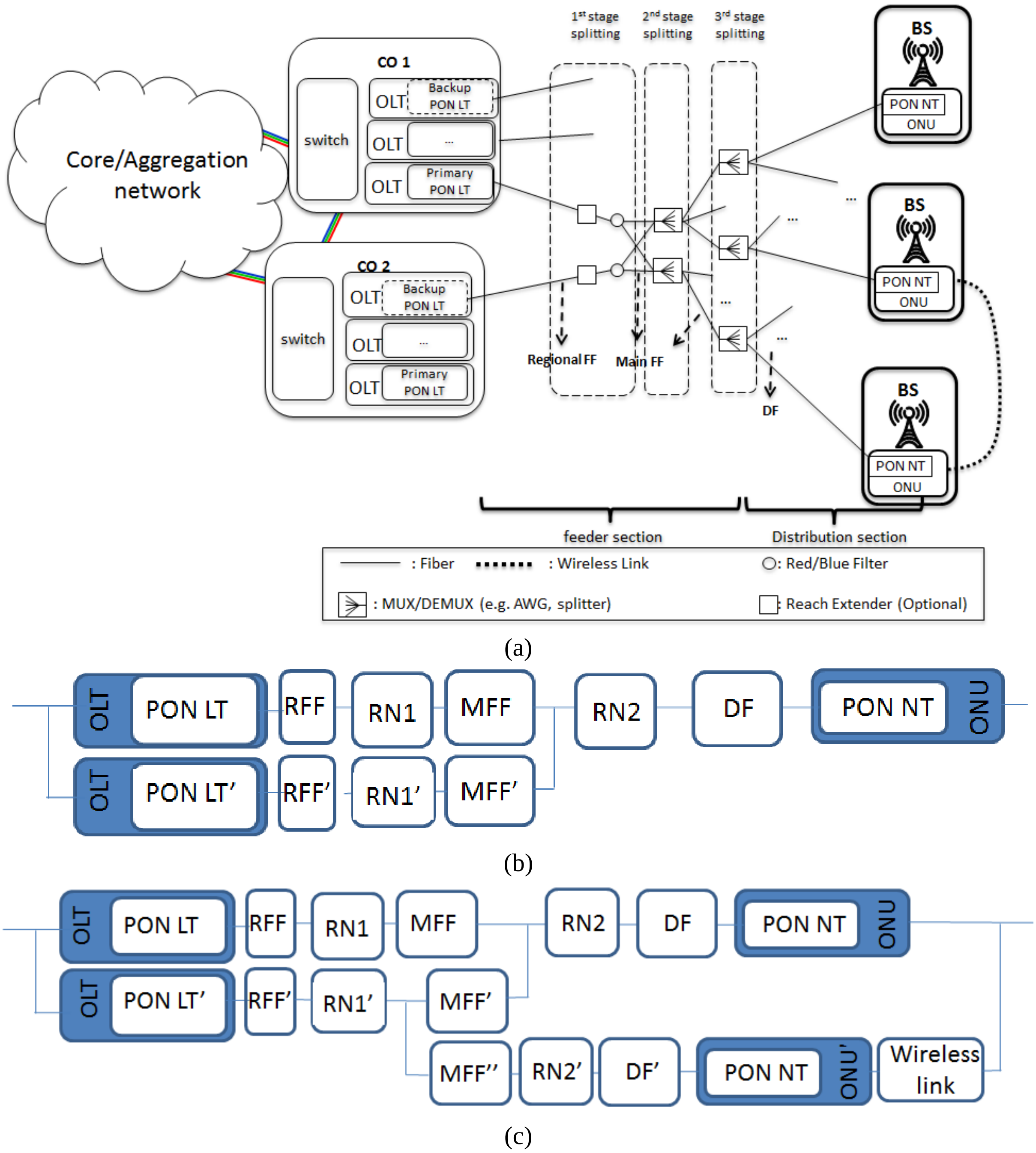



Figure 8: (a) Scheme VII: Survivable hybrid wireless optical broadband access network [8] and RBDs (b) for protection of Feeder Section (FS) and (c) for End-to-End (E2E) protection (PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; RFF: Regional Feeder Fiber; MFF: Main Feeder Fiber; RN: Remote Node; DF: Distribution Fiber)

It is particularly suitable for protection of mobile backhaul networks. This approach can flexibly support different reliability requirements and provide either full protection (E2E), including fibers and optical devices, or only feeder section (FS), i.e., FF and OLT, shared by all ONUs. For the FS protection, the backup FF and OLT are required (see the RBD shown in Figure 8 (b)). For E2E protection in Scheme VII (see Figure 8 (c)), an additional DF for backup can be avoided. Instead a microwave wireless connection is set up between two neighboring ONUs, which do not share any fiber infrastructure (i.e. they are connected to the OLT by disjoint paths). This scheme can offer high connection availability and flexibility at relatively low cost. However, it is a subject of the agreement with the end user (e.g., BS or residential users) to place the equipment required for the microwave link, offer the power connection, give access for the required maintenance, etc. A tradeoff between connection availability and cost needs to be evaluated in order to make the appropriate decision.

## III. ASSESSMENT CRITERIA

We evaluate reliability performance, deployment cost, and power consumption of the considered protection schemes. Reliability performance will be expressed in terms of Failure Impact Factor (FIF) and connection availability.

In this section we introduce the considered assessment criteria for the evaluation of the protection mechanisms. Type A protection proposed by ITU-T [3] (shown in Figure 2) is used as an example.

The reliability performance means the ability of a component/system/network to perform its required functions under stated conditions for a specified period of time. In the case of access networks the required function would correspond to, e.g., the connectivity of the OLT to any of the hosted ONUs. Each protection scheme aims at protecting the network from a given set of potential failures (e.g., only from FF failures, or from FF and DF failures, or also from equipment failures). The larger this *Protection Set (PS)* is the higher the protection capability. For example, the protection set of Type A is PS={FF} since it only offers protection to FF.

The *Failure Penetration Range (FPR)* is defined as the number of affected users/connections when a particular failure occurs. For example, a failure of the FF affects all users connected to this PON and hence, the *FPR* of an unprotected FF failure is the client count of this PON. The *FPR* of a DF failure is only one because its failure interrupts the connection of a single ONU. In most of the cases, failures of the protection set are prioritized based on their impact so that operators start protecting the components with a higher impact.

- *Failure Impact Factor (FIF)* is a parameter which indicates the affected connections of single failures at unprotected components. It can be calculated based on the *FPR* for all the components of a connection except the protected ones (i.e., except the components in *PS*) [5]. The FIF of a component *i* ($FIF_i$) is defined as the product of the unavailability of the component ($U_i=1- A_i$, where $A_i$ is the availability of the component) and its Failure Penetration Range ($FPR_i$): $FIF_i=U_i.FPR_i$.

  The *FIF* for a connection can be computed as the sum of the *FIF* of each component involved in the connection, except the protected ones. It means that the *FIF* of a fully protected connection is equal to 0. The reasoning behind is as follows: the unavailability of a component is defined as the probability of that the component has failed at time *t*. Hence, the *FIF* of a component averages the affected connections with the probability that this failure occurs. In order to calculate the *FIF* of a connection, the *FIF* is averaged for all the unprotected components.

  For the assessment we define four *FIF* degrees with respect the *FIF* of the unprotected connection (denoted as $FIF_{UP}$):

- "1": It corresponds to $0 \leq FIF < FIF_{UP}/1000$
- "2": It corresponds to $FIF_{UP}/1000 \leq FIF < FIF_{UP}/100$
- "3": It corresponds to $FIF_{UP}/100 \leq FIF < FIF_{UP}/10$
- "4": It corresponds to $FIF_{UP}/10 \leq FIF < FIF_{UP}$

- *Connection availability* is defined as the probability of the connection being operational at any point of time. RBD is often referred to as the availability model of the system (in this paper system corresponds to the connection between OLT and ONU). We devised RBDs for the connections between OLT and ONUs in order to analyse connection availability offered by different PON protection schemes. Figure 9 shows the RBD of an unprotected PON. In general, a larger protection set is associated to higher connection availability. The value of connection availability higher than 5 nines (corresponding to 0.99999) is not always required, since the aggregation network is typically with 5 nines or lower and then it limits the overall connection availability [5]. We define four connection availability degrees ranging from 6 nines ("1") to 3 nines ("4") availability.

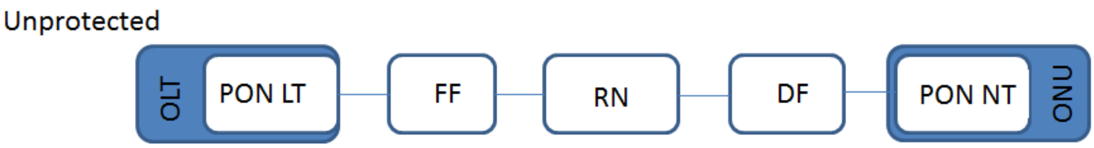



Figure 9: Example of RBD for unprotected PON
(PON LT: Passive Optical Network Line Terminal; OLT: Optical Line Terminal; ONU: Optical Network Unit; FF: Feeder Fiber; RN: Remote Node; DF: Distribution Fiber)

- *Cost*: An important feature to compare the protection schemes is to evaluate how much the new infrastructure and how many new components are associated to this scheme. Two scenarios should be distinguished:
  - Greenfield (GF) scenario: In this scenario, operators design the protected network without any existing infrastructure. The costs of the protected network are calculated as a percentage with respect to the cost of the unprotected counterpart (denoted as $Cost_{UP}$). The higher the percentage is, the higher the cost of the protected solution.
  - Brownfield (BF) scenario: In this scenario, operators are running an unprotected access network. Hence, the costs associated to this scenario include all the expenses associated to protecting the existing network. For example, the protection FF depicted in Figure 2 in GF scenario considers the cost of the protection fiber based on its length, whereas in BF scenario the cost of the protection fiber and its associated trenching based on its length needs to be considered. The reason is that in the GF scenario, the planning of working and protection fibers is done maximizing duct sharing and hence, most of the trenching is associated to the working fibers, while an operating access network may require trenching. In this paper, the cost differences of offering protection at GF and BF scenarios are evaluated.

  For our assessment we define four Cost_GF degrees as percentage of $Cost_{UP}$:
    - "1": It corresponds to Cost_GF < 10% of $Cost_{UP}$
    - "2": It corresponds to 10% of $Cost_{UP}$ < Cost_GF < 50% of $Cost_{UP}$
    - "3": It corresponds to 50% of $Cost_{UP}$ < Cost_GF < 90% of $Cost_{UP}$

- "4": It corresponds to Cost_GF > 90% of $Cost_{UP}$

Four Cost_BF degrees are also defined as percentage of $Cost_{UP}$ (it should be noticed that the BF costs might be higher than the GF costs and therefore, the degrees have been defined accordingly):

- "1": It corresponds to Cost_BF < 10% of $Cost_{UP}$
- "2": It corresponds to 10% of $Cost_{UP}$ < Cost_BF < 100% of $Cost_{UP}$
- "3": It corresponds to 100% of $Cost_{UP}$ < Cost_BF < 200% of $Cost_{UP}$
- "4": It corresponds to Cost_BF > 200% of $Cost_{UP}$

- *Power consumption*: The power consumption of telecommunication networks is currently dominated by the power consumed by access networks [9]. PONs have been shown to offer the lowest power consumption among the available access network solutions. Since operators aim at reducing power consumption (important OPEX factor), the protection schemes are compared based on the increase (in percent) of power consumption caused by the protection facilities $P_P$ with respect the power consumed by the unprotected network (denoted as $P_{UP}$). Four power consumption degrees are considered as follow:
  - "1": It corresponds to $P_P$ <1% of $P_{UP}$
  - "2": It corresponds to 1% of $P_{UP}$ <$P_P$<50% of $P_{UP}$
  - "3": It corresponds to 50% of $P_{UP}$ <$P_P$<100% of $P_{UP}$
  - "4": It corresponds to $P_P$>100% of $P_{UP}$

| | *FIF* | Connection availability | Cost_GF % of $Cost_{UP}$ | Cost_BF % of $Cost_{UP}$ | Power % of $P_{UP}$ |
|---|---|---|---|---|---|
| "1" | *[0, $FIF_{UP}$/1000)* | 0.999999 | [0,10%) of | [0,10%) | [0,1%) |
| "2" | *[$FIF_{UP}$/1000, $FIF_{UP}$/100)* | 0.99999 | [10%,50%) | [10%,100%) | [1,50%) |
| "3" | *[$FIF_{UP}$/100, $FIF_{UP}$/10)* | 0.9999 | [50%,90%) | [100%,200%) | [50%,100%) |
| "4" | *[$FIF_{UP}$/10,$FIF_{UP}$]* | 0.999 | ≥90% | ≥200% | ≥100% |

Table 1: Comparative degrees for each criterion

Since the objective of this paper is to propose a methodology to compare different protection schemes, the evaluation degrees of each criterion have been proposed as a reference. However, each operator can modify the degrees based on the critical values, on the studied scenario, etc.

## IV. EVALUATION AND COMPARISON

The protection schemes presented in Section II have been compared for a given urban scenario. For the comparison, all protection schemes have been applied to a Hybrid PON architecture, which consists of two stages of remote nodes. An Array Waveguide Grating (AWG) with 40 wavelengths is used at the first remote node, and power splitters with 1:32 splitting ratio are considered at the second stage of remote nodes as shown in Figure 10. Hence, the client count of one PON LT at the OLT is 1280.

In this study we focus on an urban area where relatively large client count and short reach need to be supported. The considered fiber lengths for working and protection RFF, MFF and DF, respectively) are presented in Table 2 [5]. The cost and availability of each fiber is proportional to the length. In our study all cost values are normalized to the common GPON ONU and given as Cost Unit (CU). In this case, the fiber cost is 4 CU/km, whereas the trenching cost is 900 CU/km. The fiber availability is 0.999985725 per km.

| Fiber Length [km] | Working | Protection |
|---|---|---|
| RFF | 6 | 11 |
| FF Ring | 8 | 8 |
| MFF | 1 | 1,6 |
| DF | 0,5 | 0,7 |

Table 2: Average fiber lengths of working and protection FF, DF and LMF.

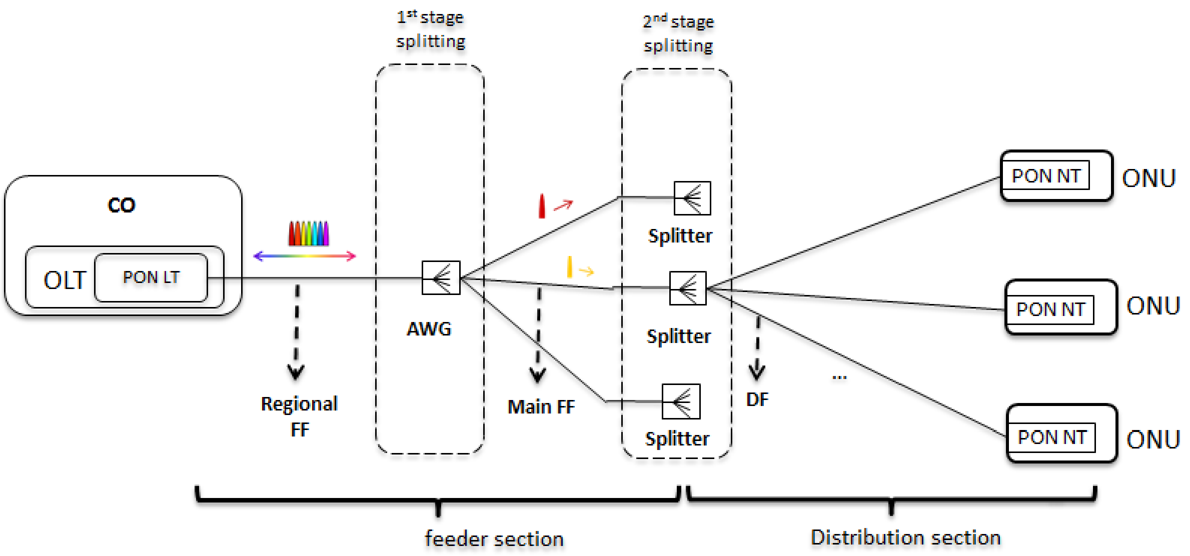



Figure 10: Basic Hybrid PON with two stages of splitting points
(PON LT/NT: Passive Optical Network Line Terminal/Network Termination; OLT: Optical Line Terminal; ONU: Optical Network Unit; CO: Central Office; FF: Feeder Fiber; RN: Remote Node; DF: Distribution Fiber; AWG: Arrayed Waveguide Grating)

The cost, power consumption and availability values of the involved components are shown in Table 3 [5, 8] proposed by operators and manufacturers of the OASE consortium [1].

| Component | Cost [CU] | Power [W] | Availability |
|---|---|---|---|
| OLT | 463 | 370 | 0,99996381 |
| PS 1:32 | 6,6 | 0 | 0,999999 |
| PS 2:32 | 6,8 | 0 | 0,999999 |
| AWG 1:40 | 12 | 0 | 0,999994 |
| AWG 2:40 | 14,4 | 0 | 0,999994 |
| OS | 2 | 1 | 0,999994 |
| Filter | 1,5 | 0 | 0,999994 |
| coupler | 1 | 0 | 0,9999993 |
| µwave link | 150 | 18 | 0,999967 |
| WiFi link | 0 | 0 | 0,999967 |
| ONU | 3,1 | 5,5 | 0,999961 |

Table 3: Component cost, power consumption and availability

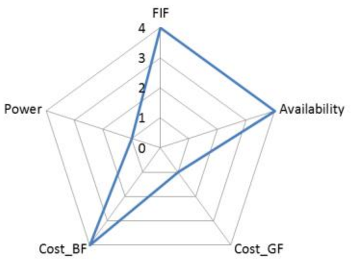
The comparative study is based on the assessment criteria presented in Section III:

- FIF degree is based on the FIF of the protected solution with respect the FIF of the unprotected architecture. The larger the set of protected components, the higher reliability performance and the lower the FIF of the solution.
- Connection availability
- Greenfield (GF) costs consider the increase of cost with respect to the unprotected solution. No trenching is considered since the network is built at once and hence, the trenching required for the unprotected solution will be reused by the protection as much as possible. Some architectures are using for protection purpose the working fibers of other PONs and hence, no additional cost is associated to backup fibers. However, the cost of purchasing and installing the wireless or microwave links is required for some of the considered schemes.
- Brownfield (BF) costs refer to the deployment of the protection scheme once the unprotected network is up and running. In this case, any fiber which is aimed at protecting a particular working fiber has a cost associated to it for the fiber itself as well as for the trenching.
- Power degree gives a ratio of the increase of power consumption with respect the power consumed by the unprotected architecture. It is important to know whether the protection scheme considers a 1+1 or a 1:1 solution (obviously 1+1 will consume more power than 1:1).

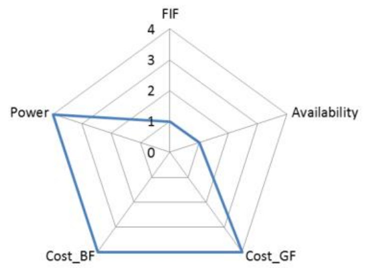
Each protection scheme has been assessed based on the criteria defined in Section III. The evaluation results are presented in Figure 11 in form of net diagrams. Each net diagram has five axes, and one axis is for each criterion. Each axis has values ranging from 1 to 4, as defined in Section III. Based on the criterion's degrees, the smaller the degree is, the better the protection scheme is. Hence, the net diagram allows an easy comparison of different schemes.

Based on these diagrams, the following remarks can be made:

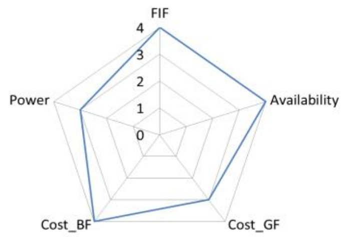
- <u>FIF</u>: The schemes that have all components protected (Schemes II, IV-E2E, VI and VII-E2E) have highest reliability performance, i.e. FIF=0. The FIF of other schemes with only FS protection decreases significantly compared to the unprotected network (at least reduce 60% reduction of FIF values).
- <u>Connection availability</u>: In general, the higher the number of protected components is, the higher the connection availability can be achieved.
- <u>GF cost:</u> Schemes I and V are less expensive than the other schemes. They require extra investment which is lower than 10% of the unprotected PON). On the other hand Schemes II and VI require extra investment even more than 100% of the unprotected solution.
- <u>BF cost</u>: Schemes I, II, III and V require significant investment due to the trenching needed for any protection fiber (they are installed just for protection purpose). This investment is avoided in the other architectures (e.g. Schemes IV and VII) by reusing working fiber of other PONs and adding a disjoint OLT or adding ports to the existing OLTs.
- <u>Power consumption</u>: The increase of power consumption is negligible in all the solutions with 1:1 protection but important for 1+1 protection schemes such as Schemes II and VI.



