Reliability versus Cost in Next Generation Optical Access Networks

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Abstract

The ever increasing demands of Internet users caused by the introduction of new high bandwidth applications and online services as well as the growing number of users and devices connected to the Internet, bring many challenges for the operators, especially in the last mile section of the network. Next generation access architectures are expected to offer high sustainable bandwidth per user. They also need to support a much larger service areas to decrease number of current central offices and hence potentially save the network expenditures in the future. Obviously, it requires high capacity and low loss transmission and optical fiber technology is the only future proof candidates for broadband access. Although this technology has already been widely deployed in the core networks, it is hard to use the same expensive devices made for core segment to solve the last mile bottlenecks, due to the low number of users sharing the network resources (and deployment cost). Therefore, the next generation optical access (NGOA) networks need to be designed with consideration of cost efficiency in the first place.

Network reliability is also turning to be an important aspect for the NGOA networks as a consequence of long reach, high client count and new services requiring uninterrupted access. Consequently, new architectures not only need to be cost efficient but also they should fulfill the increasing reliability requirements.

Although several NGOA alternatives have been proposed in the literatures, there is not yet an agreement on a single architecture. As described earlier, network expenditure and reliability performance are the two main factors to be considered. Therefore, this thesis concentrates on finding a suitable alternative for future broadband access by evaluating the reliability performance and total cost of ownership for several NGOA candidates. In particular, in this thesis we analyze the tradeoff between the cost needed to deploy backup resources and the reliability performance improvement obtained by the provided survivability mechanism.

First, we identified the suitable NGOA candidates by comparing two main groups of optical access networks, namely passive optical networks (PONs) and active optical networks (AONs), in terms of cost, reliability performance and power consumption. The initial results have shown that wavelength division multiplexing PON (WDM PON) is the most promising alternative for the NGOA networks because of its high potential capacity, low cost and power consumption. So we continued our studies by investigating two WDM-based PON architectures regarding their cost and reliability performance. The study has also included a proposed fiber layout compatible with these two candidates aiming to minimize the required investment needed to offer protection. Our primary results confirmed that hybrid PON (HPON) is the best alternative for the NGOA networks. Therefore we further analyzed this candidate
considering several variants of HPON. The most important components and sections of the HPON, which need to be protected to decrease the impact of each failure in the network have been identified. Based on these outcomes, two resilience architectures protecting the shared part of the HPON were proposed and their reliability performance parameters as well as cost of protection were evaluated. According to the results, using our proposed protection schemes a considerable improvement in reliability performance of the HPON variants can be provided at minor extra investment. We also introduced a cost efficient HPON architecture with different levels of protection for users with various reliability requirements, i.e. the protection of shared parts of the access network for all the connected users and end-to-end resilience scheme for some selected ones (e.g., business users). To gain an overall view on the cost efficiency of the proposed architecture, we evaluated the investment required for deploying these schemes considering several network upgrading paths towards a protected network. Moreover, a sensitivity analysis investigating the influence of network deployments time and the density of the users with higher availability requirements was presented.

In summary, we have shown that HPON is able to fulfill the main NGOA requirements such as high bandwidth per-user, large coverage and client count. The work carried out in the thesis has proved that HPON can also offer high reliability performance while keeping the network expenditures at an acceptable level. Moreover, low power consumption and high flexibility in resource allocation of this architecture, makes it a winning candidate for the NGOA networks. Therefore, HPON is a promising architecture to be deployed as NGOA network in the near future considering the fact that components are soon to be available in the market.

**Key words:** Fiber access network, passive optical network, reliability, techno-economic study, next generation optical access, network protection, wavelength division multiplexing
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Stockholm, Sweden
April 2013
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List of papers included in the thesis:


II. Carmen Mas Machuca, Mozhgan Mahloo, Jiajia Chen, Lena Wosinska, “Protection cost evaluation of two WDM-based Next Generation Optical Access Networks”, Asia Communications and Photonics Conference (ACP), November 2011, Shanghai, China.


V. Mozhgan Mahloo, Abhishek Dixit, Jiajia Chen, Carmen Mas Machuca, Bart Lannoo and Lena Wosinska, “Towards End-to-End Reliable Hybrid TDM/WDM Passive Optical Networks”, Manuscript was submitted to IEEE communication Magazine.

List of related papers not included in the thesis:

1 Mozhgan Mahloo, Anders Gavler, Jiajia Chen, Stéphane Junique, Viktor Nordell, Lena Wosinska, “Off-loading the aggregation networks by locality-aware peer-to-peer based content distribution”, Asia Communications and Photonics Conference (ACP), November 2011, Shanghai, China.
Acronyms

Av  Availability
AON  Active Optical Network
AWG  Array Wavelength Grating
BFF  Backup Feeder Fiber
BP  Backup Path
BW  Bandwidth
CAN  Central Access Node
CAPEX  Capital Expenditure
CO  Central Office
DF  Distribution Fiber
DT  Down Time
DU  Dense Urban
EPON  Ethernet Passive Optical Network
FF  Feeder Fiber
FIF  Failure Impact Factor
FIT  Failures In Time
FR  Failure Reparation
FTTH  Fiber To The Home
Gbps  Gigabit per second
GPON  Gigabit capable Passive Optical Network
HPON  Hybrid Passive Optical Network
HDTV  High Definition Tele Vision
LMF  Last Mile Fiber
OLT  Optical Line Terminal
ONU  Optical Network Terminator
MTBF  Mean Time Between Failures
MTTR  Mean Time To Repair
NGOA  Next Generation Optical Access
OPEX  Operational Expenditure
P  Penalty
PON  Passive Optical Network
PS  Power Splitter
P2MP  Point to Multi Point
P2P  Point to Point
RN  Remote Node
R  Rural
SLA  Service Level Agreement
TCO  Total Cost of Ownership
TDM  Time Division Multiplexing
TDMA  Time Division Multiple Access
U  Urban
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<td>Ultra Dense Wavelength Division Multiplexing</td>
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<td>WFF</td>
<td>Working Feeder Fiber</td>
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<td>WP</td>
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Chapter 1

Introduction

A growing number of the Internet users as well as introducing new applications, such as high definition television (HDTV) and multiplayer gaming, push network providers toward a new design for the next generation access networks in order to fulfill the ever-increasing traffic demands of the customers. One of the key requirements of future access networks is to provide high sustainable bandwidth per-user in a scalable way. In this regard, optical fiber technology is considered as one of the most promising candidates for the future access networks due to its ability of providing high capacity [1][2].

Next generation optical access (NGOA) networks are expected not only to provide high sustainable bandwidth for each user, but also to cover large areas [3]. Extending the passive reach from a few kilometers up to several tens of kilometers allows for merging metro and access networks into a single segment. This enables large coverage with tens of thousands of users in one service area, making it possible to reduce the number of central offices (referred to as the node consolidation). Node consolidation has a potential to offer operational cost saving [4][5].

Recently a large number of studies have been done aiming to propose a good candidate for the NGOA network with an emphasis on wavelength division multiplexing (WDM) based technologies [6][7]. In [6], several passive optical network (PON) architectures such as XGigabit capable PON(XGPON), 10G Ethernet PON (EPON) are introduced as the candidates for future access networks. Although the bandwidth provided by these technologies is larger than the currently deployed time division multiplexing PONs (TDM PONs), e.g., GPON and EPON, it is not high enough for NGOA networks. Paper [7], introduces several alternatives for the next generation PON including some variants of hybrid PON. A number of European projects involving partners from both academia and industry (e.g. photonic integrated extended metro and access network (PIEMAN) [8], multi-
service access everywhere (MUSE) [9]) have been targeting research issues related to the future optical access networks. PIEMAN and MUSE evaluated two different solutions that combine classical TDM PON architectures with wavelength division multiplexing (WDM) channel allocations as well as employing optical amplification and transparent long-haul feeder transport to support large coverage. The recent FP7 European large scale integrated project “optical access seamless evolution (OASE)” [10], where we were involved in, was also examining fiber-to-the-home (FTTH) within a multi-disciplinary approach to provide a set of technological candidates for NGOA. Each of the proposed approaches in the literatures has their own pros and cons. However, there is still lack of successful approach that can meet a variety of technical and economical criteria. Therefore, finding an appropriate network architecture, which can take advantages of fiber communication technology is an important research issue for both industry and academia.

One of the key criteria for NGOA networks is the cost efficiency. Access network is more cost sensitive than aggregation and core segments, since it is shared among less number of users and its expenses should be affordable for the residential users. Therefore, any proposed approach needs to be cost efficient in order to be deployed. Consequently, required investment for the access network turns to an important factor in the assessment of each NGOA candidate.