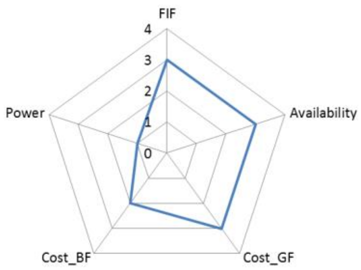

(a) Scheme I



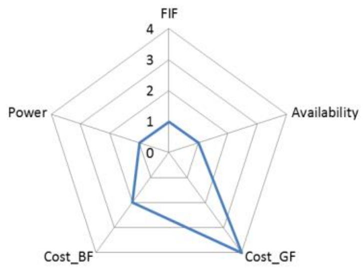

(b) Scheme II



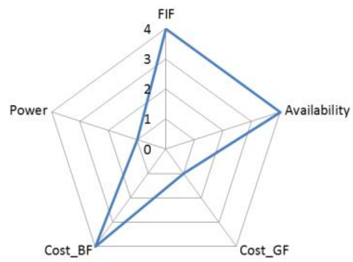

(c) Scheme III



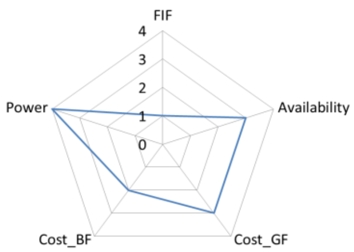

(d) Scheme IV-FS



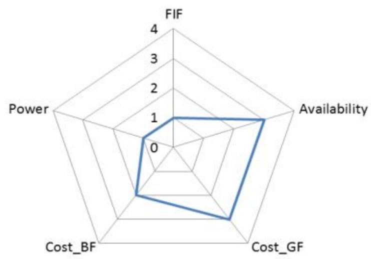

(e) Scheme IV-E2E



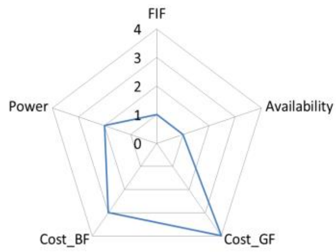

(f) Scheme V




(g) Scheme VI




(h) Scheme VII-FS




(i) Scheme VII-E2E

Figure 11: Net diagrams for protection schemes reviewed in Section II

Figure 12 shows the comparison of the four schemes offering the FS protection only. It can be observed that all the schemes do not increase significantly the power consumption with respect the unprotected solution. Furthermore, the net diagrams of Schemes I and V are overlapping (see blue and green lines in Figure 12), because the duct sharing is utilized in both schemes. Schemes I and V offer lower GF cost than Schemes IV-FS and VII-FS, while the BF cost is higher for Schemes I and V. This is due to the fact that in GF Schemes I and V do not require duplication of the OLT. On the other hand, these two schemes have higher BF cost due to the trenching required for the disjoint fibers. Last but not least, the connection availability in these solutions is of 3 nines when protecting only FF, and 4 nines when protecting also the OLT. The FIF of Scheme VII-FS is so good since the only unprotected elements (power splitter, LMF and ONU have very low FPR), compared with the other schemes that do not protect the OLT LT and/or the AWG, both having high FPR.

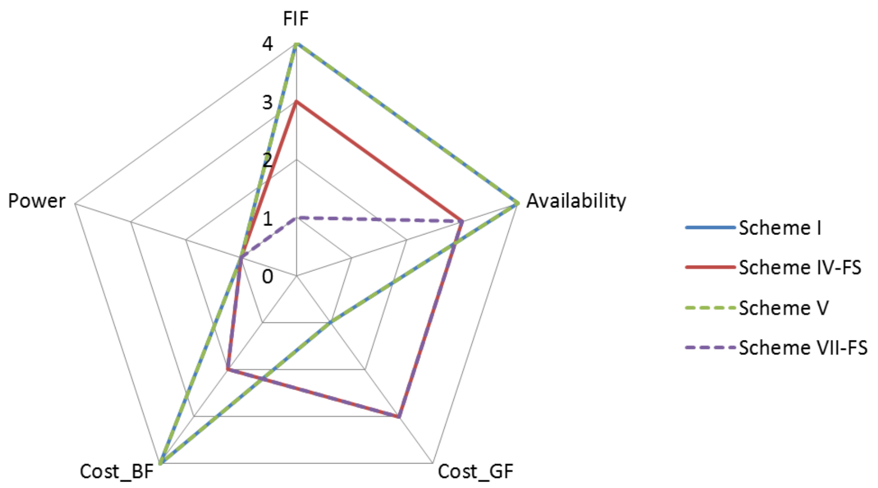



Figure 12: Comparison of FS protection schemes

Figure 13 depicts the comparison of the schemes offering E2E protection. It can be observed, that the increase of power consumption of the 1+1 solutions such as Schemes II is significant compared with the other solutions. Regarding FIF, all solutions offer protection to all network components (hence FIF~0) except Scheme III. Moreover, Schemes III and VI requires lower GF cost than Schemes IV-E2E, and VII-E2E, which require more than duplication of the deployment cost of the unprotected PON. Protection of Scheme VI is based on existing WIFI routers and hence, it does not require extra investment for protection. When comparing the BF cost, the costs required by Schemes II and III explode due to the trenching associated to the protection fiber. The other schemes require similar costs as in the GF scenario, since all the installation can be done on demand, i.e., by reusing existing working infrastructure and adding components and/or wireless links where needed. Last but not least, the connection availability higher than 5 nines is offered by all the schemes except Scheme III which protects neither the OLT nor the ONU, and Scheme VI which does not protect the ONU.

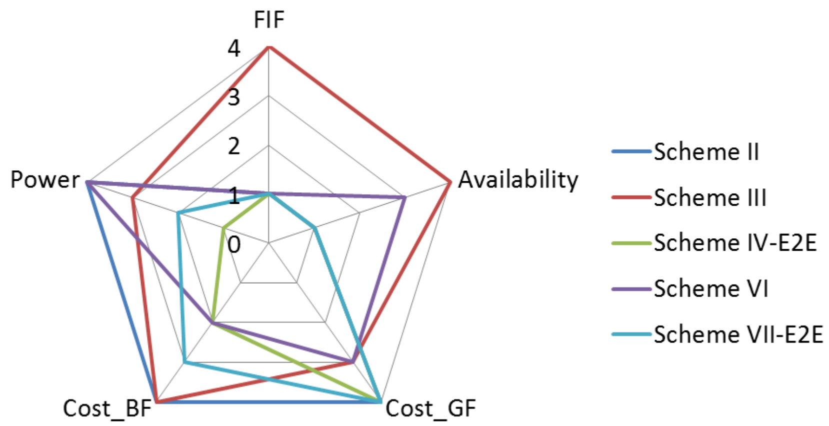



Figure 13: Comparison of end-to-end protection schemes

## V. CONCLUSION

This paper has presented a set of assessment criteria to compare different protection schemes. These criteria are based on reliability parameters such as Failure Impact Factor (FIF) and connection availability, as well as cost parameters such as the investment required in greenfield and brownfield scenarios and the increase of power consumption compared to the unprotected network. The proposed criteria have been used to compare 7 representative protection schemes proposed in the literature, which differ on the number of protected components, and the technology used for protection (fiber, wireless, etc.). For a particular urban scenario, the protection schemes have been applied to next generation optical access architecture referred to as Hybrid PON with a client count of 1280. The assessment shows that schemes with FIF=0 offer high connection availability (more than 6 nines) and relatively high brownfield cost. However, in case where an operator aims at offering connection availability close to 4 nines and designing the protected access network in the greenfield scenario, options providing feeder section protection can offer lower costs, because not all the components need to be duplicated. It is shown that it is difficult to find a single solution best for all possible cases. The best protection scheme depends on the requirements of the operator and the deployment area.

Moreover, it should be noted that in this paper we considered a certain urban scenario as a use case for presenting the evaluation results. However, the proposed assessment methodology is general and can be applied to any other deployment areas, e.g., rural areas. Obviously, the conclusions from the comparison of the schemes may be different from the one presented in this paper.

## ACKNOWLEDGEMENT

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## 5.3 Paper J7

ADVANCES IN NETWORK PLANNING

# Advanced Dynamic Migration Planning toward FTTH


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# Advanced Dynamic Migration Planning Towards FTTH

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*Abstract*—**This paper proposes a dynamic migration planning methodology for communication networks. Aiming at providing optimal technical performance, the approach takes into account dimensioning of network infrastructure and services, as well as evaluation of revenues and costs. As a result, the migration planning method provides a cost-effective network deployment plan based on an optimal stepwise upgrade strategy. Market information, existing infrastructure, costs and demand forecasting are then considered in order to determine this strategy by solving a combinatorial optimization problem. It is described theoretically, and a techno-economic evaluation framework is introduced to assess its financial feasibility. The model is a suitable guideline to tackle migration problems commonly solved by using anticipated, single and multi-period planning techniques. Considering a particular example, a study on migration towards Fiber to the Home (FTTH) is analyzed. Fiber to the Cabinet/Building (FTTC/FTTB) architectures are then proposed as possible intermediate steps in the migration path to FTTH. Finally, a case study for an existing access network is analyzed.**

***Keywords- Dynamic Migration Planning, Techno-economic Study, Optical Access Networks, FTTx, Multi-Period Planning.***

## I. INTRODUCTION

The migration of a telecommunication network can be approached as a multi-period planning problem. Its solution involves demand forecasting, dimensioning of network infrastructure and processes as well as the evaluation of their economic costs. The resulting upgrade plan is a network deployment strategy that defines a stepwise migration path, which is a temporal sequence of network layouts called migration steps.

Network migration also entails careful evaluation of revenues, capital (CAPEX) and operational (OPEX) expenditures. Hence, the upgrade plan specifies what investments are required at each point in time. Specifically, the CAPEX needed to upgrade the network from one migration step to another as well as annual OPEX contributions are part of the solution. The best deployment plan is therefore, the one that minimizes the Total Cost of Ownership (TCO) while guarantying optimal technical performance.

Dynamic migration is useful for multi-period planning of core and wireless/wireline access networks. For instance, operators are facing the challenge of upgrading their networks to bring fiber and high speed wireless to their customers. In particular, fiber-based access has become essential to provide multimedia services that demand high quality standards. This has forced operators to focus their efforts on the promotion of models to assess financial feasibility for fiber deployment. This goal can be achieved by temporarily deploying hybrid fiber-copper FTTC/B solutions on the migration path to FTTH. As strategy, this exploits the unused potential transmission capacity of installed copper lines while optimizing costs and profitability.

This paper presents a generalized model to study network migration problems. As an example, the approach is defined to analyse technical and financial feasibility for migration towards FTTH. The framework studies vertically integrated operators, who are those providing both services to end customers and network connectivity, i.e., layer 2 (Ethernet), layer 3 (IP) access, to service providers [1]. The analysis is focused on target migration areas that can comprise Dense Urban (DU), Urban (UR) and Rural (RU) area types. Each area may connect customers classified as Single Family Units (SFU), Multi-Dwelling Units (MDU) and Business Dwelling Units (BDU). Moreover, network dimensioning and cost modeling are performed based on the services bought by customers and the operator's existing infrastructure. In order to achieve its goal, the migration planning model defines full copper, FTTC/FTTB architectures to be steps on the transition to FTTH.

This paper is organized as follows. Section II studies the generalized dynamic migration strategy. Section III describes the techno-economic framework for migration planning. Section IV defines a model for migration planning towards FTTH. Section V presents a case study and finally, section VI concludes the paper.

## II. GENERALIZED DYNAMIC MIGRATION PLANNING

### *A. Generalized Migration Model*

The goal of migration planning is to upgrade an existing infrastructure to a target network architecture. However, direct migration is not always feasible due to the high costs involved. A solution would then be to implement network architectures that gradually outperform infrastructure's capabilities.

If we model a migration step as a state "*s*" defining a network architecture, then, an upgrade plan is simply a temporal sequence of states that configure a migration path. As discussed in [2], this problem can be tackled by introducing a set of "S" states [1, 2, .., s, .., S], with state "S" representing the target network layout. For this set, Figure 1a illustrates a state diagram that depicts all possible forward transitions between migration steps.

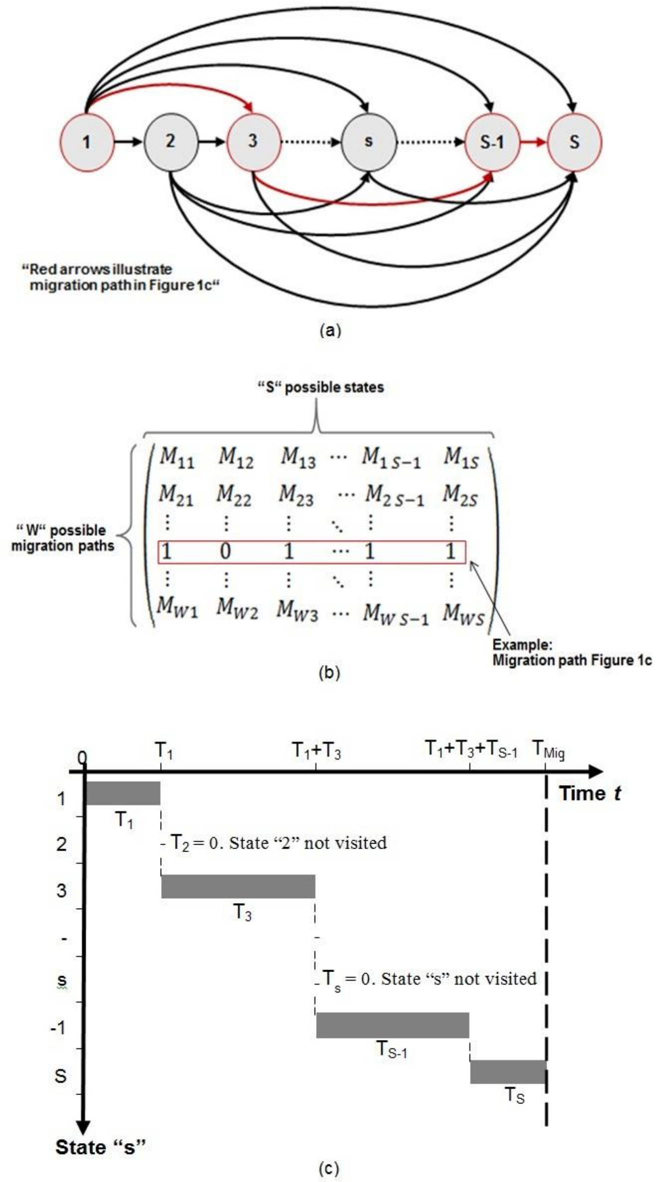


Figure 1. a) Generalized migration state diagram; b) Generalized Migration matrix M; c) Illustration of a migration path from state $x$ = 1 to the target state S subject to migration period $T_{Mig}$ and holding times $T_s$.

In general, a network infrastructure may be heterogeneous, which means that it consists of several coexisting architectures. Thereby, any existing network might define a layout of "*S-1*" initial states or conditions $x \in [1, \dots, S-1]$. Given this hybrid design, how to determine its optimal upgrade plan towards "*S*"?. The first step is to establish candidate migration paths, which are derived for each initial condition "*x*" from the state diagram. We can model these paths as rows of a binary migration matrix $\boldsymbol{M}$, whose structure is shown in Figure 1b. It has "*S*" columns, each one referring to a state. The matrix element $M_{i,j} \in \{0,1\}$, indicates whether the state defined by the $j_{th}$ column is visited, $M_{i,j} = 1$, or not, $M_{i,j} = 0$, by a network following the $i_{th}$ path. Therefore, this $i_{th}$ candidate migration path is a S-dimensional row vector whose first nonzero element is "*x*", since backward transitions are not allowed. On the other hand, $\boldsymbol{M}$ has "*W*" rows that represent the candidate paths of all the "*S-1*" initial conditions. As a result, $\boldsymbol{M}$ contains all the possible migration paths of a heterogeneous network infrastructure that connects subscribers within a service area.

A migration path consists of "*S*" holding time intervals $T_s$, $s \in [1, \dots, S]$, where $T_s$ is the time in years the network stays at the architecture defined by state "*s*". For every candidate path, we can define a vector $\boldsymbol{T_{hold}} = (T_1, T_2, \dots, T_{S-1}, T_S)$, with each component representing a holding time $T_s$. As an example, Figure 1c depicts a migration path with initial condition $x$ = 1 and $\boldsymbol{T_{hold}} = (T_1, 0, T_3, 0, \dots, 0, T_{S-1}, T_S)$. Given a migration period $T_{Mig}$, in the second step, a techno-economic evaluation of the problem is made. Its goal is to determine, per existing initial state "*x*", both the path and its corresponding $\boldsymbol{T_{hold}}$ that minimize costs and maximize profit. Therefore, for the most general case, the network deployment plan must define "*S-1*" optimal paths. This optimization and evaluation process will be discussed in detail in the next section.

## III. Techno-Economic Framework for Dynamic Migration Planning

Given a target architecture "*S*", a set of migration steps and "*S-1*" initial conditions; migration planning towards "*S*" can then be formulated as a combinatorial optimization problem. It is solved via an exhaustive search method, which is implemented using the techno-economic framework shown in Figure 2. It comprises definition of input information, revenue and cost modeling, network and service dimensioning, as well as evaluation [3].

### *A. Objective Function and Constraints*

The best upgrade plan is defined by the migration paths that yield maximal profitability at minimum cost. For a network segment with initial condition "*x*", its objective function is then the profit, which is the total revenue minus the TCO. In general, this TCO is the sum of the OPEX and CAPEX contributions from all visited states in the migration path. Thus, given a forecast interval and a planning horizon of length $T_{Mig}$, the following constraints apply for every candidate path in $\boldsymbol{M}$:

- For each component $T_s$ of $\boldsymbol{T_{hold}}$, if state "s" is not visited, $T_s = 0$, otherwise $T_s$ must fulfill $T_{Min} \leq T_s \leq T_{Mig}$. The parameter $T_{Min}$ represents the installation time needed to deploy capacity when a migration occurs. Additionally, $T_s$ is assumed to be a positive integer.
- The sum of the vector components of $\boldsymbol{T_{hold}}$, must equal $T_{Mig}$.

### *B. Definition of Input Information*

The goal is to upgrade an existing heterogeneous network; therefore, its relevant input information is defined and processed as follows:

- Market information such as existing customer types and the services offered to them is collected.

- Service areas, their number of connected users per customer type and traffic demands are determined.
- The existing network infrastructure is described. It gives a detailed view on installed architectures, their technologies and number of connected users. This information defines user groups with common initial condition "$x$". Therefore, for the subscribers belonging to a customer type within a service area, a matrix $\boldsymbol{M}$ is set up to list the candidate paths of the existing initial states "$x$". The following section explains how this is modeled for migration towards FTTH.
- Price books are used as input for both CAPEX/OPEX and revenue calculation.
- Migration analysis uses expected evolutions of traffic demands and costs to find the optimal upgrade strategy. Therefore, a forecast interval equal to $T_{Mig}$ is set up to make these predictions. Also $T_{min}$ is fixed as a constant input parameter.

For each existing user group with initial condition "$x$", the set of vectors $\boldsymbol{T_{hold}}$ per candidate path that fulfill the constraints are calculated. Thereby, both these candidate paths and $\boldsymbol{T_{hold}}$ vectors define the search space of the optimization problem.

### *C. Dimensioning, Modeling and Evaluation*

The members of a user group with initial condition "$x$", within a matrix $\boldsymbol{M}$, are simultaneously migrated following the same path. The objective function of the group is optimized by sequentially selecting from the search space a candidate path. Thus, for every existing user group with initial condition "$x$", the following analysis is made on each candidate vector $\boldsymbol{T_{hold}}$ of the selected path:

- Network component costs and traffic demands predictions are calculated over the forecast interval. For the candidate path, the network dimensioning module reads out both the corresponding matrix row and $\boldsymbol{T_{hold}}$ from left to right. Whenever a state transition occurs, based on predicted demands, dedicated dimensioning is used to calculate the infrastructure required to visit the next state.
- The CAPEX model, for each state transition in the path, calculates the costs to buy, upgrade and install the infrastructure. The total CAPEX is the sum of the contributions at all migration steps over $T_{Mig}$.
- The OPEX model calculates the costs to keep the network operational. Following [4], these costs include service provisioning, operational network planning, marketing, renting, energy consumption, maintenance and reparation, as well as pricing and billing. For each visited state "$s$", the model calculates the annual OPEX contributions over the corresponding component $T_S$ of $\boldsymbol{T_{hold}}$. The total OPEX is the sum of the contributions at all steps.
- The revenue model estimates income based on predetermined service types. These are defined according to the technical capabilities needed to run a service on the network. Thereby, the product portfolio of the operator is mapped to these service types. When a state transition occurs in the path, service dimensioning calculates the potential coverage for each service. The reason is that any architecture performs different for each service, thus, the better the coverage is, the higher the service type that can be provisioned on the network. The model predicts the number of users in the group who upgrade their services due to network migration. Consequently, using the pricing defined per service type in the price books, the total revenue is calculated as the sum of the income contributions from the users at all steps over $T_{Mig}$.

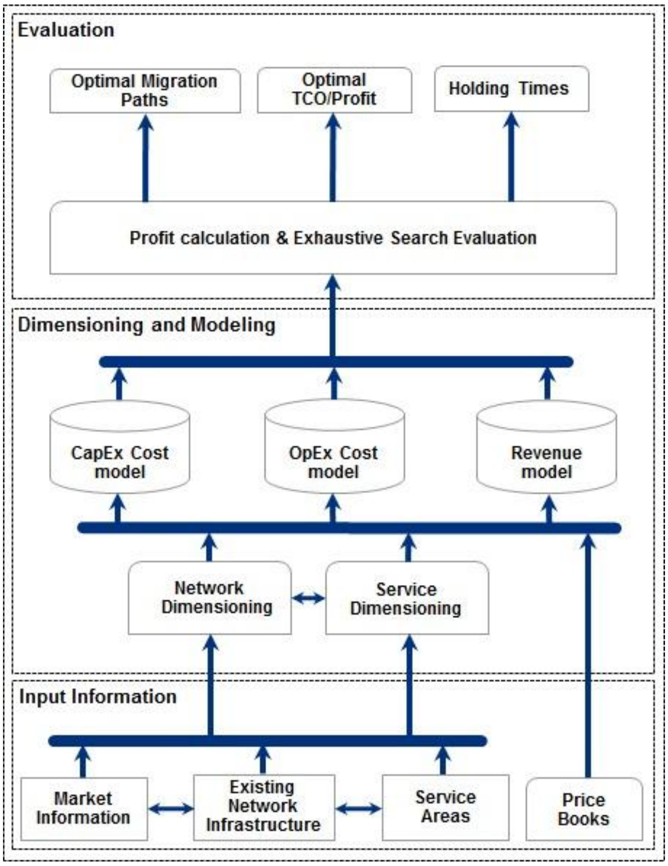


Figure 2. Techno-Economic framework for dynamic migration planning.

Once all the candidate solutions are selected and analyzed, the evaluation phase calculates per candidate path and $\boldsymbol{T_{hold}}$ the total profit. The path and its corresponding $\boldsymbol{T_{hold}}$ that maximize profitability are selected as the optimal upgrade plan. The solution vector $\boldsymbol{T_{hold}}$ schedules the migration of the group, and dictates what investments are made at each point in time. Furthermore, the optimal path explicitly defines the type of architecture to deploy at each step. As an example, in the following section the generalized model is defined for dynamic migration towards FTTH.

## IV. DYNAMIC MIGRATION PLANNING TOWARDS FTTH

This section formulates the migration planning model towards FTTH for fixed broadband access networks. The architectures and the technologies used to implement them are introduced in order to define the migration steps.

### A. FTTx Network Architectures

Fixed broadband access networks are made up of fiber, copper, coaxial cable, and power line solutions. The most popular scenarios are based on either hybrid fiber-copper or full-fiber oriented deployments. These variants define the FTTx architectures shown in Figure 3, which mainly differ on how far the optical fiber gets.

Unlike full copper (FC) and FTTH architectures, FTTC/B represent hybrid optical-copper access networks. These hybrid solutions implement optical networks from central offices (CO) to remote nodes located in the outside plant. These nodes are street cabinets (SC) and access points (AP) for FTTC and FTTB respectively. From these nodes, copper networks are rolled out to span customer premises equipment.

Recently, Fiber to the Distribution Point (FTTDp) or Fiber to the Street (FTTS) has been proposed to shorten the last copper segment to end users. Furthermore, Fiber to the Desktop is trying to extend the FTTx concept to the inhouse fiber solution. In order to keep the model simple, these cases have not been included in the presented version. Therefore, our model will only consider FC, FTTC/B as intermediate migration architectures.

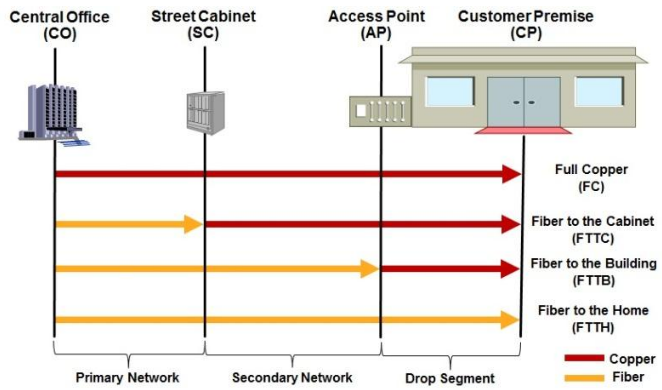


Figure 3. FTTx Architectures.

### B. Copper-Based Access Networks Technologies

The copper-based segment of FC/FTTx architectures can be implemented with Digital Subscriber Line (DSL) technologies, which connect DSL Access Multiplexers (DSLAM) to modems installed at customer premises. The most common variants are Asymmetric DSL2+ (ADSL2+) [5] and Very High Speed DSL2 (VDSL2) [6], which with vectoring or phantom mode can increase its capability for the same copper drop segments, but with some limitations [7]. As an alternative to DSL, Data Over Cable Service Interface Specification (DOCSIS) provides high speed transmission capacity over existing hybrid fiber-coaxial (HFC) networks [8].

### C. Fiber-Based Access Networks Technologies

Fiber-based networks represent the optical segment of FTTx architectures, and can be deployed using Active (AON) or Passive (PON) Optical Network technologies. Nowadays, as shown in [9] Next Generation Optical Access (NGOA) is targeting longer distances and higher transmission bandwidths with solutions such as GPON, WDM PON, Hybrid PON, NG-PON2 and Active Optical Ethernet. These technologies allow a wise integration with copper-based solutions.

### D. Migration Planning towards FTTH

Migration towards FTTH is modeled by defining the target state as *S = FTTH*. If we consider Greenfield (G) subscribers, i.e., users who need complete installation of infrastructure, then, migration can be studied using five states: Greenfield (G), Full Copper (FC), FTTC (C), FTTB (B) and FTTH (H). Thereby, any state $s \in [G, FC, C, B, H]$ and there may be four initial conditions $x \in [G, FC, C, B]$.

The subscribers are within a target migration area that may span a country, state, city or small town. This area may include DU, UR and RU area types, or service areas, which are defined by their user densities (customers/ $\text{km}^2$ ). In general, each of these areas serves three customer types, i.e., SFU, MDU and BDU. For the users belonging to a customer type within an area type, let us define a five-state diagram and its $15 \times 5$ migration matrix $\boldsymbol{M}$ as shown in Figures 4a and 4b respectively. Furthermore, let us divide these users into four groups, each one containing subscribers with a common initial condition "*x*". As shown in Figure 4b, each user group within an area type has a limited number of possible migration paths, which indeed depends on its initial condition "*x*". The state diagram determines for each state "*x*" the candidate migration paths (rows) in $\boldsymbol{M}$. Therefore, the members of a user group can simultaneously be migrated to FTTH following the same migration path over a planning horizon $T_{Mig}$.

From the previous analysis, for a target migration area covering DU, UR and RU area types, each one serving SFU, MDU and BDU users, the generalized migration planning model towards FTTH is defined as:

- There are 3 area types $\times$ 3 customers types per area = 9 migration matrices $\boldsymbol{M}$.
- There are 3 area types $\times$ 3 customers types per area $\times$ 4 user groups per customer type = 36 migration paths, user groups and initial conditions "*x*".
- For a user group within an area type with initial condition "*x*" equal to G, FC, C or B there are 8, 4, 2 or 1 candidate migration paths respectively (see Figure 4b).

The starting network layout may be heterogeneous because the states "*x*" define several FC/FTTx coexisting architectures. Additionally, for the generalized problem, the goal of is to independently migrate 36 user groups by finding 36 optimal migration paths. Nonetheless, the model can be adjusted to study simpler scenarios by just removing matrices and/or rows that represent nonexistent service areas and/or user groups.

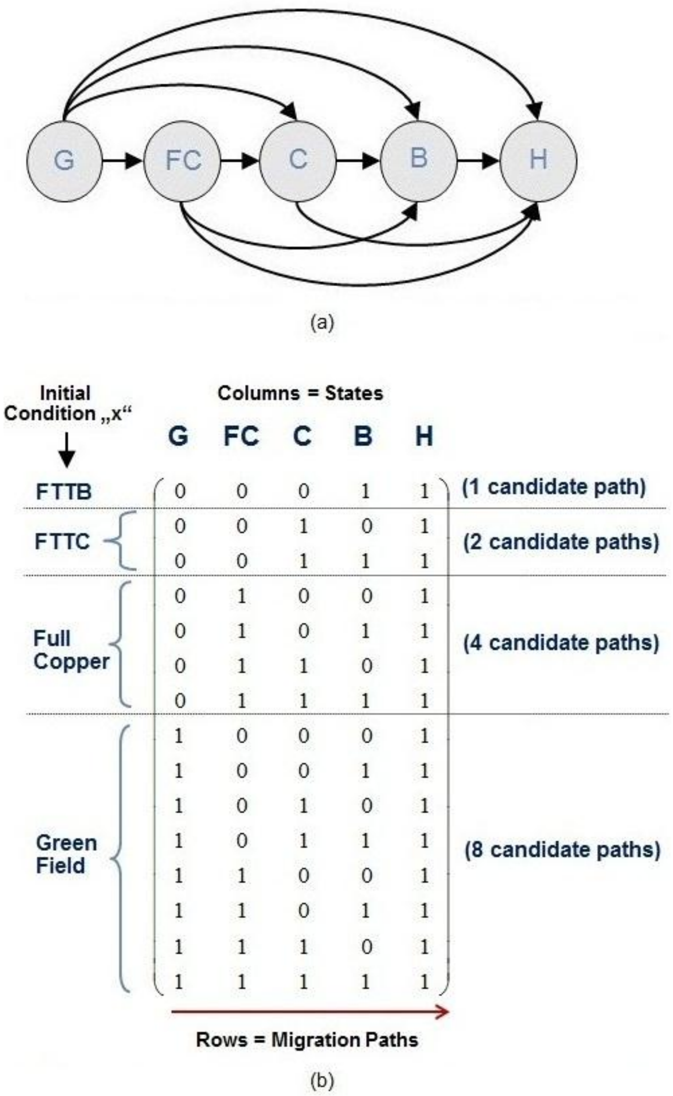


Figure 4. a) Five-state diagram for migration towards FTTH; b) Migration Matrix for users belonging to a customer type within an area type.

In order to find the migration plan, the techno-economic framework follows the steps explained in the previous section. However, for the sake of clarity, in the definition of input information, DU, UR and RU service areas as well as their number of SFU, MDU and BDU users must be determined. Besides, a $15 \times 5$ migration matrix $\boldsymbol{M}$ is set up for each customer type within an area type. The existing user groups per matrix and their initial states "*x*" are defined. Moreover, for each migration step, the network dimensioning module calculates the components in central offices, street cabinets, access points as well as cabling. Furthermore, the revenue model defines five service types:

- Service type 1: VoIP and narrowband internet.
- Service type 2: triple play (broadband internet, VoIP, TV).
- Service type 3: broadband internet, VoIP and high definition television.
- Service type 4: broadband internet, VoIP, high definition television and interactive services.
- Service type 5: "Carrier class profile" which provides layer 2 and layer 3 bit stream access, at high speeds, to service providers.

## V. CASE STUDY

### *A. Case definition*

Let us study migration towards FTTH for an operator in the city of Bogotá D.C, Colombia. Relevant input information is [10]:

- A DU area of 477.8 $\text{km}^2$ serves 504.783 subscribers installed with FC and FTTC architectures.
- A RU area of 1298.2 $\text{km}^2$ serves 1.126 subscribers installed with FC architecture.
- Due to density population there is not UR area.
- FC solutions are point to point ADSL2+ copper networks. On the other hand, FTTC is a Point to multipoint (P2MP) network implemented with GPON/VDSL2 technologies. It uses fiber rings that offer protection at the primary network segment shown in Figure 3.

Columns 1 to 5 in Table 1 detail how users are distributed per area and customer type as well as per initial condition "*x*". With this input information, let us use GPON/VDSL2 technologies to dimension the FTTx architectures with protected primary network segments. Therefore, in the end, the goal is to reach a GPON-based FTTH solution. This problem requires 6 migration matrices $\boldsymbol{M}$, three for each existing area type, thus one per customer type. Moreover, there exist 6 and three user groups within the DU and RU areas respectively. Considering $\mathrm{T_{Mig}} = 10$ years, $\mathrm{T_{min}} = 1$ year, the techno-economic framework is used to determine the optimal upgrade strategy.

### *B. Results and Analysis*

Column 6-11 in Table 1 present the optimal migration paths along with their holding times $\boldsymbol{T_{hold}}$. Additionally, columns 12-14 show the optimal accumulated profits, revenues and TCO per user and month calculated over $\mathrm{T_{Mig}}$. From column 12, we see that the operator profits from DU users, which means that their monthly generated revenue (column 13) is higher than the cost (column 14) to migrate them towards FTTH. Therefore, there exist 6 optimal paths in the DU area. Nonetheless, the RU area is unprofitable, since the average monthly TCO is not compensated by the revenues from its users, and thus migration is not feasible. The three $\boldsymbol{T_{hold}}$ vectors shown in Table 1 for the RU area, only represent the holding times that lead to minimum loss. Profitability can then be achieved by increasing revenues and/or decreasing the TCO.

| Area Type | Customer Type | Initial State "x" | Distribution of subscribers | Number of subscribers | Optimal migration path | Holding Times $T_{Hold}$ [years] | | | | | Optimal Profit [Euro/User] Monthly | Revenue [Euro/User] Monthly | Optimal TCO [Euro/User] Monthly |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $T_G$ | $T_{FC}$ | $T_C$ | $T_B$ | $T_H$ | | | |
| Dense Urban | SFU | FC | 99% | 164960 | FC → FTTC → FTTH | 0 | 2 | 6 | 0 | 2 | 6 | 37 | 31 |
| | | FTTC | 1% | 1830 | FTTC → FTTH | 0 | 0 | 8 | 0 | 2 | 15 | 45 | 30 |
| | MDU | FC | 99% | 245388 | FC → FTTC → FTTB → FTTH | 0 | 2 | 4 | 2 | 2 | 17 | 40 | 23 |
| | | FTTC | 1% | 2722 | FTTC → FTTB → FTTH | 0 | 0 | 6 | 2 | 2 | 26 | 48 | 22 |
| | BDU | FC | 74% | 66590 | FC → FTTC → FTTH | 0 | 2 | 6 | 0 | 2 | 49 | 91 | 42 |
| | | FTTC | 26% | 23293 | FTTC → FTTH | 0 | 0 | 8 | 0 | 2 | 60 | 101 | 41 |
| Rural | SFU | FC | 100% | 787 | Negative profit | 0 | 4 | 2 | 0 | 4 | -55 | 32 | 87 |
| | MDU | FC | 100% | 139 | Negative profit | 0 | 6 | 2 | 0 | 2 | -61 | 30 | 91 |
| | BDU | FC | 100% | 200 | Negative profit | 0 | 4 | 4 | 0 | 2 | -70 | 31 | 101 |

Table 1. Optimal migration strategy for the case study.

Increasing the prices, of the services offered to RU users, by the amount necessary to compensate the profit deficit is not a solution to reach profitability in this case. By checking the worst case in Table 1, the monthly revenue from a rural BDU should be increased at least 70 Euro/month to compensate a 101 Euro/month cost. Increasing revenues by only raising prices affects market growth. Nevertheless, if the objective of the operator is to achieve, instead of profit, coverage without losses, then, profitable DU customers can subsidize RU users as shown in Figure 5a. Cross subsidy reduces the investment deficit, and has to be complemented with business and marketing strategies that encourage customers to upgrade their services to the highest service type they can buy.

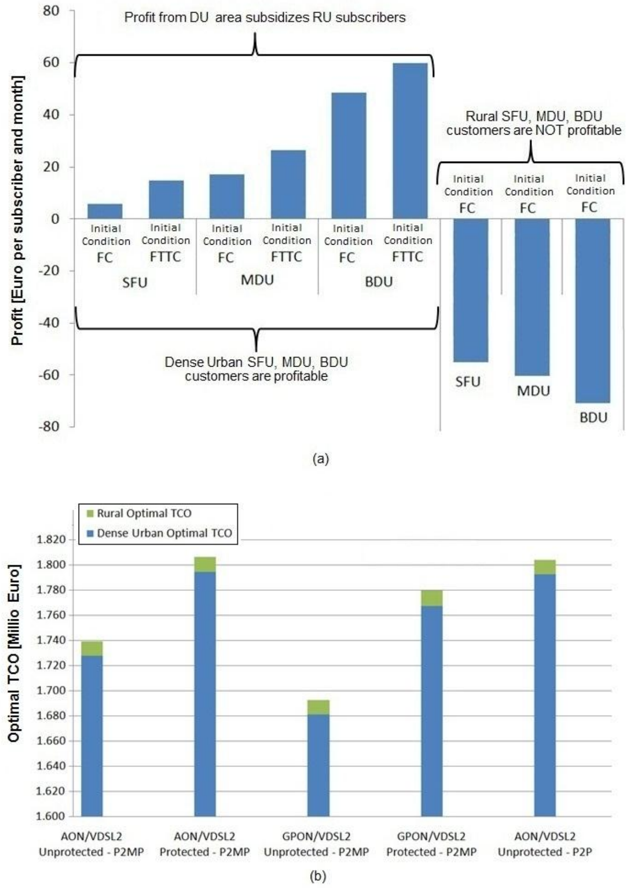


Figure 5. a) Average profit per user and month; b) Optimal TCO for migration alternatives.

In order to decrease TCO, we can study how migration costs change by considering alternative pairs of optical/copper technologies. Therefore, let us define four additional alternatives to implement our FTTx architectures:

- P2MP unprotected access network implemented with GPON/VDSL2.
- P2MP protected access network implemented with AON/VDSL2.
- P2MP unprotected access network deployed with AON/VDSL2.
- Point to point unprotected access network implemented with AON/VDSL2.

Figure 5b, shows the TCO obtained for each alternative using the techno-economic framework. Although less tolerant to failures, unprotected solutions are cheaper than their protected counterparts. But in fact, this makes these deployments inadequate for massive markets, since penalties due to service unavailability impact profitability. Furthermore, it can be seen that the TCO of GPON solutions is cheaper than the counterparts based on AON Ethernet. This illustrates the advantage of PON solutions due to their low energy consumption. Therefore, the initial P2MP protected access network deployed with GPON/VDSL2 is the best choice as it increases availability, and in the long run is cheaper than AON alternatives.

The TCO needed to migrate a RU subscriber is high, since rural installations require more effort in terms of infrastructure deployment, fiber trenching, and maintenance and reparation. Besides, in most cases, it is difficult to increase user adoption rates in RU areas with low densities. Therefore, providing coverage and services to this type of territories is normally not an appealing issue for operators.  From this discussion, it follows that in general a migration strategy must be aware of these key points:

- Profitability can be achieved by reducing costs. The adoption of technologies with high technical performance and low CAPEX and OPEX in the long run is an alternative solution. Therefore, a good knowledge on both the quantitative impact of technologies on network costs and their main cost drivers is required.

- Suitable marketing strategies and pricing rules, aiming at producing higher revenues, can increase user adoption rates. This encourages subscribers to upgrade their services, and lures potential customers to connect to the network.
- Cross subsidies between users can propel migration to FTTH in areas with profit deficit. This is a solution only if optimal profitability is not a concern for operators.

Migration towards FTTH cannot always be feasible. Hence, the proposed migration approach could be extended to study target states $s \in [G, FC, C, B, H]$, in order to determine what the best final state "$s$" per user group is. This would allow a better, and more generalized definition of the optimal network deployment plan.

## VI. Conclusions

The generalized migration planning model suggests a stepwise upgrade approach. It determines an optimal network deployment plan that maximizes profit while guaranteeing technical performance. We have shown that the calculation of this plan includes a techno-economic analysis that comprises service and network dimensioning, as well as evaluation of revenues and costs. In particular, the generalized model is formulated for migration towards FTTH. This example shows that an accurate definition of the migration steps is mandatory to tackle the network migration problem properly. We discuss a case study which illustrates that migration is not always feasible. Although profitability can be achieved by increasing revenues and/or decreasing the TCO, we show that migration could be possible, if instead of profit, the objective is to achieve coverage without losses. Hence, profitable users can subsidize unprofitable areas. The analysis shows that any migration strategy has to be aware not only of the technical, but also the economic constraints of the problem to be solved.

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## 5.4 Paper J9

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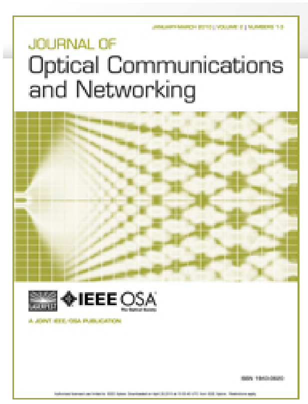
# Methodology for a Cost Evaluation of Migration Toward NGOA Networks

Carmen Mas Machuca, Mario Kind, Kun Wang, Koen Casier, Mozhgan Mahloo, and Jiajia Chen



# *Methodology for A Cost Evaluation of Migration towards NGOA Networks*

C. Mas Machuca, M. Kind, K. Wang, K. Casier, M. Mahloo, J. Chen

***Abstract*— Evolution of optical access networks promises to bring higher bandwidth to more customers. However, this evolution towards the so-called Next Generation Optical Access (NGOA) networks also introduces additional challenges that operators and/or vendors have to address: How to properly estimate and compare different NGOA architectures and their evolutionary paths in terms of their economics. Calculating the Total Cost of Ownership (TCO) for NGOA networks is a very complex target as it needs to involve a good knowledge of the technology, the existing network infrastructure and any migration-related process. In this paper a complete methodology is presented for evaluating the TCO of the migration towards a NGOA network. It contains a detailed description of which key aspects have to be considered, which process they affect and how they are translated into costs in a logical manner. Finally it also shows how this methodology has been applied to particular selected cases and how it gives a detailed view of all costs involved in migration. This approach opens up opportunities to cooperate in techno-economic research using it as a base. Both operators and vendors can also utilize this approach to get useful economic background of their future investments and potential sales.**

***Index Terms*—Next generation optical access (NGOA), cost modeling, migration**

## I. Introduction

The constant evolution in smarter devices, richer applications and always connectedness of customers through multiple devices at once, drive the continuous increase of hunger for bandwidth. Operators keep competing for customers by means of high bandwidth (traditionally downstream but also more and more upstream) as well as low fares and more symmetric cloud services.

In order to offer the customers high bandwidth, operators are looking at the possibilities and advantages of optical access networks. One of their interests is the immediate possibilities to put higher bandwidth connections on the market, while keeping an eye on the longer term evolution and their economics. An important question for operators is: "Which technology, architecture, and components do I choose at which time to be best in terms of total cost of ownership (TCO) in the future as well?"

Optical access network technologies are being revised and extended continuously towards next generation solutions. Major standardization organizations and their members are working on the next generation or even the generation after the next generation of optical access network technologies. For example, FSAN [1] has detailed the next generation of GPON (Gigabit Passive Optical Network), referred as NG-PON1 [2], and is currently investigating the generation after the next generation, referred as NG-PON2 (see [3]). However, the specification of a new technology generation which is the most cost-efficient for a certain service area is still difficult since it should be compliant with the requirements given by the operators (in terms of service, network, business and operational aspects), which are complicated to be assessed, especially the ones with strong time dependency. Overall, this could significantly impact operators in several ways. Hence, a generic methodology is required and proposed in this paper, so that the operators could find the best migration strategy compliant with their own requirements.

Besides, a new trend for the network design (e.g. longer transmission distances allow operators to serve larger areas with more users by reducing the number of central offices, the so-called concept of node consolidation [4]), makes the operators face the complexity increased by the tie up between infrastructure and technology. A certain technology might be an excellent solution for a certain point in time in Greenfield, but might limit the ability to be a proper next generation approach gradually migrated from the current deployed infrastructure and technology. This optimization problem – the network migration over time – demands a technical as well as techno-economic analysis.