The investment cost is important but it is not the only driven factor. Expanding size of the service areas as a consequence of node consolidation as well as higher availability expectation of the users turns network reliability performance to a new challenge for the network operators. A higher number of clients served by one central office (CO) increases the failure penetration range, since a large number of customers can be affected simultaneously via a single breakdown in the network. As a result, it becomes vital to provide an acceptable level of reliability performance in emerging NGOA. It should be mentioned that there is always a tradeoff between expenses related to providing backup resources and level of network reliability. Operators would minimize failure impact but are not willing to pay a lot of extra investment for protecting the individual users. Therefore economic and reliable NGOA architecture should be developed to fulfill the operators’ requirement. In this regard, any NGOA candidate should be able to provide an acceptable level of reliability performance at minimum capital expenditures (CAPEX) and operational expenditures (OPEX). Consequently, any proposed resiliency mechanism for these NGOA alternatives should to be further assessed regarding the expenditures needed for protection.

1.1 Contribution of the thesis

The OASE project came up with four NGOA architectures: hybrid WDM/TDM PON (HPON), WDM PON, two-stage WDM PON and next generation active optical network (NG AON). This thesis is based on the outcome from the work done in the
frame of the OASE project and focuses on analyzing the two WDM-based PON architectures selected by this project considering the following key aspects:

- Total cost of ownership (TCO): including both CAPEX and OPEX
- Reliability: connection availability and failure impact factor
- Cost versus reliability: The extra expenditures of providing protection

**Paper I** of this thesis has evaluated several deployed optical access networks regarding their cost, power consumption and reliability performance, in order to find a potential direction towards appropriate architectures for the NGOA network. As stated in **Paper I** and [7][11], passive optical networks (PONs) especially the ones based on the WDM technology are the promising candidates for the future access networks. Therefore in **Papers II** and **III** we studied the reliability performance and cost of the deployments considering protection of the shared part of the network for two WDM-based NGOA candidates, i.e. HPON and ultra-dense WDM PON.

According to the results presented in [12] and **Papers II** and **III** of this thesis, HPON can satisfy all the NGOA requirements such as high capacity per-user, long reach and large client counts as well as low investment cost. Hence, in **Papers IV** and **V**, we further assessed different variants of this architecture in the context of reliability performance as well as the additional CAPEX caused by offering different levels of resiliency for various user profiles. **Paper IV** first identified the most important parts to be protected in the network aiming to minimize the impact of any single failure. Based on these results two novel protection schemes have been proposed in **Paper IV**, in order to efficiently improve the resiliency of HPON. According to the outcome of **Paper IV**, the reliability performance of HPON architectures has been improved to an acceptable level for residential users via our resilience mechanisms, whereas high connection availability requirement (i.e. 99.99%) for the business access could not be always satisfied. Therefore, in **Paper V** a cost efficient end-to-end protection scheme has been proposed, which can flexibly upgrade the reliability performance of some selected users. Furthermore, **Paper V** includes a comprehensive techno-economic study for our protection schemes.

**1.2 Outline of the thesis**

This thesis addresses the reliability challenges for optical access networks especially minimizing the cost of improving the connection availability and failure impact. The thesis is organized as follows.

We describe different classes of optical access network architectures in Chapter 2. The evaluation methodology used for our resiliency and cost analyses can be found in...
Chapter 3. Chapter 4 presents our contribution on techno-economic study of various architecture options presented in Chapter 2 in terms of TCO and reliability performance. It begins with an analysis of currently deployed optical access networks carried out in Paper I and continues with an evaluation of two promising NGOA candidates, namely HPON and ultra-dense WDM PON, which includes the key findings in Papers II and III. Then, based on Papers IV and V, a complete investigation of the protection schemes and the corresponding added cost for several variants of HPON is included in Chapter 5.

Finally, the conclusion and main highlights of the researches contained in this thesis along with several possible future directions are presented in Chapter 6. A brief summary of each paper and the contributions of the author are provided at the end of the thesis.
Chapter 2

Optical Access Network Architectures

Fiber optic communication is the future proof technology for the last mile segment of the networks, offering high capacity and long reach. There are several optical access architecture options currently deployed or being standardized, which can be used as a basis for further development of new candidates for the NGOA networks.

Most of the deployed optical access networks nowadays have a tree-based fiber topology with a central office (CO) connected to multiple optical network units (ONUs) located either at the end users premises (referred to as Fiber-To-The-Home FTTH) or close to the users (e.g. in a street cabinet). The network infrastructure consists of fibers and some either splitting or switching devices referred to as the remote nodes (RNs). The optical line terminal (OLT) is located at the CO and it is connected to the RN via optical fibers. In this thesis the fiber link between the OLT and RN is denoted as feeder fiber (FF), whereas the fiber connecting RN to the end user is referred to as distribution fiber (DF) (see Figure 2.1(a)).