A number of techno-economic studies have been performed on different types of optical access networks in order to estimate the required investments. Initial studies considered Greenfield scenarios and evaluated the capital expenditures (CAPEX) to install and start operating a network [5, 6]. However, these studies disregarded

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operational expenditures (OPEX) such as service provisioning and failure management, which have the same importance as CAPEX proved in [7]. Furthermore, most operators are already operating access networks and hence techno-economic studies should not only consider Greenfield scenarios but also brownfield scenarios. Some studies addressed the operation situation covering both CAPEX and OPEX aspects for TDM PON [8, 9] and NGOA [10]. However, the study of the migration process and the involved cost has been slightly addressed. In [11] a time-step migration planning from Greenfield or ADSL (asymmetric digital subscriber line) network towards traditional GPON or AON (active optical network) was presented, but this model is still lack of consideration of NGOA as well as the different roles of providers. In [12] a migration cost evaluation of core networks has been solved using meta heuristics but it does not get the intricacies in the economic modeling. In [13], the different options that cable operators have in the migration of their networks have been presented. It is a comprehensive methodology in understanding the basic principles of the cable network market with an in-depth analysis of existing players, technology deployments and demand in terms of existing take rate. Several migration paths from/towards different technology options have been analyzed, but they lack in long-term perspective for fiber and backhaul technologies (e.g. NG-PON 2 strategy) as well as overall cost analysis (e.g. covering both OPEX and CAPEX).

With this in mind, this paper tries to overcome the issues aforementioned in the existing techno-economic studies and reduce the previously outlined uncertainty for selecting the appropriate NGOA technology from cost perspective. This is done by presenting the methodology to perform a complete TCO estimation for different technologies within an encompassing techno-economic study. The study is focusing on the migration of the widely deployed current optical access technologies towards NGOA concerning both infrastructure and technology upgrade. Risk is also an important aspect but is not in the scope of this TCO evaluation.

Furthermore, the different types of provider roles have been taken into account when evaluating the costs and identifying who is paying which cost. This framework distinguishes the physical infrastructure provider (PIP), which owns and maintains the passive infrastructure (e.g. real estate companies, municipalities, utilities); from the network provider, which operates (and typically owns) the active equipment (e.g. incumbent operators, new independent operators, broadband companies).

In the following section, the motivation and rational as well as the most important migration aspects are addressed (Section II). Section III describes the methodology for the total migration cost computation. Section IV provides a detailed description of the cost modeling. The application of the proposed methodology to the particular case of migration starting from a GPON has been presented in Section V. Finally, Section VI concludes the paper.

## II. Migration towards Next Generation Optical Access Networks

New service and user requirements will force operators to enhance their access networks to offer more bandwidth to the users (e.g. 300 Mbit/s average sustainable bitrate per customer in 2030 has been used as realistic requirement based on the scenarios detailed in [14]). This enhancement can be achieved either by upgrading the existing networks, for example, by reducing the splitting ratio of an existing GPON, or by migrating towards NGOA solutions. Before the decision is taken, operators should carefully evaluate the costs associated with the different alternatives and study the impact on users.

The migration will clearly have several points of impact on the cost structure of the network operator, and it is crucial to focus on identifying the most relevant cost elements during the whole migration process. A key aspect in the migration is time. The operator can choose the migration start date, the duration of the migration and the way to migrate new and existing customers. Obviously, costs and timing will largely depend on the network to migrate from, i.e. the starting scenario. Finally it is important to also consider the impact that migration of the access network will have on the aggregation segment, especially considering the possibilities of node consolidation.

This section aims at identifying the aforementioned most important aspects to be taken into account in migration towards NGOA networks: (A) migration cost overview, (B) starting time and duration of the migration, (C) starting scenario, and (D) node consolidation and aggregation network.

### A. *Migration cost overview*

In order to evaluate the cost associated with the migration of an existing access network towards a NGOA solution, three costs should be evaluated:

- The costs related to the operation of the deployed access solution until all its users are migrated to the NGOA. Then, it can be dismantled.
- The costs related to the NGOA which include the planning, purchasing, installation and operation of the NGOA network given the penetration curve. The penetration curve determines the expected number of users and hence will impact the required equipment and infrastructure as well as the corresponding costs for service provisioning, fault management, etc. In case the existing access solution has already rolled out an optical distribution network (ODN), the NGOA could reuse the deployed ODN and therefore, it would be expected much lower investments required on the infrastructure.
- The cost to migrate users from the existing access network to the NGOA. This cost refers to the customer individual migration including customer specific network and service (re-)configurations and manual switchover on physical layer when there is no ODN coexistence. This cost is related to the service provisioning process, which includes any activity related with adding, changing and cancelling customers to the network. In particular, a special attention should be given to the process of migrating customers. Since this process scales with the customer of the existing access network, it should be as automatic, fast and smooth as possible (zero-touch solutions are targeted). Furthermore, an important challenge during migration is to minimize the user service disruption time.

All these costs should be evaluated for each year of the migration and for all the areas that should be migrated. The operator may decide migrating different areas sequentially or in parallel depending on other parameters such as the expected churn rate, existing competition, etc.

## *B. Migration starting time and duration*

Two key time parameters should be considered for the migration process: 1) the starting time, that is, the year when the migration is initiated; and 2) the duration (e.g. in years). These two values play an important role on the cost and on the overall business study. Their impact on the cost depends on the penetration curve, which gives the number of users joining the access network: initially connecting to the existing access network and during/after the migration, connecting to the NGOA network. The more users are connected to the existing access network at the migration starting time, the higher will be migration cost. On the other hand, the earlier users will have access to higher bandwidth, the higher incomes could be expected.

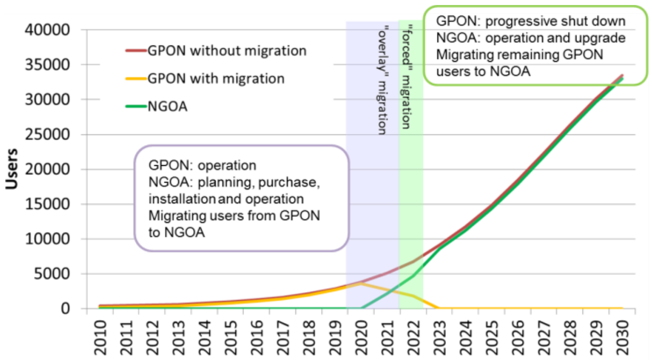



Figure 1 Example of penetration curve and the migrated users from existing GPON towards NGOA in 2020 and considered cost categories

Furthermore, the policy to migrate users from an existing access network to the NGOA network is a key aspect during the whole migration process. The migration of each customer has an associated effort and cost, and therefore a compromise between the resources that can be dedicated to the migration process and the number of users that should be migrated, has to be found. Most of the migration processes foresee the co-existence of both existing and targeted networks, allowing a smooth migration of users. However, when the number of remaining users in the existing access network is below a given threshold, a “forced” migration is done so that the traditional access network can be torn down and does not have any related cost (i. e. power, maintenance, etc.).

A particular example is shown in Figure 1 for migration starting from GPON. If no migration or upgrade is performed, the curve “GPON without migration” shows the increasing number of users in the network, where for the sake of comparison the customer base has been left unchanged. The migration towards NGOA starts in 2020 and lasts three years. Initially, the migration process allows the coexistence of both GPON and NGOA solutions, which is referred as “overlay” migration and implies a continuous and smooth migration of users from GPON to NGOA networks. However, the last phase of the migration requires a “forced“ migration of the remaining users to the NGOA. This last stage allows the operator disconnecting and dismantling the equipment of the GPON network, while operating only the NGOA network. It can be observed, that the later the migration, the more users have to be migrated. Furthermore, the more aggressive the penetration curve, the more users have to be migrated. A useful feedback from the study is the evaluation of the worthiness of different migration alternatives given an expected penetration curve for a migration starting time and duration.

## *C. Starting scenario*

There are two migration scenarios that operators may face: the Network Provider (NP) brownfield scenario, where an operator is already running an optical access network; and the NP Greenfield scenario, where the operator has a purely copper based access network. There is a third possibility for an operator which is to start from a pure Greenfield scenario, but since this scenario is not a migration case, it has not been considered in this paper. However, this case could be considered as a simplified case with no initial network and therefore, any cost will be associated with the NGOA network.

- The NP Brownfield scenario considers the migration from existing traditional optical access solutions to NGOA networks. In this case, the fiber infrastructure and equipment exists for a traditional access area. For instance, the operator runs GPON, or AON already. In NP Brownfield scenario operators can increase the offered bandwidth by upgrading the existing network (e.g. when running a GPON, a reduction of the splitting ratio could increase the offered bandwidth) or by migrating to an NGOA solution.
- The NP Greenfield scenario assumes a migration from non-optical access networks (e.g. copper network) where some cable ducts may be available to be used by optical cables. Apart from the available ducts, all the other NGOA related equipment and infrastructure such as cables, optical filters, OLTs, etc. are taken into account when evaluating the migration cost. In that case, no upgrades are considered, but rather a migration towards high bandwidth NGOA solutions.

## *D. Node consolidation and aggregation network*

Traditional access areas have been defined based on the limitation in terms of transmission reach and offered bandwidth of the existing technologies (e.g. 20 km and 32 or 64 users in GPON). However, new technologies allow longer transmission reach and much higher bandwidth, which allow reducing the number of required central offices and therefore, expecting also a reduction of the associated costs. Node consolidation means grouping several traditional access areas into larger areas so-called NGOA service areas whose central offices are labelled as metro access nodes [15]. The node consolidation degree is defined as the relative difference between the number of traditional central offices and the number of metro access nodes in a given network scenario. The main difference in the network architecture is that in non-node consolidation scenarios, the OLT is located at the local exchange, whereas in node consolidation scenarios, the OLT is located at the central access node (CAN) and requires longer feeder fiber.

When considering migration, the operator may aim at evaluating the cost benefit from node consolidation. In order to have an overall picture on TCO analysis, the savings of node consolidation associated with the smaller aggregation network should be expected and included in the study. Hence, the aggregation network cost should be modelled in the cost evaluation of any migration study towards NGOA, as shown in the next section.

## III. Total Migration Cost Computation Methodology

This section gives an overview of the methodology used for the calculation of the migration study business case, indicating all relevant input parameters and boundary conditions of the study, comprising TCO building blocks, deployment conditions, demand scenario and aggregation cost model.

The proposed framework for the migration cost evaluation is depicted in Figure 2. Three calculation models – topology, architecture and operational (OPEX) model – are linked together in the context of the migration business case which leads to the total cost of ownership. Initially, the definition of the migration scenario has to be given in terms of:

- node consolidation degree, that is, whether node consolidation is considered or not. If it is, it gives the percentage of the central office reduction. This parameter will also define the distances from the (metro) access node and the user.
- area type, which defines the surface, user density, etc. It differs significantly from dense urban (DU) to rural (R) areas (i.e. rural areas are wider and have fewer users than dense urban areas).
- penetration curve, that shows the expected number of users per year which is likely to join the network.
- starting and new architecture: it gives the existing and the targeted architectures to be considered in the migration.
- time frame and migration start time and duration. The time frame defines the complete time frame of the cost study (e.g. 2013-2030) and the migration duration falls within the time frame (e.g. 2020-2023).

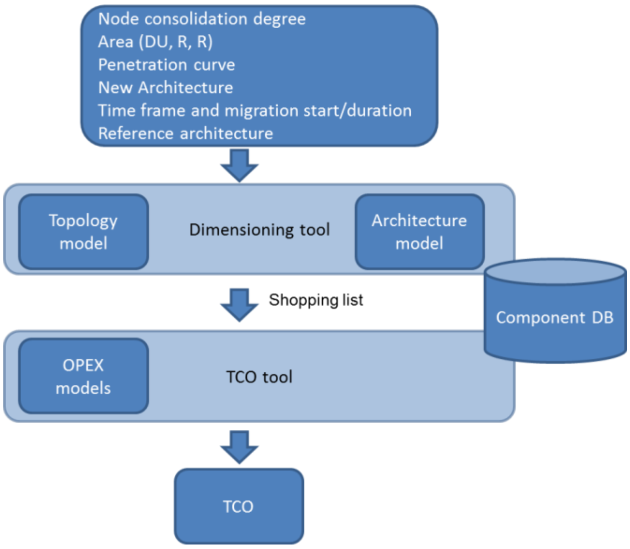



Figure 2 Migration cost evaluation methodology

The first two steps in the methodology are focusing on the network dimensioning from both architecture and topology view. Such an approach is clearly suited to dimension both existing and future networks. The result of the network dimensioning is a “shopping list” containing for each year, the list of components that are needed and where they should be placed. Furthermore, there is a component database which includes, for every single infrastructure and network component considered in any architecture, the cost, power, failure rate, expected maintenance and reparation time as well as the number of required technicians. This information on the network dimensioning and the equipment characteristics are used in process based models which allow calculating the OPEX of the network. Based on the shopping list and its costs and the process model outcomes, the TCO of each year can be computed. The TCO thus includes CAPEX and OPEX. In the following subsections the detailed methodology used in the three dedicated models is presented.

### *A. The Topology Model*

The topology model calculates the length of the ducts, cables and fibers in the network to connect all customers to the splitters and the central office as shown in Figure 3.

Different topology models exist in literature: geometric [16], block clustered models [6], evenly distribution models [7], based on open street map [17], etc. The topology model should take into account the amount of free duct space which can be reused and the specific characteristics of the area in which we make a distinction between dense urban, urban and rural area types. Additionally two topology model implementations could be done making a distinction between point-to-point and point-to-multipoint optical distribution network. These will be nearly the same in the duct locations and amounts, but clearly have a big difference in the cabling types and fiber count. Parameterization in the model allows choosing between active and passive networks, select the region type, number of customers and free duct space.

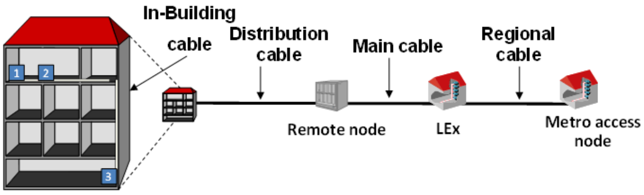



Figure 3 Topology model

### *B. The Architecture Model*

The architecture model calculates the amounts of equipment to install at the different physical connection points (e.g. splitter locations, central office, etc.) in order to light up the fiber cabling for which the topology has been calculated in the previous subsection. This calculation is based on the coupling between the different types of equipment taking into account their characteristics, how they are interconnected, aggregation factor of splitters, reach extenders which are needed when exceeding a certain distance, etc.

Different alternative architecture models have been constructed in cooperation with the technical experts of new and existing technologies. In this manner different architecture models have been constructed for which the details are described in the following section. These models are linked to the topology models in terms of compatibility, allowing or disallowing combinations of topology and architecture. Again parameterization allows selecting the architecture model to use and which split ratio to use.

### C. The OPEX Model

The combination of the topology and architecture model will calculate the shopping list in length of ducts, cables and fiber-count per cable as well as all equipment to light up the fiber from central office to the customer. Connecting customers to this network and operating this network will lead to important operational expenditures. The OPEX model starts from the information on expected customers, migration timing, shopping list and equipment characteristics to make an estimation of these operational expenditures.

The OPEX model uses flowchart based process models, for which we used the standardized business process modeling notation (BPMN) [18] and complements this with activity based costing [19] to make an estimation of the OPEX for running this process. Several such BPMN models are linked to the shopping list to get an idea of maintenance costs, and linked to the customer adoption and migration timing to get an idea of the customer provisioning and migration costs. The details of the processes and the input for these models can be found in the following section.

## IV. Cost modeling

The cost modelling proposed in this evaluation distinguishes two types of costs: (i) CAPEX and (ii) OPEX. Furthermore, and in order to support business model analysis, the cost modelling also takes into account the business role responsible of each cost factor: customer premises equipment (CPE), physical infrastructure provider (PIP) and/or network provider (NP).

### A. CAPEX

CAPEX refers to any cost related with the infrastructure or equipment, that is, the cost of any duct, fiber, or component, which needs to be purchased and installed before the access network becomes operable. CAPEX can be classified as:

- PIP Infrastructure (referred as “PIP Infra”) such as fiber cables, ducts, trenching and installation costs, cabinet, optical distribution frames (ODF), etc. which are required to interconnect any user of a given area to the Optical Line Termination (OLT) at the Central Office (CO) of the operator.
- PIP Equipment (referred as “PIP Equip”) includes cost of the any required passive equipment at the remote nodes such as power splitters, wavelength splitters, etc.
- In house Infrastructure (referred as “In house Infra”) such as in house cabling, optical sockets and installation costs required at the customer premises.
- Customer Premises Equipment (CPE) (“referred as CPE Equip”) includes the Optical Network Terminal (ONT) cost as well as its installation cost.
- Network Provider equipment costs (“NP Equip”) includes the cost of the OLT as well as any active equipment in the field such as reach extenders, Ethernet switches, etc.
- Specific migration costs: The cost evaluation of the equipment that is only required during the migration period, and allows the co-existence of two parallel access deployments (the traditional and the NGOA network). This migration specific equipment is only required for some migration scenarios such as from GPON to time/wavelength division multiplexing PON (TWDM PON) or wavelength selective WDM PON (WS WDM PON).

### B. OPEX

OPEX refers to any cost required for the operation of the network. OPEX can be classified as:

- Fault Management (FM) which is the cost associated with the reparation of any failure (both equipment and infrastructure) except the CPE failures, which is given as a separate cost. Any operator can apply its own process model. As an example, we propose a fault management process consisting of three main parts: pre-processing of the failure, failure reparation and post-processing of the reparation [20]. The fault management process is triggered by the number of expected failures of any of the network components, which is given by their Failure in Time (FIT) rate. The pre-processing includes the detection, help desk, opening Trouble Ticket (TT), etc. and has been assumed to be the same for all failures. The reparation of the failure depends on the network component that has failed. Each network component has associated with a Mean Time To Repair (MTTR), average reparation time, a travelling time to the failure location and the number of required technicians. It distinguishes PIP FM from NP FM depending on the type of failure.
- Fault Management of the CPE (CPE FM): the modelling of CPE FM considers that no technician goes to the customer location to repair the ONT, but rather a new ONT is shipped to the user. Therefore only the pre- and post- processing of the reparation is counted, which includes any required test and the TT closing is also assumed to be the same for all other failures.
- Energy gives the energy cost of the power consumed by any network equipment including the cooling equipment. The CPEs power is excluded here, but listed as an independent factor. The energy cost differs depending on the equipment location (central office or cabinet).
- CPE Energy is the energy cost of the power consumed by the CPE, which is usually paid by the user and has a different cost than the power paid by an operator.
- Service Provisioning (SP) is the cost associated with any activities related to adding, changing and cancelling customer services. It differentiates the operational costs of different NGOA solutions. Again, any operator can apply its own process model. As an example, we propose the process published in [20]. Many factors have impact on the SP cost such as: the required fiber, equipment, the possibility of remote configuration, the type of ONT, human resource and travelling etc. to connect a new customer or changing the services.
- Floor space includes the cost of the floor space required by the OLTs, ODFs, etc. at the operator premises as well as any active equipment space or cabinet required in the field. The cost is modelled according to the number of the equipment and the footprint of the equipment. Necessary working space for technicians and cooling required space are also considered in the modelling.

### C. Access and aggregation network cost models

In order to have a fair comparison between the different architectures and node consolidation degrees, both access and aggregation networks should be modelled and considered in the cost evaluation. The access network is defined as the network required to interconnect any user to the OLT either located at the Local Exchange (LEx) when non node consolidation is considered, or to the CAN also called metro access node when there is node consolidation. The aggregation network interconnects the OLT to the core Point of Presence (POP). Therefore, when node consolidation is considered, the coverage of the access network is much larger so that it reduces significantly the required aggregation network.

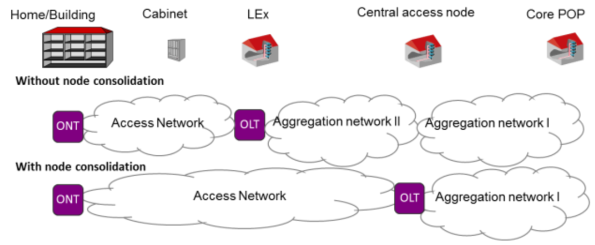



Figure 4 Access and aggregation networks

*1) Access network cost model*

The access network cost modelling includes CAPEX and OPEX required to interconnect any customer to the OLT. The cost modelling takes into account the business role (customer, PIP and NP) responsible of each cost factor, as shown in Table 1.

*2) Aggregation network cost model*

The aggregation network model is shown in Figure 4. In general, this network segment is split into two parts, the aggregation network I and II. The aggregation network I is always present, connecting the metro access node with the core network location. The aggregation network II is only dimensioned in scenarios without node consolidation. In the node consolidation scenario, the aggregation network II is part of the feeder access network and dimensioning subject to the specific technology used in the ODN. Any aggregation costs have been considered as NP cost.

TABLE 1 ACCESS NETWORK COST CLASSIFICATION

| | ***CAPEX*** | ***OPEX*** |
|---|---|---|
| **Customer** | CPE Equip<br>In house Infra | CPE FM<br>CPE Energy |
| **PIP** | PIP Infra<br>PIP Equip | PIP FM |
| **NP** | NP Equip | NP FM<br>NP Energy<br>Service Provisioning<br>Floor space |

From a detailed transport technology perspective, WDM in different flavours is used. The uplink interface of the OLT is a coloured interface. Depending on the consolidation scenario, the OLT uplink interfaces are multiplexed first with passive WDM or DWDM technology between LEx and CAN and between CAN and core POP. At the core location, DWDM transponders are used to support grey or colourless interfaces at routers. From the Ethernet layer perspective, 10Gbit/s interfaces transparently transmitted over the WDM transport layer between LEx and core POP are assumed. In addition, a price decrease is assumed (3%), while power costs are also taken into account. Beside active technology, passive components are taken into account as well with a one-time investment fee per required fiber per kilometre.

When applying the network dimensioning to the node consolidation, additional fiber links for connecting LEx and CAN are required. It is computed considering that 50% of the trenching and duct is required. The number of additional fibers is calculated based on the number of LEx that have to be connected to the new OLT location (CAN). However, these fibers are grouped into different ducts based on the aggregation factor of each case (i.e. how many traditional access areas are grouped into one new consolidated area).

## D. *Cost evaluation*

The cost evaluation is performed for each year. The evaluated costs depend on the time frame (i.e. either before, during, or after migration). The CAPEX and OPEX aspects included in each migration phase have been summarized in Figure 5. The cost evaluation can be done as non discounted or as Net Present Value (NPV).

# V. CASE STUDY

Let us apply the proposed methodology to the particular case of an operator running a GPON with 1:32 splitting ratio and evaluating the best solution in order to increase the offered bandwidth to the users and offer them 300 Mbit/s. In this case, the operator could consider the possibility to keep using GPON but reduce the splitting ratio from 32 to 8 or to migrate to time and wavelength division multiplexing (TWDM) PON. TWDM PON [21] offers the capability to reuse the GPON infrastructure while increasing the bandwidth with the use of WDM technology. In this case, the TWDM PON could reuse the power splitters in the field, and use 40 wavelengths, so that the client count is 1280. Furthermore, the operator could also evaluate the possibility of node consolidation. Let us denote as NNC the non-node consolidation scenario and as NC the node consolidation scenario. Although the splitting ratio reduction of the GPON is not a real migration but rather an upgrade of the architecture, we will use this term in order to simplify the naming of the scenarios.

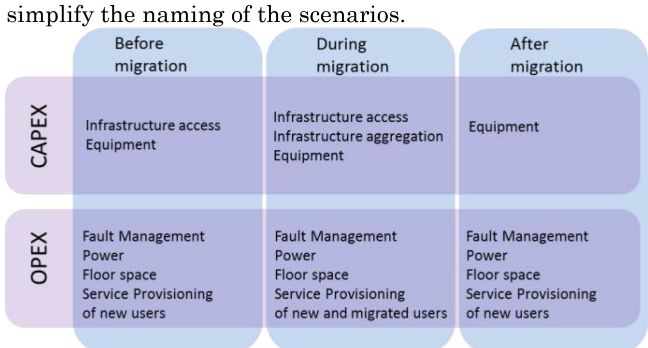



Figure 5 Different TCO considered at each migration phase

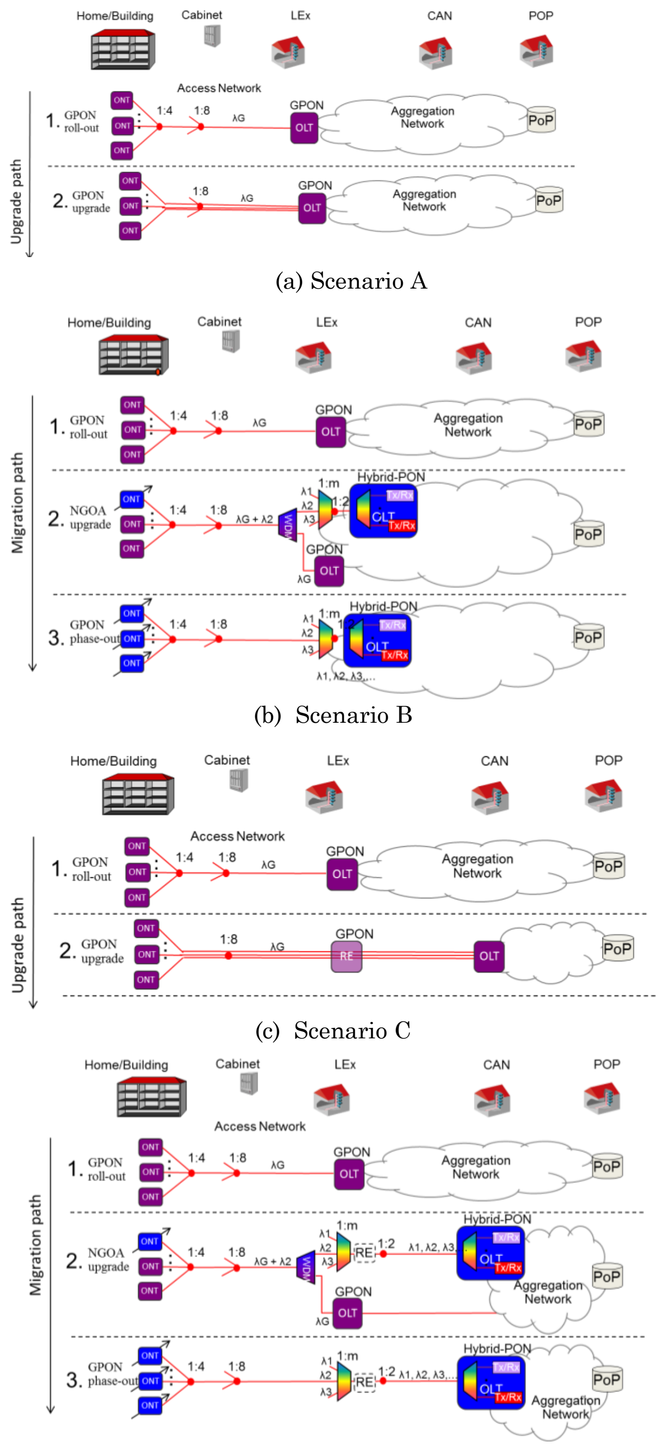
Four possible migration scenarios are evaluated:

- Scenario A: (NNC) GPON 1:32 -> (NNC) GPON 1:8
- Scenario B: (NNC) GPON 1:32 -> (NNC) TWDM PON 1:32/40λ
- Scenario C: (NNC) GPON 1:32 -> (NC) GPON 1:8
- Scenario D: (NNC) GPON 1:32 -> (NC) TWDM PON 1:32/40λ

The migration path for each migration scenario has been depicted in Figure 6.

TABLE 2 CONSIDERED ARCHITECTURE DURING EACH MIGRATION PHASE AT EACH SCENARIO

| SCENARIO | BEFORE MIGRATION | DURING MIGRATION | AFTER MIGRATION |
|---|---|---|---|
| A | GPON | GPON | GPON |
| B | GPON | GPON+TWDM PON | TWDM PON |
| C | GPON | GPON | GPON |
| D | GPON | GPON+TWDM PON | TWDM PON |




(a) Scenario A

(b) Scenario B

(c) Scenario C

(d) Scenario D

Figure 6 NP Brownfield alternatives for the particular case of an existing GPON 1:32**.**

So, for the migration cost evaluation, the cost that has to be evaluated differs depending on whether is before, during or after the migration period. Table 2 summarizes for each of the alternatives presented as example in the previous section, the architectures that should be evaluated for each time frame. The costs considered for each scenario and phase, are the ones summarized in Figure 5.

TABLE 3 PART OF THE SHOPPING LIST CORRESPONDING TO GPON1:32 IN DENSE URBAN AREAS WITHOUT NODE CONSOLIDATION

| | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|
| GPON OLT Line Card 8-Port without optics (2 slot shelf space) | 45 | 24 | 34 | 49 | 66 | 66 | 66 |
| GPON OLT Plugable B+ GPON | 359 | 194 | 275 | 388 | 524 | 524 | 524 |
| GPON OLT Shelf (18 tributary slots+2 uplink slots) | 5 | 3 | 4 | 5 | 7 | 7 | 7 |
| OLT - Floor Space Dense Urban [per year in m²] | 18 | 9 | 11 | 13 | 15 | 17 | 20 |
| ODF (fiber termination OLT side) - terminated fibre | 4800 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 |
| ODF (system side,CO/CAN) - connected fibre | 359 | 194 | 275 | 388 | 524 | 524 | 524 |
| Duct Multitube - 4 OLT-RN[km] | 103 | 26 | 26 | 26 | 26 | 26 | 26 |
| Fiber Cable 12f OLT-RN[km] | 633 | 158 | 158 | 158 | 158 | 158 | 158 |
| Fiber Cable Installation OLT-RN[km] | 633 | 158 | 158 | 158 | 158 | 158 | 158 |
| Microduct-10-7mm OLT-RN incl. Installation [km] | 42 | 10 | 10 | 10 | 10 | 10 | 10 |
| Microduct-6-7mm OLT-RN incl. Installation [km] | 96 | 24 | 24 | 24 | 24 | 24 | 24 |
| Digging OLT-RN [per Route_km] | 31 | 8 | 8 | 8 | 8 | 8 | 8 |
| Duct 100 mm diameter OLT-RN incl. Installation [km] | 31 | 8 | 8 | 8 | 8 | 8 | 8 |
| RN Branching Box - Large & Installation (192 fiber) | 625 | 156 | 156 | 156 | 156 | 156 | 156 |
| RN - Fiber Splicing Preparation [per cable] | 10000 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 |
| RN- Fibre Splicing (Fusion) | 64497 | 16124 | 16124 | 16124 | 16124 | 16124 | 16124 |
| RN- Optical Splitter - 1:32 | 2097 | 524 | 524 | 524 | 524 | 524 | 524 |

## A. *Application of the methodology*

The operator aiming at evaluating the four different migration scenarios could apply the methodology presented in Section IV. Therefore, in order to have a complete migration network scenario, the following factor should also be defined:

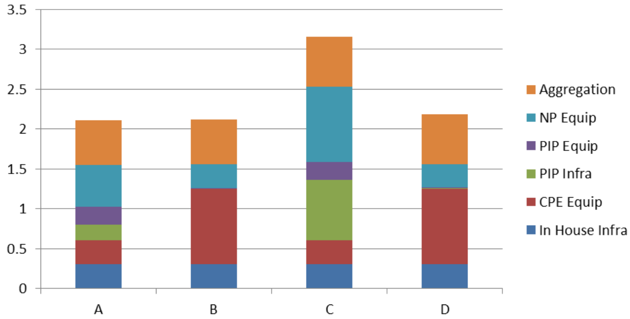
- The area type, which in this case, the area type is dense urban. A traditional dense urban area covering 5 km2 and 15600 subscribers is considered for NNC. In a NC scenario with consolidation degree of 87.5% [4], the covered area is 14 km2 and 44500 subscribers. Please note, that the consolidation degree reflects a country wide optimization and does not scale linear.
- The penetration curve, which in this case, is the "likely" penetration curve defined in [22].
- The time frame is defined from 2013-2030; the migration starting time is 2020 and duration of the migration process is 1 year.
- The discount factor is 5% for the infrastructure and 10% for the equipment, while the considered inflation rate is 3%.

Once the migration scenarios have been completely defined, the dimensioning can be performed. In this case, the dimensioning is based on the geometric model [16] and using the architecture models presented in [23]. The result of the dimensioning, gives for every year and scenario, the number of elements to be acquired. The part of results from

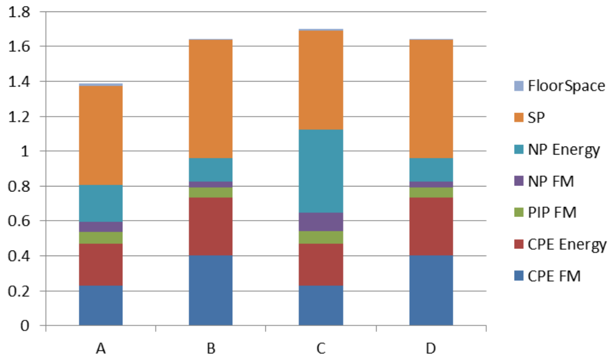
2013 to 2020 for GPON 1:32 are presented in Table 3.

The resulting shopping list is one of the inputs of the TCO evaluation tool, which in combination of the component database and the OPEX models, is able to compute the yearly costs during all the time frame. Based on Table 2, the architecture considered during each year is defined. For example, for Scenario B, GPON should be considered from 2013 to 2019, both GPON and TWDM PON should be considered in operation in the migration year 2020 and only TWDM PON should be consider from 2021 to 2030 (considering migration duration time of one year). During the migration year 2020, any specific migration equipment should be computed as well as the extra cost of migrating the users from GPON to TWDM PON.

The impact of the starting time and duration of the migration from GPON to TWDM PON can be found at [24].




(a)




(b)

Figure 7 Average CAPEX (a) and OPEX (b) per connected user per year [CU/year user]

### B. *TCO Results*

Let us compare each migration scenario in terms of average TCO per year per connected user with the most important CAPEX and OPEX parameters shown in Figure 7 (a) and (b), respectively (CAPEX components in blue and OPEX components in red). In this case, it can be observed that the solution with lower cost is A, which encourages upgrading GPON. However, in terms of further bandwidth increase, the upgrading case is less flexible and more complex than migration because they may require re-splitting and/or additional fibers. Still, when foreseeing node consolidation, the migration of TWDM is encouraged, as alternative C compared to D needs a significant larger CAPEX per user due to the relatively high investments required to connect the existing GPON OLT location to the metro access node. It has to be mentioned, that in this study, the savings which could be obtained due to the closing of LEx has not been included. The cost values presented here are normalized to the common baseline of the GPON ONT and referred to the cost unit (CU).

The four proposed migration scenarios have been also compared based on the yearly investment as depicted in Figure 8. In order to keep the graph readable, the total cost (including both CAPEX and OPEX) is shown. It can be observed that in 2020, which is the considered the migration starting year, there is an investment peak, which is significantly important for solutions with node consolidation (C and D), since the infrastructure towards the metro access node is required. However, it can also be observed that the solutions without node consolidation (A and B) require important investment around 2028 in order to cope with the high foreseen demands at the aggregation network II and hence the operator can reap the rewards of their investment on node consolidation.

In this particular case study, alternative C needs a significant larger CAPEX per user due to the relatively high investments required to connect the existing GPON OLT location to the metro access node as well as the higher OLT cost. Furthermore, the yearly cost comparison shows that although the investment required for the node consolidation alternatives is higher in the migration year, it can reap the rewards of their investment a few years later due to the savings in aggregation costs

## VI. Conclusion

The increase of services and terminals are causing a drastic growth of the bandwidth required per users. The increase of players in the telecom area competing for the same users, force operators to update continuously the service portfolio while increasing the offered bandwidth at competitive prices. However, in order to keep having benefits, the cost should be kept as low as possible. The different alternatives that operators have, that is, either to

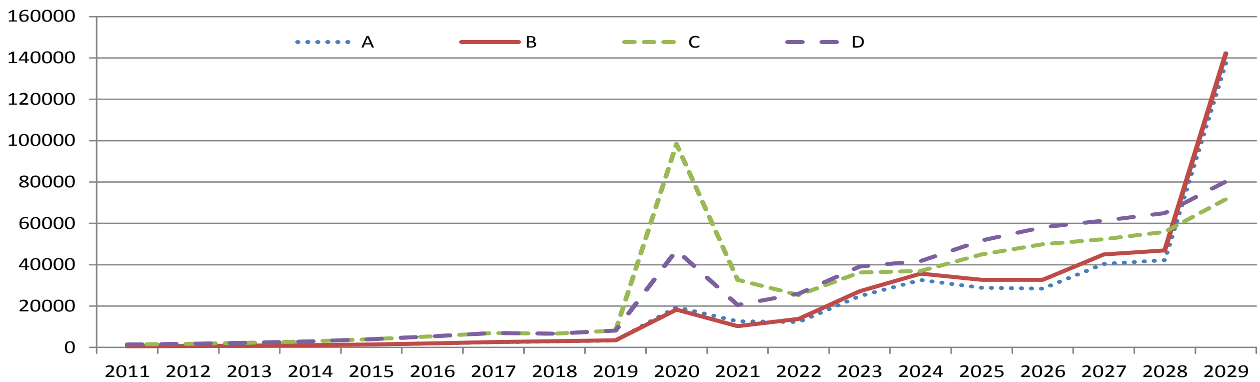



Figure 8 Yearly total cost [CU] associated with each migration scenario (illustrated in Figure 6) in one DU area

upgrade their networks or to migrate to Next generation Optical Access networks, should be carefully evaluated in terms of cost and other parameters such as service interruption time, duration, etc.

This paper proposes a methodology to evaluate the complete migration process, highlighting the most important aspects and applying to the particular case of a GPON network. The methodology consists of three steps:

(1) Investigating and setting the context of the migration study focusing on the most important aspects and parameters in such migration and in the hand of the operators.

(2) Dimensioning the network by calculating the topology consisting of ducts, cables and fibers with a distinction between fiber rich (e.g. point-to-point) and fiber poor (e.g. point-to-multipoint) topologies. This should be also linked to dimension the architecture to obtain the required equipment to light up the network. Both together lead to a shopping list and CAPEX estimation for the whole migration process.

(3) Estimating the operational expenditures linked to this shopping list and the migration process based on logical process models.

The outcome of the calculation approach is the total cost of ownership. By selecting and combining topology, architecture and operational models, this methodology allows to generically calculating various next generation optical access networks for any cost comparison at any level depending on the interests of the different players in telecom areas. As such this can be used for analyzing the effects of changes in the migration approach and duration, the architectures to migrate from and to, etc. and compare in this way a large variety of scenarios.

The paper presents an example showing the power of this methodology for the estimation of the migration scenario from GPON to TWDM PON solution. Together with GPON upgrading approach, the total four alternatives have been compared, in terms of average cost per user per year, as well as the yearly cost evolution. The average cost comparison has specified the average CAPEX and OPEX parameters for each alternative which allows the different players in telecom area to identify the key cost factors and drivers.

## ACKNOWLEDGMENT

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## 5.5 Paper J11

# Total cost reduction achieved by offering protection in PON architectures

C. Mas Machuca · J. Chen · L. Wosinska

# Total Cost Reduction Achieved by Offering Protection in PON Architectures

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**Abstract** Offering protection in access networks has been thought to be significantly expensive. This paper proposes a new way to provide protection in TDM and WDM PONs. It is shown that very low extra investment is needed to provide protection in the case when it is foreseen during network planning. It is also studied how the total cost is reduced due to the significant diminution of the OPEX related to the failure management.

***Keywords*** *Passive optical network (PON), protection, capital expenditures (CAPEX), operational expenditures (OPEX)*

## 1 Introduction

The high bandwidth required by the new services and the high reliability requested by the users (broadening from business to residential users), are forcing network operators to upgrade their networks [1]. However, due to the high market competition, operators are trying to obtain benefit margins by minimizing the investments on infrastructure in order to be able to keep restricted service prices and high reliability. Hence, in this paper a new cost-efficient way to provide protection in fiber access network is proposed. Unprotected and protected architectures are compared in terms of costs and connection availability, showing the significant increase of connection availability at very low increase of infrastructure expenses.

On the other hand, several fiber access network architectures have been developed over the years, e.g., point-to-point (P2P), active optical network (AON) and passive optical network (PON). Because of its passive point-to-multipoint structure, PON is able to offer the relatively low deployment cost, low power consumption and high resource efficiency, and hence it is considered as the most promising solution. Currently, Time-Division Multiplexing (TDM) PON is the dominating fiber access technology. Two major standards for TDM PONs have emerged, Ethernet PON (EPON) [2] and gigabit PON (GPON) [3]. Due to huge potential to increase reach, splitting ratio and bandwidth on a per customer basis, Wavelength Division Multiplexing (WDM) PON [4, 5] have been considered as a strong candidate for next-generation PONs.

Therefore, in this work we extend our preliminary work in [6] and consider two types of fiber access networks:

- Time-Division Multiplexing Passive Optical Network (TDM PON): This access network utilizes Time Division Multiplexing technique to share the capacity of a single transceiver located at the central office among several users. The remote node consists of a power splitter that broadcasts the downstream signal to all the users.
- Wavelength-Division Multiplexing Passive Optical Network (WDM PON): This access network associates a different wavelength to each user and using the WDM technique, they share the same fiber. At the central office, as many transceivers as connected users, are required.

In PONs, users are connected the central office (CO) of the operator by optical fiber. The equipment located at the user side is referred to as Optical Network Unit (ONU), whereas the equipment located at the operator CO is denoted by Optical Line Terminal (OLT). Usually, one CO can host several OLT cards, each of which supports one PON. For TDM PON the OLT includes one single transceiver shared by all the connected end users while for WDM PON it consists of multiple transceivers each of which is dedicated to one ONU. At a remote node (RN) there is a passive splitter (power splitter if TDM PON and wavelength splitter, i.e. arrayed waveguide grating AWG for WDM PON). The fiber interconnecting OLT and RN is referred to as Feeder Fiber (FF), while the fiber interconnecting RN with ONU is referred to as a Distribution Fiber (DF). This paper is focusing on fiber protection since compared with other network components the fiber failure rate is much higher and, consequently fiber failures (mostly fiber cuts) are dominating. We propose reliable fiber layout design for PONs where protection can be offered at relatively low investment cost (CAPEX) while dramatically reducing operation expenditures (OPEX) because of lower service interruption penalty. Figure 1 shows a typical protection scheme for PONs

[7]. The advantage of this scheme is that duplicated transceivers at the OLT and each ONU are not required. For the protection, an extra 1:2 optical switch (OS) is needed at the OLT to switch signals between working and protection FFs and DFs respectively. An additional power splitter or AWG per PON is required at the RN to connect protection FF and DFs. At the ONU side, a 1:2 splitter is added before transceiver (T/R) to connect the working and protection DFs.

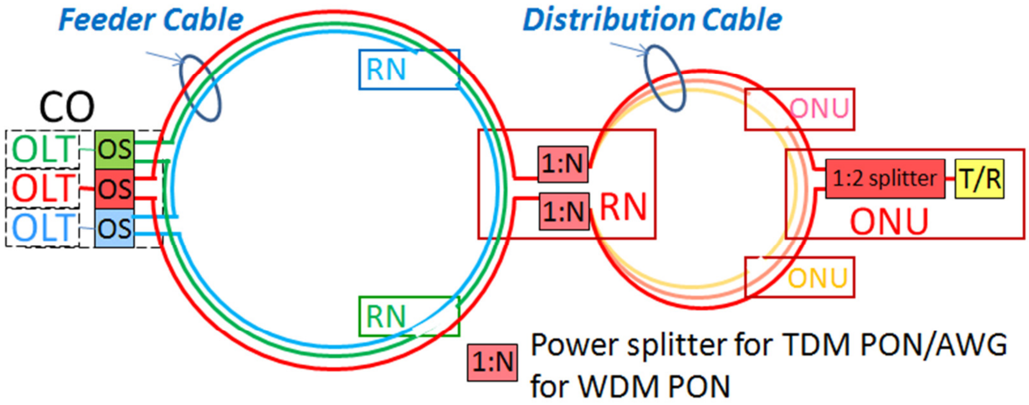



*Figure 1 Protection scheme for PON*

The reminder of this paper is organized as follows. Section 2 describes our proposed fiber layout design as well as its configuration for different populated scenarios. In Sections 3, 4 and 5, we study the investment cost, failure related operational cost and total cost, respectively. Finally, the conclusions are provided in Section 6.

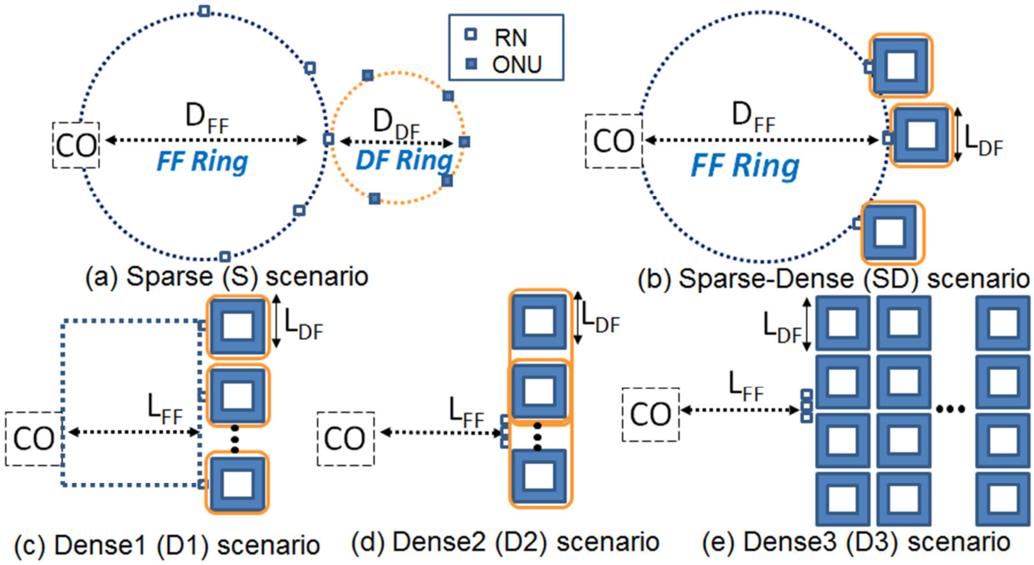



*Figure 2 Fiber layout configurations for the different populated areas*

# 2 Fiber layout design

The main objective of the proposed fiber layout is to use the existing infrastructure for protection as much as possible. This objective can be achieved by using dark fiber for protection purposes, or in case there is no dark fiber available (e.g. not foreseen during the planning process) new fiber can be pumped though the existing ducts. For example, Figure 1 shows a closed feeder ring which has been built using the unprotected feeder ring (i.e. a ring that connects all the RNs to the CO but lacks of an arch connecting the two furthest RNs) by adding new duct between the two furthest RNs and connecting protection fiber in the opposite direction against the working fiber (and even pumping the fiber if needed). Due to the high sharing ratio of the working and backup paths, the proposed scheme is able to provide protection of the infrastructure with minor additional investment cost.

We consider five different scenarios (shown in Fig. 2) which are associated to different types of population distribution areas and employ our proposed fiber layout design accordingly. To make the results comparable, we assume 32 PONs each of which hosts 32 ONUs for all scenarios. The values of parameters shown in Table 1 (we derived the values according to the expressions presented in the Appendix) for different scenarios are calculated based on a constraint that the maximum distance between any ONUs and OLT is limited to 20km. Usually, the travel speed (TS) of the technician(s) to go to a particular location is different in urban and rural areas. In this paper we assume TS of 50km/h in sparse areas and 20km/h in dense areas.

- ***Sparse (S) scenario:*** This scenario corresponds to the areas where both ONUs and RNs are sparsely populated and can be distributed along a ring (Fig.2a). An operator would dig along the partial ring adding RNs to the FF and ONUs to DF. The FF ring has a diameter of $D_{FF}$ and the DF ring has a diameter of $D_{DF}$. Our proposed protection will be offered by closing the FF and the DF rings and burying the protection fiber in the opposite direction.
- ***Sparse-dense (SD) scenario:*** This scenario combines the sparse RN distribution with a higher concentration of users (e.g. residential/business clusters). The RNs are distributed along a partial ring similarly to the

previous scenario. The users are distributed following the Manhattan network model [8], which is a square grid distribution of users. $L_{DF}$ denotes the length of block and street side (see Fig. 2b). We take the value from [8] and set $L_{DF}$=0.133km. In this case, in order to serve all the users of the same block, a DF duct around the block has been assumed (Fig.2b). The protection is achieved by closing the ring and burying protection fibers in the opposite direction.

- ***Dense scenario:*** This scenario assumes that RNs and ONUs are located in a network compatible with the Manhattan network model. Three different variants have been considered:
    - Dense1 (D1): The RNs are located in the same "vertical" street, each placed at the block they are serving. We let $L_{FF}$ denote the distance from the CO to this vertical street for FF length calculation (see Fig. 2c). The unprotected FF connects CO with each RN, whereas the protected proposed scheme closes the FF ring following the street distribution (Fig.2c).
    - Dense2 (D2): The RNs are co-located at the closest point to the CO, whereas the ONUs are distributed similarly to D1 scenario (Fig.2d). The FF follows a straight line from CO to RNs and the protected solution installs a protection FF through the parallel street. The DF rings are designed to achieve fiber disjoint rings.
    - Dense3 (D3): This scenario (Fig.2e) is identical with D2 scenario except that the DFs are required to serve 4x8 blocks. The protected DF rings have different layouts to achieve fiber disjoint rings while using as much common ducts as possible.

*Table 1 Parameter values* * *for different scenarios*

| | Travel speed (TS) [km/h] | $D_{FF}/L_{FF}$ [km] | $D_{DF}/L_{DF}$ [km] |
|---|---|---|---|
| S | 50 | 4,8 | 0,4 |
| SD | 50/20 | 5,11 | 0,133 |
| D1 | 20 | 13,37 | 0,133 |
| D2 | 20 | 11,54 | 0,133 |
| D3 | 20 | 18,67 | 0,133 |

*We derived the values for different scenarios based on the expressions presented in the Appendix.

# 3 Investment cost study

In this section we study the investment cost (i.e. capital expenditures CAPEX) associated with deployment of all the considered schemes. We follow the methodology presented in [9] for the CAPEX calculation. The total investment cost includes two parts, namely, fiber related CAPEX and component related CAPEX.

The first part consists of only fiber and its installation cost (i.e. trenching, pumping and splicing) which is highly dependent on fiber layout design. Our proposed approach is general and applicable to any types of PON. If applying it to TDM and WDM PON (see Figure 1), the fiber related investment cost is exactly the same. The price of fiber as well as the corresponding charge for the installation is based on data provided by the European OASE project [10]. Figure 3 shows the results of the fiber related CAPEX per user in different populated areas for both unprotected and protected schemes. It can be clearly seen that providing protection does not require doubling of the fiber related CAPEX when our proposed fiber layout design is applied. It is because in this case fiber layout design offers the possibility to provide disjoint protection path for a specific ONU by utilizing the trench/duct for the working paths of the other ONUs as much as possible, and hence saves large cost of extra civil work on trench/duct for the protection. Furthermore, it is obvious that sparse area S requires highest fiber related cost, due to its relatively low sharing ratio of trench/duct. It can be noticed that D2 and D3 require higher fiber related CAPEX than SD and D1, in particular when protection is provided. It is because we assumed the maximal reach of 20km for all the scenarios, which in turn makes the average fiber length in D2 and D3 longer than in SD and D1.

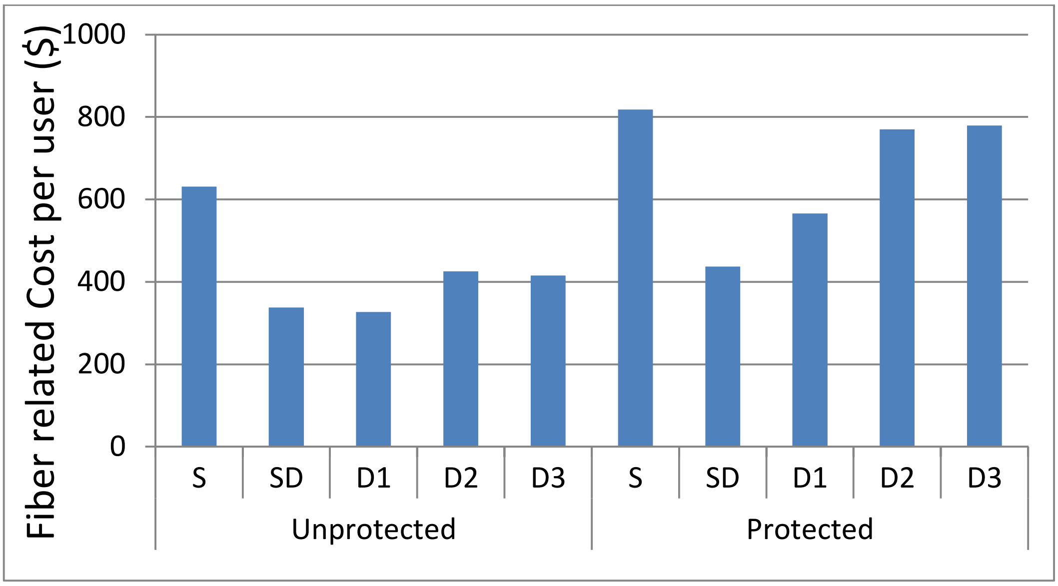



*Figure 3 Fiber related cost per user ($)*

The component related CAPEX includes component cost as well as installation cost which can be calculated as a product of the installation time and the hourly rate for operator's employee. Figure 4 shows the component cost for the unprotected and protected scheme for both TDM and WDM PONs. The component cost on a per-user basis is not varied in different populated scenarios where the same number of connected ONUs in total is considered. The input data for the component prices are obtained from the European OASE project [10]. It can be seen in Figure 4 that the components for PON using WDM technology are more expensive than for TDM PON, but on the other hand much higher capacity per user can be offered by WDM PON and it scales better than TDM PON. Furthermore, one can expect that after several years this cost in particular for WDM PON will be reduced, since the prices of the components are predicted to decrease over time (Moore's law). Compared with unprotected scheme, our considered protected scheme does not require much additional component cost. It is mainly because the duplicated transceivers at the OLT and each ONU are not needed.

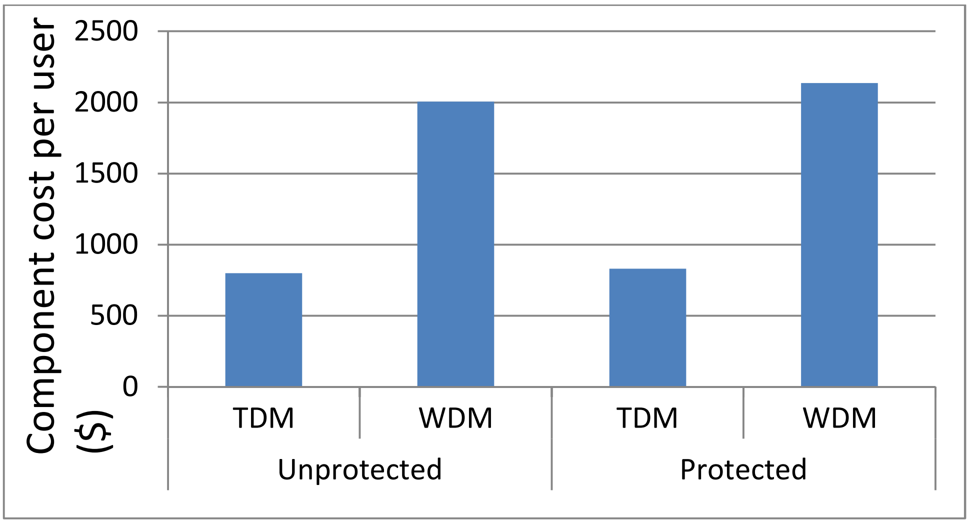



*Figure 4 Component cost per user ($)*

Figure 5 shows the cost of the component installation which is calculated by using the realistic figures collected in [10]. For the equipment located at RN, the related travel time should also be included in the entire installation process. It makes the installation cost slightly different in distinct populated scenarios. Besides, the installation cost for WDM PON is always higher than in TDM PON, as setup of AWG takes more time than power splitter at RN.

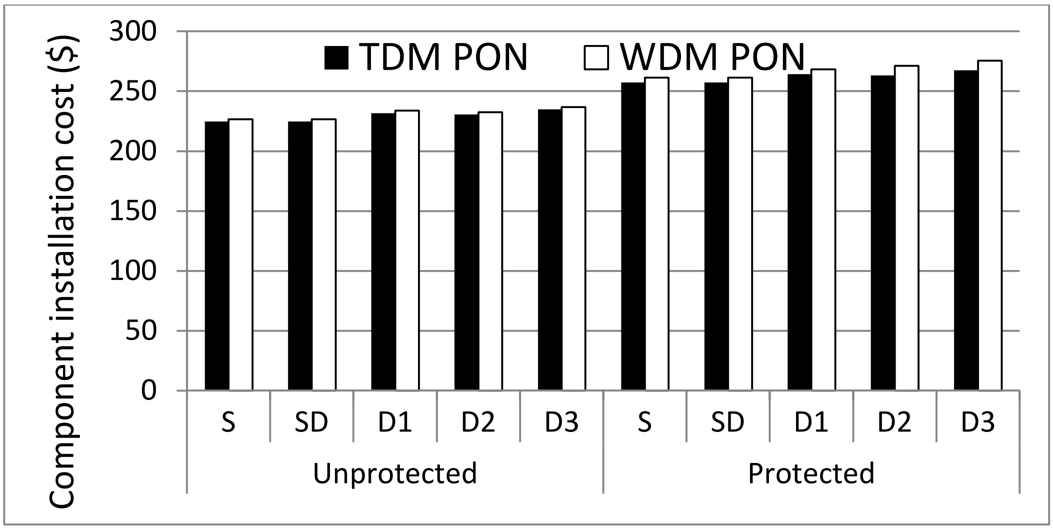



*Figure 5 Component installation cost per user ($)*

Figure 6 shows the total CAPEX for TDM and WDM PONs in the considered scenarios. It has further confirmed that regardless of population density the proposed fiber layout design is able to support protection provisioning with minor extra investment.

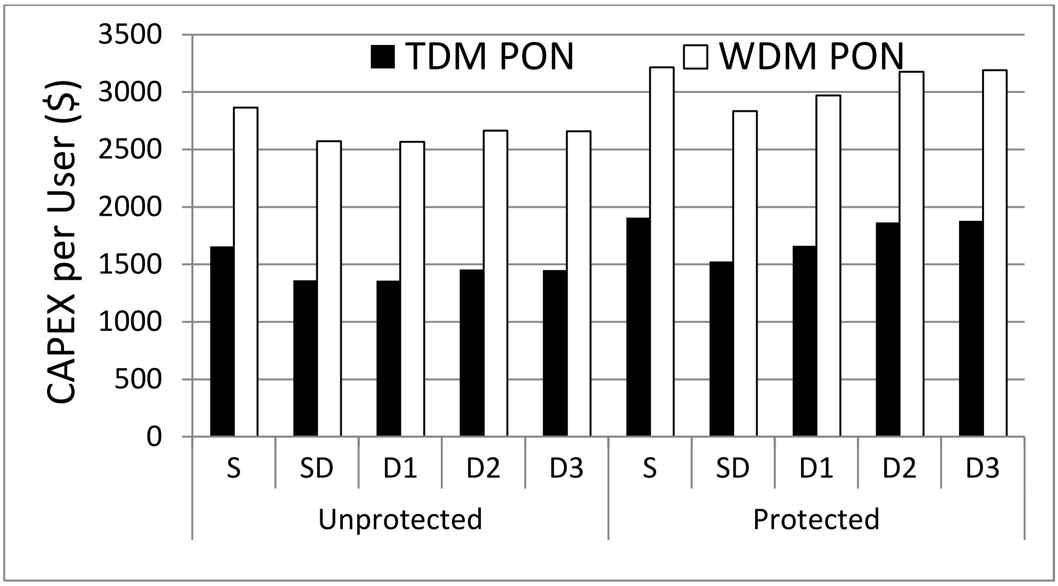



*Figure 6 Total CAPEX cost per user ($)*

# 4 Failure related operational cost study

Two operational costs are directly related with network failures: failure reparation costs (OPEX_FR) and the penalties that should be paid due to the service interruption (OPEX_PE). We employ the OPEX model presented in [9] to calculate the failure related OPEX. OPEX_FR depends on the network lifetime, the total number of network components (including equipment and fiber), and for each component, the expected number of failures, the number of persons required to repair the failure, the Mean Time to Repair, and the travelling time to reach the failure location. OPEX_PE is computed based on the duration of the ONU connection interruption and the type of user. So far it has been assumed that only service interruption for a business user (BU) is associated with penalties (1200 $/hour [9]). However, in the near future even residential users will also request reliable connectivity and consequently, OPEX_PE will be also associated to the residential users.

Figure 7 shows OPEX_FR and OPEX_PE for business users per year and Figure 8 displays the connection unavailability. It can be observed that OPEX_FR is significantly lower than OPEX_PE. OPEX_FR of protected architectures is slightly higher than in the unprotected cases due to the fact that there are protection switches and more fiber which can fail. However, OPEX_PE associated to the protected scenarios is significantly lower than for the unprotected cases, which strongly justify offering protection in access networks.

Since OPEX_PE is highly dependent on the penalty associated to the disconnection time, the unavailability is also shown and a significant decrease is observed for all the protected scenarios (from 4 to almost 5 nines availability).

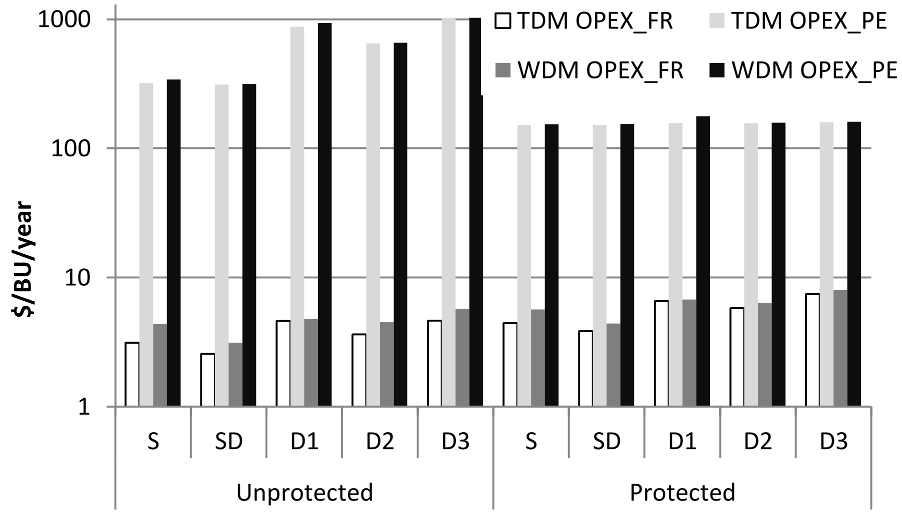



*Figure 7 Failure Reparation (FR), Penalty (PE) per BU per year*

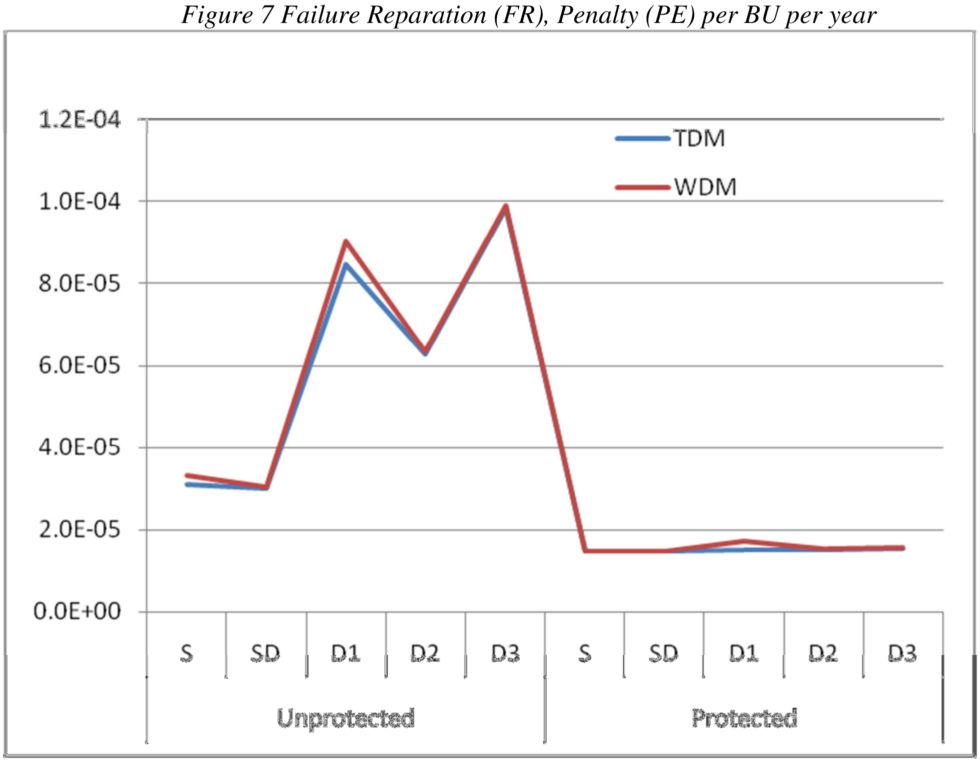



*Figure 8 Connection unavailability for different scenarios*

# 5 Total cost comparison

In order to get a clear understanding of the protection benefits, the total cost comparison of CAPEX and OPEX for a network operational time of 10 years is shown in Fig. 9. It can be observed, that for all the considered areas, the total cost is significantly lower for protected access networks, which strongly supports the proposed schemes. The penalties in dense areas are much higher due to the higher concentration of business users, which causes operational costs to be higher than CAPEX. The decrease in penalty costs causes overall savings for all the protected scenarios. In protected scenarios, CAPEX is significantly higher than OPEX, even in dense areas (opposite to the unprotected scenarios). The savings when offering protection to the all users are especially significant for dense areas which can reach up to 13,5M$ for TDM PON operational time of 20 years.

Figure 10 shows the impact that different network operational times have on the total network cost. The longer operational time implies the higher operational cost, which increases the total cost. The increase of time affects significantly the costs associated to penalties for unprotected scenarios, making the cost increase much more important than in protected scenarios. Figure 11 shows the impact of penalty level on the overall network cost (operational time: 20 years). It can be observed that the increase of the penalty level affects significantly unprotected dense areas where there are more business users and more penalties are expected. In contrast, the penalty level does not significantly affect the total cost of protected sparse and sparse-dense areas due to the low number of business users requiring penalty and the low connection interruption time.

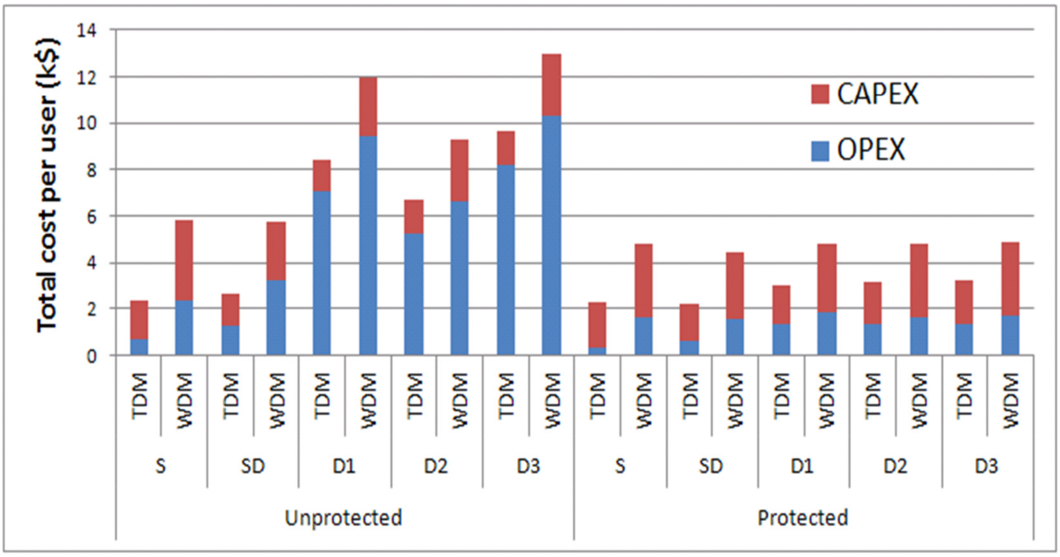
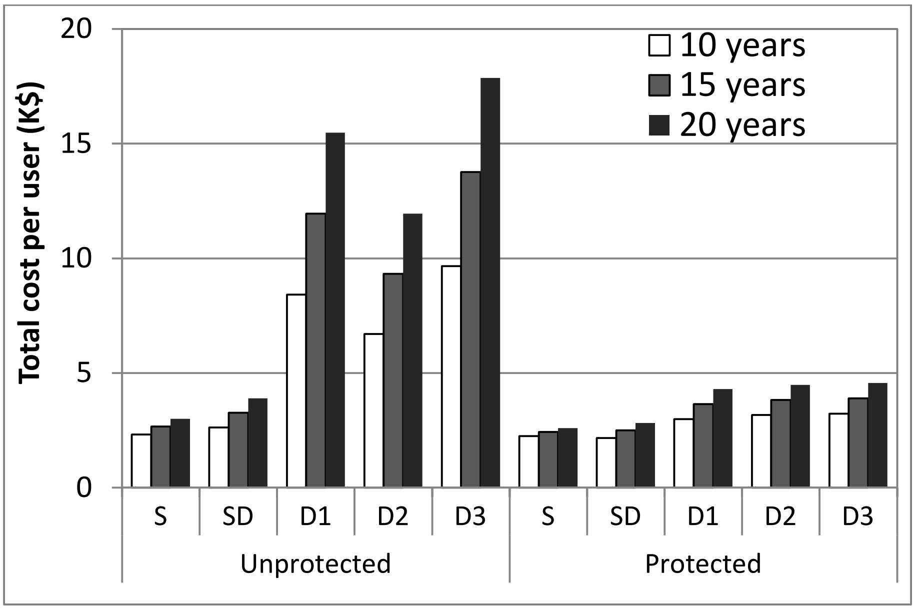
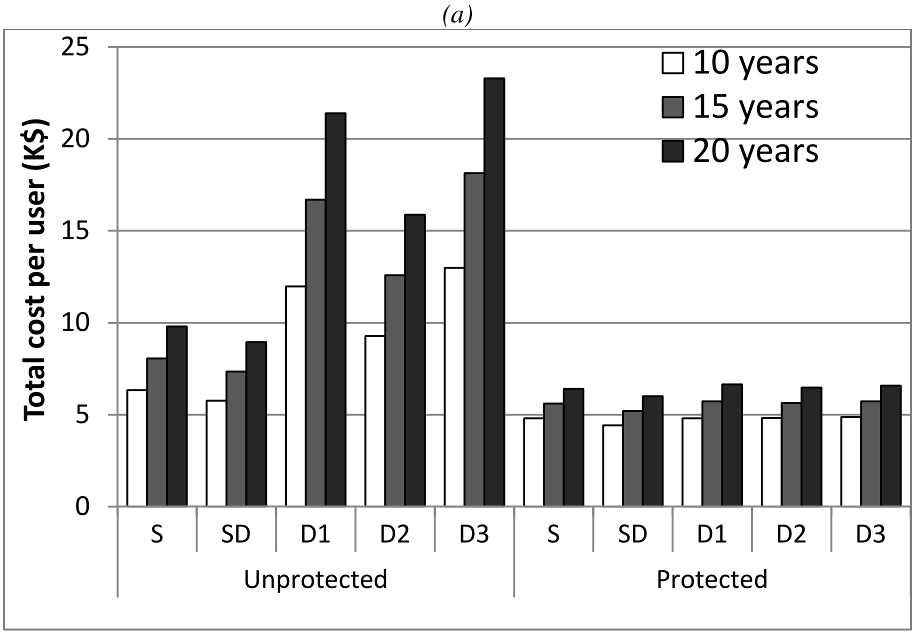



*Figure 9 Total cost per user (k$) for a network operational time of 10 years*

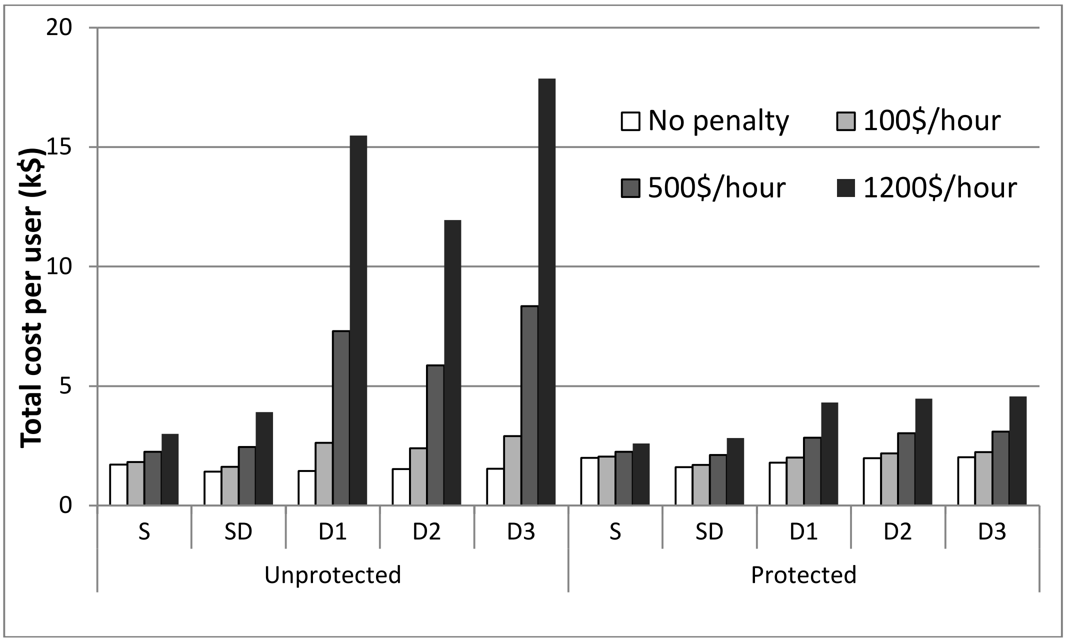



*(a)*

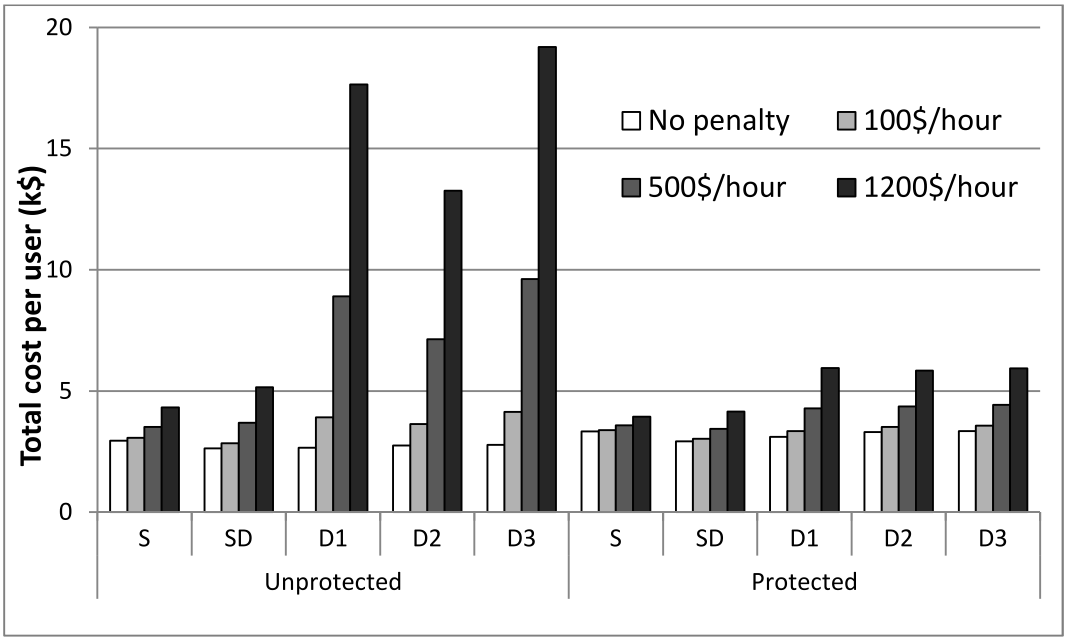



*(b)*

*Figure 10 Impact of network operational time on total cost in (a) TDM PON and (b) WDM PON*




*(a)*




*(b)*

*Figure 11 Impact of penalty cost on total cost in (a) TDM PON and (b) WDM PON*

# 6 Conclusions

This work shows the economic benefits of employing protected access networks. A new cost-efficient way to provide protection in fiber access network is proposed where a significant increase of connection availability can be achieved at very low increase of infrastructure expenses. It is shown that in this way the total cost per user can be effectively reduced due to the savings in terms of penalty costs related to the connection unavailability. The cost benefits have been shown to be crucial for business users but it is expected to also concern the residential users in the near future. Finally, we would like to point out that our proposed way to deploy working/protection FFs and DFs can be compatible with next generation PON.

# 7 Acknowledgement

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007- 2013) under grant agreement n° 249025 (OASE).

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# Appendix

In the Appendix, Expressions 1-6 are used to derive the parameter values shown in Table 1:

- Sparse (S)

$$\frac{\pi D_{FF}}{33}16+\frac{\pi D_{DF}}{33}16\leq 20 \quad (1)$$

- Sparse-Dense (SD)

$$\frac{\pi D_{FF}}{33}16+2L_{DF}\leq 20 \quad (2)$$

- Dense1 (D1)

$$2*16*L_{DF}+L_{FF}+2L_{DF}\leq 20 \quad (3)$$

$$L_{FF}+34L_{DF}\leq 20 \quad (4)$$

- Dense2 (D2)

$$L_{FF}+17L_{DF}\leq 20 \quad (5)$$

- Dense3 (D3)

$$L_{FF}+10L_{DF}\leq 20 \quad (6)$$

## 5.6 Paper J10

OPTICAL COMMUNICATIONS

# Migration Cost Analysis for Upgrading WDM Networks

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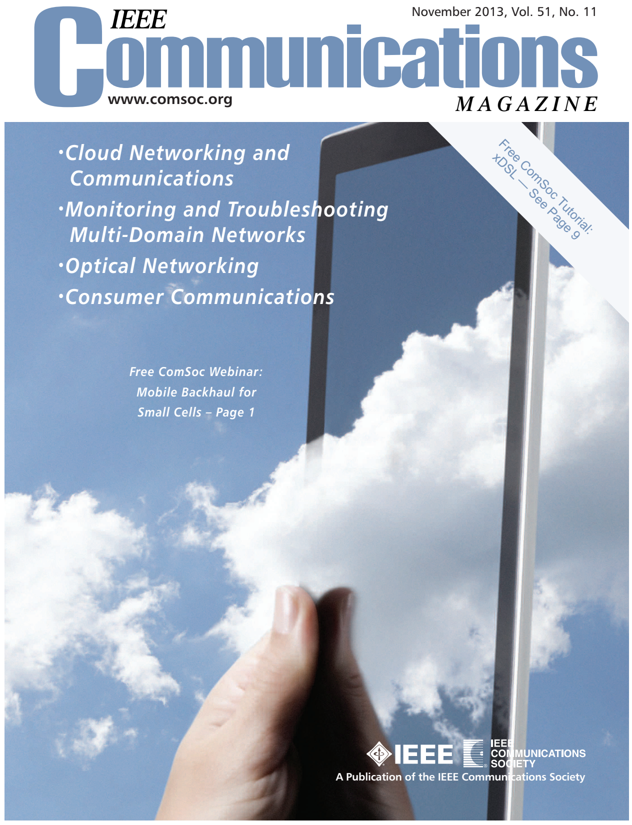

# Migration cost analysis for upgrading WDM networks

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***Abstract*—We present a generic step-by-step methodology for evaluating the total cost of migrating from a capacity-exhausted WDM network to different upgraded alternatives. The presented methodology is the first effort to provide a generic evaluation framework (allowing the evaluation of scenarios with different traffic growth rates, optical technologies, network architectures and resource allocation algorithms) that considers both, capital and operational, expenditures of the upgraded alternatives to then identify the lowest cost option. Previous works have just evaluated specific scenarios or only CapEx or OpEx (not both).**

**As a way of illustration, the proposed methodology was applied to compare the migration cost of two upgrading scenarios. The methodology allowed identifying the lowest cost alternative, categorizing the key cost factors of CapEx and OpEx and evaluating its impact on the migration cost. Surprisingly, results for the study case presented show that migrating to an automatically provisioned network does not necessarily lead to cost savings.**

***Index Terms*— Optical networks, Capital expenditure, Operational expenditure, Migration costs.**

## I. INTRODUCTION

Currently, most transport WDM networks operate statically, i.e. lightpaths are established semi-permanently. Although the high capacity of these lightpaths is underutilised (10-25% [1]), the ever increasing Internet traffic (annual growing rates of 35-50% [1]) and the emerging world wide deployment of Fiber to the *x* (FTTx) can mean that such high capacity might not be enough to meet the Quality of Service requirements of massive multimedia applications. Facing capacity exhaustion, network operators will require an evaluation methodology that allows them selecting the most suitable migration alternative. In this paper, we propose such methodology, using the migration cost as the determining selection aspect.

Migration strategies can be gradual or of the “big bang” type. The former is suitable to cope with heterogeneous traffic growth rates across the network. Thus, partial network upgrading is carried out as different network sectors face capacity exhaustion. The latter type occurs, for example, when the network operator migrates to a new technology, incompatible with the previous one, or when a big contract is secured, forcing a general network capacity upgrade.

Examples of upgrading alternatives dealing with capacity exhaustion are:

- Increasing the number of channels/fibres in some network zones (gradual migration) or across the whole network (big bang migration), maintaining bit rate and static operation.
- Increasing the bit rate of some/all (gradual/big bang migration) wavelengths and maintaining the static operation of the WDM network.
- Increasing the bit rate of wavelengths and migrating to dynamic operation like e.g. automatically switched optical network (ASON). The introduction of a control plane for dynamic lightpath establishment/release represents a big bang migration strategy.

This paper focuses on big bang migration strategies, as they are the most complex, risky and expensive to perform.

The first two migration examples represent what we call a static migration scenario (lightpaths remain permanently established in the updated network scenario) whilst the third one represents a dynamic migration scenario.

The Migration Cost (MC) is determined by:

- the *Differential Capital Expenditures* (D-CapEx), which is any investment on new space, infrastructure and equipment required to perform the migration.

- the *Operational Expenditures* (OpEx), which are the costs of running the network during its operation period.

Considering a big bang migration strategy, the static and dynamic migration scenarios exhibit a different temporal evolution of the MC, as illustrated in Fig. 1. The upper part of Fig. 1 shows the temporal evolution of the traffic load, measured as the utilisation of the network capacity, starting at $t_0$, when the traffic load is equal to $\rho_0$. As time passes (intermediate time periods, denoted as $T_i$, could correspond to months, years or triennials as defined by the operator), the traffic load increases until reaches a point ($\rho_{Max}$, defined by the network operator) when the network capacity is considered exhausted again and a new upgrade must be done. The middle section of the figure shows the evolution of MC for the static case. It can be seen that all the new equipment required to perform the upgrade must be installed at the instant $t_0$. Thus, the D-CapEx part of the MC evolution shows a sharp increase at the instant $t_0$ and then, no more new investment is required until the next upgrade. The OpEx part of the MC instead shows a monotonic increase due to the yearly increase of cost parameters (energy, salaries, etc). In the dynamic scenario instead (lower part of Fig. 1), the wavelength/transmitter/receiver requirements of a dynamic network are dependent on the traffic load [2-3]. This allows installing the equipment necessary to operate the network during the first time period, delaying the acquisition/installation of remaining equipment to coming time periods. The investment carried out in future periods is significantly lower than that of the first instant, where the big bang migration strategy required a general technological upgrade.

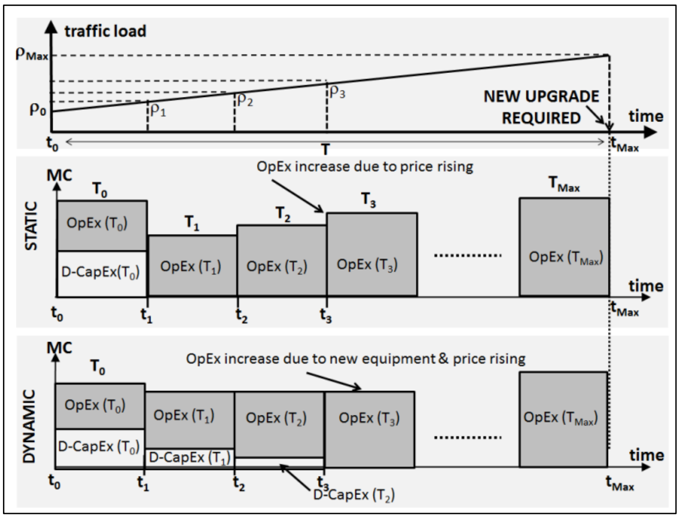



Fig. 1: Traffic load growth and Migration Cost (MC) evolution for static and dynamic upgrading alternatives.

In this paper, we aim at providing a generic techno-economic methodology that allows evaluating the MC of a WDM network near to capacity exhaustion. The methodology is general enough as to allow the evaluation of different initial/upgraded scenarios, with different traffic growth rates, technologies, network architectures and resource allocation algorithms.

## II. RELATED WORK

Previous work addressing the evaluation of migration scenarios has not been able to give a complete answer to the question of what upgrading scenario is the best. Mostly, they have analysed the cost of different configurations independently, without taking into account that during a migration process some network components can be re-utilised by the new network configuration. Additionally, most works have focused either in CapEx (not D-CapEx) or OpEx, but not in both simultaneously.

In [2] the number of wavelengths required in static and dynamic networks (CapEx) was quantified. Results showed a lower wavelength requirement from dynamic operation, but only at low traffic loads or if wavelength conversion is provided. OpEx was not considered and a migration analysis was not carried out.

In [4] the CapEx of a static WDM network was evaluated for transparent and opaque nodes. Transparent networks were shown to require a lower CapEx than opaque ones. OpEx was not considered and no migration analysis was carried out. In a later work, CapEx and OpEx were evaluated, taking into account the physical impairments of links [5]. Results showed again significant savings of transparent networks. However, migration scenarios - where a significant part of the equipment can be re-utilised, were not analysed.

Similarly, in [6-7] the OpEx of static and dynamic WDM networks were evaluated. Only some aspects of the OpEx were considered (provisioning and failure reparation costs). Results showed a benefit of dynamic operation with savings of up to 81% in the OpEx. Still, CapEx was not considered and OpEx was incomplete.

## III. MIGRATION COST EVALUATION METHODOLOGY

Let $MC(T)_{A,B}$ be the total cost of migrating from network scenario A to scenario B, operating under scenario B during period T. A network scenario is defined by the network components (equipment and infrastructure) and its operation mode (static or dynamic resource allocation algorithm). $MC(T)_{A,B}$ is given by the sum of two components:

- D-$CapEx_{A,B}$: *Differential CapEx* comes from any new or upgraded equipment, infrastructure and space required in nodes, links and the management system to migrate from network scenario A to B. This cost is made of the sum of the acquisition, installation and configuration costs of the new/upgraded equipment, infrastructure and space required. The acquisition cost is dependent on the number, type and cost of new components (delivered in the headquarter premises of the network operator). It does not include equipment or infrastructure already deployed by scenario A, which will continue being utilized by scenario B. In the case of requiring new infrastructure/space, the cost of buying/fitting new infrastructure/space must be included here. The equipment installation and configuration costs depend on the number of technicians required to perform this task, their salary rate, the time required to complete the task, travel costs and, eventually, living costs. Equations detailing acquisition, installation and configuration costs can be found in [8]. Note that, depending on the traffic demand increase, it can happen that the investment in new or upgraded components in scenario B is carried out in stages (dynamic scenario, Fig. 1). D-CAPEX also takes into account the time dependence of cost parameters (e.g. salary, equipment).
- $OpEx(T)_B$: This is the cost incurred to maintain the new network scenario B operative during T. This includes the cost associated to maintenance, energy consumption, failure reparation procedures and renting of space, infrastructure or equipment (if necessary) in nodes, links and the management system. In this case, old and new equipment must be considered. Maintenance cost is dependent on the number of technicians in charge of lightpath provisioning and general maintenance tasks and their salary. The energy consumption expenditure depends on the energy cost (USD/kWh), number and power consumption of all the equipment and infrastructure. Finally, the failure reparation cost is dependent on the number of failures experienced by the network during T, the cost of the spare components, the number of technicians required to repair a failure, their salary rate, the time required to repair the failure as well as the travel costs associated to the movement

of technicians/spare pieces from/to the headquarter to/from the failure location. Equations detailing the evaluation of these costs can be found at [8].

The methodology for a network operator to determine the most suitable migration alternative is summarized as follows:

1) Define the initial (A) and migration (B) network scenarios by detailing node architecture, link configuration and management system used.
2) Determine the value of the expected yearly traffic growth rate and the traffic loads $\rho_0$ and $\rho_{Max}$ (Fig. 1).
3) Determine the operation period T, as described in [8].
4) For each migration alternative (network scenario) B:
   **a)** Determine the number of investment instants; that is, the number of times that the network operator must incur in a new D-CapEx. In the static case this number is equal to 1. In the dynamic case, it is a function of $\rho_0$, the traffic growth rate and the traffic load at which the equipment requirement of the dynamic network becomes equal to the equipment required by the static network [2,3], as described in [8].
   **b)** For each investment instant, evaluate *D-*$CapEx_{A,B}$, considering the cost contribution of new elements in nodes, links and the management system required by network scenario B as described in [8].
   **c)** Evaluate $OpEx(T)_B$ considering the spending on energy, failure reparation and network maintenance in nodes, links and the management system of network scenario B as described in [8].
5) Select the migration alternative with the lowest $MC(T)_{A,B}$, equal to the sum of *D-*$CapEx_{A,B}$ for all the investment instants plus the value of $OpEx(T)_B$.

## IV. METHODOLOGY APPLICATION: AN EXAMPLE

This section aims at illustrating the application of the methodology proposed to compare the migration cost of specific network scenarios for the NSFNet topology, made of 14 nodes interconnected by 25 cables [2].

*Step 1: Initial/migration scenarios definition.*

We consider the following initial network scenario (A) and two upgraded alternatives (B1 and B2):

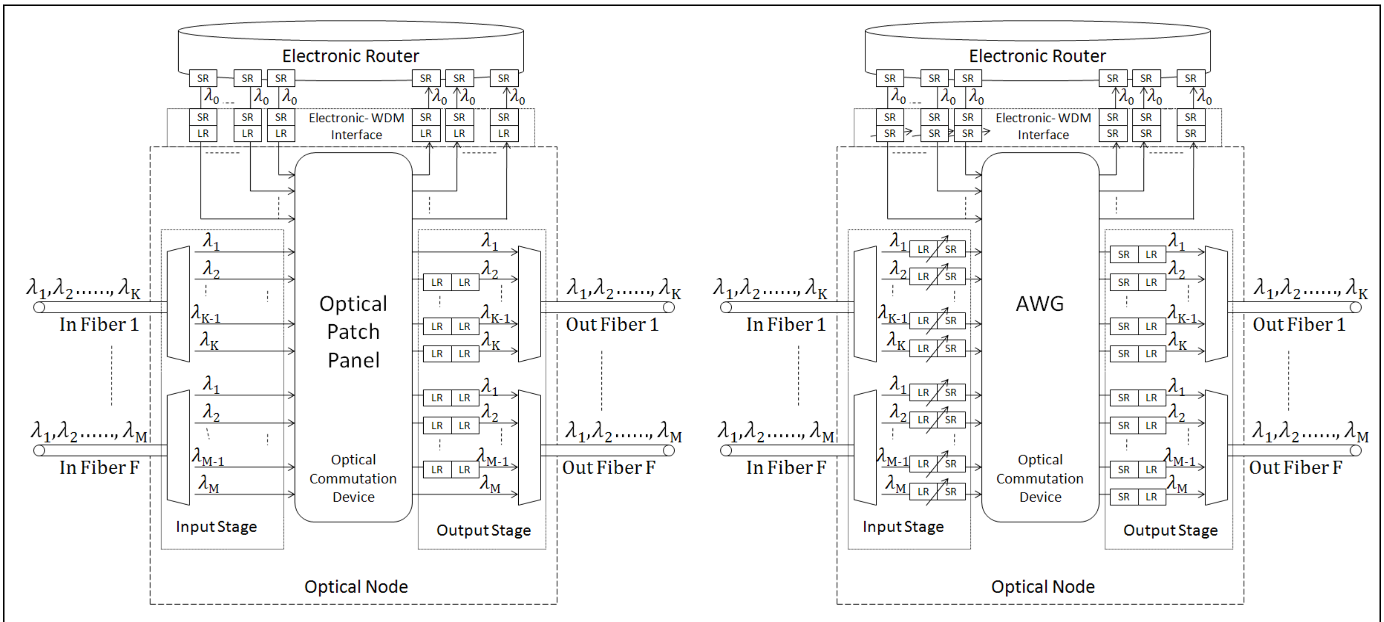
<u>Scenario A:</u> a static WDM network of 10 Gbps per wavelength, close to capacity exhaustion. We assume that a lightpath between each pair of optical nodes is established in a semi-permanent basis and that single-link failure can be survived by implementing shared path-protection. Source traffic is assumed to follow an ON-OFF behaviour. The traffic load offered by each individual connection to the network is given by the fraction of time such connection is in ON state.

The node architecture assumed for the static network is shown in Fig. 2(a), a classical node architectures with minor variations to decrease the power consumption. The interface between the electronic router and the optical node is made of fixed transponders of transmission and reception. A transponder of transmission is made of a short-reach (SR) receiver plus a long-reach (LR) transmitter. A transponder of reception is made of a long-reach (LR) receiver plus a short-reach (SR) transmitter. There are 13 transponders of transmission and 13 transponders of reception (a lightpath per node pair). At the output stage, the optical signals of the different wavelengths are regenerated by a pair of LR receiver/LR transmitter and multiplexed into the corresponding output fibre. The LR transponders could also be used as wavelength converters. In this stage there are several outputs without LR-LR regeneration: as such outputs receive the signals generated at the node, they do not need to go through additional regeneration in the output stage. For the NSFNet topology, there are 13 of such signals.

Each link uses EDFAs to mitigate the attenuation of the optical signal. EDFAs operate in the automatic gain control (AGC) mode with one or more control loops to resolve gain transients as a consequence of channel dynamics. Given the AGC mode, that a typical EDFA amplifier covers approximately a spectrum of 30 nm and that the ITU-T DWDM grid establishes 0.8 nm between neighbour wavelengths, the EDFA amplifier can accommodate up to 37 wavelengths. In this initial scenario, the range of wavelengths per link varies from 6 to 13 wavelengths (least and most loaded links, respectively).

<u>Scenario B1:</u> bit rates are increased to 40 Gbps maintaining static operation. An increase of the bit rate means the same data transmitted in shorter periods. This leads to a decrease in the duration of the mean ON period and therefore, a decrease of the traffic load. This is the simplest upgrading scenario: all bit-rate sensitive devices (e.g. transmitters and receivers) must be replaced for components of higher bit rate.

<u>Scenario B2:</u> bit rates are increased to 40 Gbps and network operation is changed to dynamic mode. End-to-end reservation of lightpaths requested on demand is assumed. As in scenario B1, the increase in bit rates will lead to a decreased value of traffic load. Unlike scenario B1, by dynamically allocating network resources, at low traffic loads the network might require a lower number of components to operate. This upgrading scenario is the most complex, mainly because a control plane must be added to the management system to dynamically allocate network resources.



(a) Static optical node architecture for scenarios A and B1 (b) Dynamic optical node architecture for scenario B2.

**Fig. 2: Node architectures [8]**

We consider the node architecture shown in Fig. 2(b). The main differences with respect to the static node architecture are: SR-SR tunable transponders of transmission in the interface stage; tunable LR-SR transponders, with wavelength conversion capability, in the input stage; an optical commutation device based on passive arrayed waveguide gratings (AWGs), and the use of fixed SR-LR transponders with wavelength conversion capability, at the output stage.

The same link configuration as in the static case is assumed. The only difference lies in the number of wavelengths, now varying from and from 4 to 13 wavelengths, depending on the value of the traffic load.

*Step 2: Traffic growth rate, maximum and initial traffic load*

We assume a traffic growth rate equal to 30% [1] and a value of $\rho_{Max}$ equal to 1. As the bit rate is increased 4 times, the initial traffic load, $\rho_0$, is equal to 0.25.

*Step 3: Operation period.*

According to the expressions presented in [8], with a traffic growth of 30% per year and an initial traffic load of 0.25, the network will operate during 5 years until a new upgrade is needed.

*Step 4.a. Number of investment instants.*

For scenario B1 only one investment instant is required. For scenario B2 instead 3 investment instants are required, calculated as in [8]. In this case, depreciation equal to 7% per year is considered in the acquisition of equipment in the investment instants $t_1$ and $t_2$.

*Step 4.b. Evaluation of D-CapEx.*

To evaluate the D-CapEx, the components of scenario A that change due to the migration process must be identified. These are: 13 fixed transmission transponders SR-LR at 10 Gbps (1500 km reach, which is the length of the longest links in NSFNet) and 13 fixed reception transponders LR-SR at 10 Gbps (1500 km reach) in every node for any updating alternative; as many output stage fixed regenerators 3R at 10 Gbps (1500 km reach) as the number of outcoming wavelengths of the node minus 13 and – when migrating to dynamic operation, an optical commutation device and a control plane component in charge of lightpath provisioning. The link configuration does not change in any of the alternative upgrading scenarios.

Table 1 shows the new/upgraded components of scenario B1 and B2 with respect to scenario A (components of scenarios B1 (B2) already existing in scenario A not included). The first column lists the different scenarios, the second and third columns correspond to the description and number of components, respectively (f($\rho_i$) denotes a number that depends on the traffic load at instant $t_i$). In scenario B1 the number of outgoing wavelengths is given by the number of working lightpaths plus backup wavelengths [8]. In scenario B2 the capacity of each link is a function of the traffic load, the maximum acceptable blocking probability per connection and the survivability required [8]. For this same scenario, the number of transmitters and receivers is a function of the traffic load and the maximum acceptable blocking probability per connection [3]. The fourth column shows the cost of buying, installing and configuring the new or upgraded component at instant $t_0$. The cost, expressed in NCU (Normalized Cost Unit), has been normalized to the cost of a 10 Gbps transponder of 750 km reach, using the data of [4]. The following columns are related to operational aspects.

**Table 1: D-CapEx and OpEx related parameters of components in scenarios B1 and B2**

| Scenario | Component description | Number of components [8] | Normalized Cost Unit (NCU) [4,10] | $FIT$ [4,8] | $MTTR$ [h] [4,8] | $p$[W] [8] |
|---|---|---|---|---|---|---|
| B1 | Fixed transmission transponder SR-LR at 40 Gbps (1500 km reach) | 13 | 2.585 | 256 | 2 | 70 |
| | Fixed reception transponder LR-SR at 40 Gbps(1500 km reach) | 13 | 2.585 | 256 | 2 | 70 |
| | Output stage fixed 3R regenerators at 40 Gbps(1500 km reach) | Number of outgoing wavelengths– 13 | 3.62 | 256 | 2 | 70 |
| B2 | Tunable SR-SR transmission transponder at 40 Gbps | $f(\rho_i)$ | 1.2·2.585 | 931 | 2 | 15 |
| | SR-SR Fixed reception transponder at 40 Gbps | $f(\rho_i)$ | 1.2·2.585 | 250 | 2 | 15 |
| | Input stage tunable LR-SR transponder at 40 Gbps | $f(\rho_i)$ | 1.2·3.62 | 815 | 2 | 70 |
| | AWG-based optical commutation device at 40 Gbps | 1 | (75·Port Number+ 800)/cost reference transponder | 200 | 6 | 0 |
| | Output stage fixed SR-LR transponder at 40 Gbps | $f(\rho_i)$ | 3.62 | 256 | 2 | 70 |
| | Control plane for configuring and releasing dynamic lightpaths | 1 | 20 [9] | - | - | - |

D-CapEx results show that scenario B1 yields a much lower D-CapEx than B2: 2498 NCU for scenario B1 vs. 5966 NCU for scenario B2, made of the sum of the normalized D-CapEx for each of the 3 investment instants: 5267, 427 and 272 NCU, respectively. This higher D-CapEx for the dynamic case comes mainly from the higher number of components to be upgraded (in particular, transponders).

*Step 4.c. Evaluation of OpEx.*

Regarding energy, we assume 0.15 USD/kWh (www.energy.eu) and the power consumption listed in the right most column of Table 1 for each component.

Concerning failure reparation, the FIT and MTTR values of node components are listed in columns fifth and sixth of Table 1. FIT and MTTR for cables is 114/km and 8h, respectively. For the optical amplifiers, these statistics are 2000 and 6 h, respectively. The field technician salary rate is assumed equal to 0.01 NCU/h according to the data used in the OASE project (www.ict-oase.eu). We assume 1, 2 and 3 technicians to repair a network node component, an optical amplifier and a cable failure, respectively. The mean travelling time from the technician base to any place in the NSFNet network is assumed equal to 8.5 h.

Regarding network maintenance, the number of technicians in charge of the management system and service provisioning is assumed equal to 6 in scenario B1 and equal to 2 in scenario B2, as proposed in [7]. These technicians are assumed to generate a monthly cost equal to 1.2 NCU (www.ict-oase.eu). The cost of energy and salaries are assumed to increase 3% per year.

Fig.3 compares the normalized OpEx. It can be seen that dynamic operation leads to a higher failure reparation and energy cost than the static case. Failure reparation is driven by the cost of the replacement component. In the dynamic case, the use of tunable components with higher FIT and cost than the static case leads to a higher failure reparation cost. In fact, for the studied case, 35 and 11 node failure events with a mean failure reparation cost equal to 1.8 NCU and 1.5 NCU occur in the dynamic and static scenario, respectively (the number and cost of link failure events is the same on both cases). In terms of energy, the higher number of components in the dynamic case and their higher energy consumption also causes higher energy cost.

Despite the higher costs of failure reparation and energy consumption, the dynamic scenario leads to a lower overall OpEx than the static scenario. As previously reported, this is due to the significant savings produced by the diminished number of technicians in charge of the management system and service provisioning.

*Step 5. Comparison of migration costs*

As depicted in Fig. 4, the lower OpEx of the dynamic scenario does not imply a lower migration cost. The migration to a dynamic scenario (B2) results in a significantly higher migration cost than maintaining the static operation (almost 2 times more expensive, with a normalized MC of 3311 NCU and 6607 NCU, for scenarios B1 and B2, respectively). That is, the OpEx savings are not enough as to compensate the investment in new components. We obtained similar results regarding the convenience of dynamic operation for a traffic growth rate equal to 50%. This result highlights the importance of evaluating simultaneously OpEx and D-CapEx, as very different conclusions can be arrived to if only one of these costs is evaluated.

The presented methodology not only allowed quantifying D-CapEx and OpEx, as shown in Fig. 4, but also enabled the identification of the key factors contributing to the MC. For example, for this study case, the key cost factors are: component cost, salary of technicians and cable length.

Fig. 5 shows the value of the normalized MC of scenario B2 (MC of scenario B1 varies similarly, although on a different scale) as the values of these 3 most impacting aspects increase/decrease in 25% and 50%. The results show that the component cost is the parameter most affecting the value of the MC: an increase of 25% (50%) of component cost leads to an almost linear increase of the MC (24% and 47%, respectively). However, the MC is almost insensitive to variations of the salary of technician or the length of cables: an increase of 50% of salary of technicians/length of cables leads to an increase of just 1% on the MC. This implies that the MC would not change significantly if the same scenarios were analyzed in an European-country size network, where the average cable length can be up to 10 times shorter than in a continental network as NSFNet.

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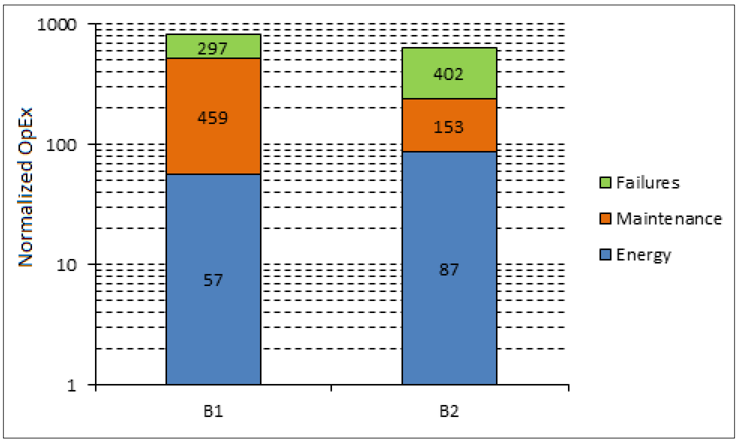


**Fig. 3. Comparison of normalized OpEx for migration scenarios B1 and B2 .**

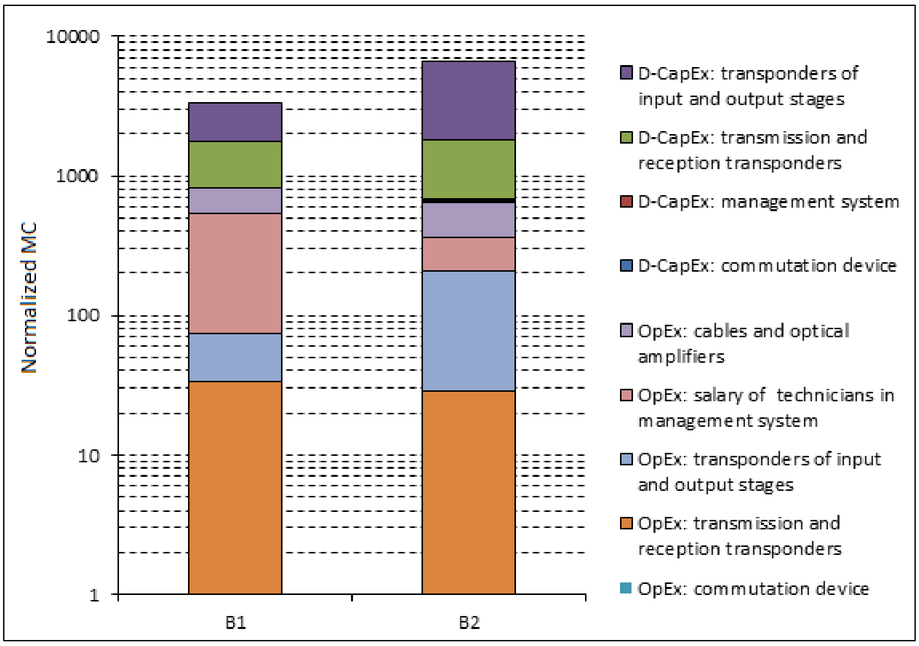


**Fig. 4. Migration cost for scenarios B1 and B2, detailing the contribution of D-CapEx and OpEx aspects.**

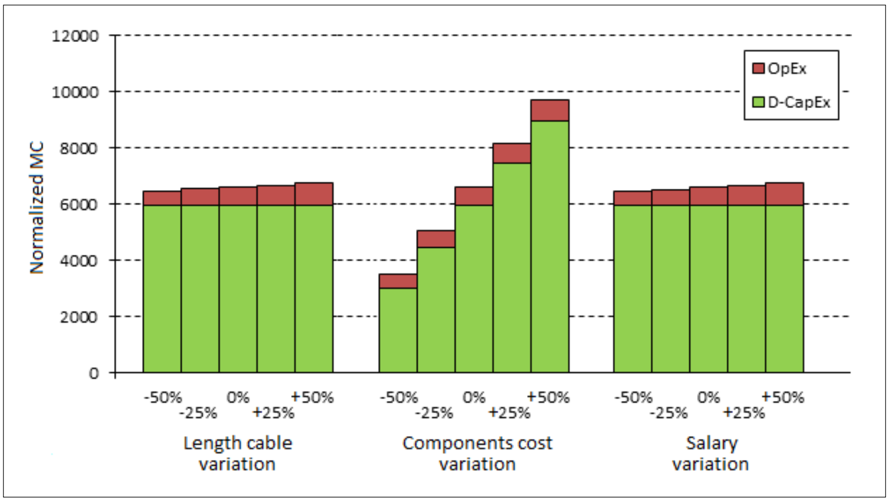


**Fig. 5. Sensitivity analysis of the migration cost as a function of its most influential parameters**

## CONCLUSIONS

The techno-economic methodology presented is the first effort aiming at addressing the general problem of selecting an optical network upgrading alternative. Instead of just analyzing a case with very specific assumptions on technologies, network architectures or algorithms - as previous work has done, hampering the application of their study to other cases, our method can be applied to a very wide range of upgrading situations.

We expect this methodology will help network designers to identify the lowest cost migration alternative as well as the key factors affecting the migration cost. Thus, the impact of technical decisions on migration costs can be evaluated.

The limitations of this work that should be addressed in future research are related to the following assumptions: the entire network reaches a capacity saturation state at the same time, during an upgrading process no topology changes are performed and all possible users require a lightpath during network operation. By relaxing these limitations, the research in the area can lead to a systematization of the upgrading process of optical networks in such a way that novel computer assisted network upgrading process tools can be developed.

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