![Figure 2.1. Different physical connection points and fiber segments in optical access networks.](image)
In some cases, the physical infrastructure may consist of more than one splitting point between the CO and the ONUs (see Figure 2.1(b)) in order to increase the number of users connected to each OLT. In general, in such networks, multiple remote nodes can be deployed. However, in this thesis we consider at most two splitting points, where the fiber connection between RN1 and RN2 is called DF and the end user and RN2 are connected through last mile fiber (LMF).

Besides high splitting ratio, the long reach capability of fiber access networks also makes it possible to co-locate several conventional COs in one place, which is referred to as a central access node (CAN). This concept is called node consolidation and it offers a great potential to minimize the deployment and operational cost of NGOAs. The degree of consolidation is defined as a ratio between the number of the CANs and old COs.

One way to categorize optical access networks is based on the type of devices located in the field, namely either passive, with no power supply in the outside plant, or active otherwise.

Another widely used classification is related to the way that OLT communicates with ONUs. Two typical categories are referred to as point to point (P2P) and point to multi point (P2MP). When there is a dedicated physical connection through fiber directly from the OLT to the ONU, it is defined as P2P. Whereas using a multiplexing technique that leads to sharing the resources (e.g. fiber) among end users is categorized as P2MP. However some architectures such as WDM PON have a P2P connection in wavelength layer, while they can be considered as P2MP in the fiber topology.

Fiber to the X (FTTX) where X can be “home”, “building”, “curb” or “cabinet” is a generic term for access network architectures where all or parts of the existing copper-based infrastructure is replaced with fiber technology [13]. In this thesis we are considering the fiber to the home (FTTH) or building (FTTB) meaning that the fiber is the only transmission medium used in the access part. In this case the optical network units (ONUs) are located inside the customer’s home or in the basement of the buildings. This chapter will give a general view regarding different classes of optical access architectures.

2.1 Active optical network (AON)

The remote nodes in AONs consist of the active Ethernet switches, which consume power. Currently AONs use Ethernet as a service carrier between active components, and the data is switched over in the electrical domain. So the data plane is not fully optical. In this section, two most common AON access architectures are introduced.
2.1.1 Active star

In this architecture, RN consists of an active Ethernet switch, which implies the need of power supply in the outside plant (see Figure 2.2). Moreover, the optical signal from OLT is terminated at the switch, which makes the data plane not transparent. The advantage of this architecture is related to the fact that ONUs can communicate with each other directly through the Ethernet switch without going back to the OLT if not needed. Feeder fiber is considered as a shared medium meaning that this architecture has a P2MP topology. Active star has a high degree of flexibility in terms of the network design and is a mature technology. But its main disadvantage is high operational cost and power consumption coming from the active components in the RNs.

![Figure 2.2. Schematic view of the active star architecture.](image1)

2.1.2 Home run

Home run is categorized as active optical access network, and it uses Ethernet as the service carrier in the access network. One dedicated fiber is deployed between CO and each ONU without any intermediate equipment in the outside plant (see Figure 2.3). The point-to-point nature of this architecture makes it less complex and more secure than the shared-medium systems (e.g., active star, PON), but with the drawback of higher cost per-user resulting from dedicated fibers and transceivers. Besides, it is hard to deploy home run in dense areas, due to the huge amount of required fibers.

![Figure 2.3. Schematic view of the home run architecture.](image2)

2.2 Passive optical network (PON)

PON is the promising candidates for the future access networks due to its simplicity, transparency and low power consumption. This architecture is able to offer high capacity on a per-user basis at relatively low cost. PON has a passive RN, which connects several ONUs to the OLT using optical fiber links and is categorized as a P2MP architecture in the fiber topology. As the feeder fiber is shared among many
ONUs, a certain multiple access technique is needed to divide the available resources between users in the same PON.

### 2.2.1 TDM PON

This approach utilizes time division multiple access (TDMA) technique, which forces ONUs to send their packet in the upstream direction during pre-defined time slots to avoid traffic conflicts. In the downstream direction packets are broadcasted to all ONUs using a power splitter at RN (see Figure 2.4), leading to a less secure connection. This type of PON is already deployed widely using the standardized TDMA protocols namely gigabit-capable passive optical network (GPON) and Ethernet passive optical network (EPON). GPON is mostly deployed in North America and Europe, while Asia-Pacific countries such as Japan have EPON enabled TDM PON installed in their access networks [14].

In TDM PON, the bandwidth per ONU is limited by the fact that the single wavelength is shared by all users connected to the same OLT. In case of GPON, the maximum standardized downstream bandwidth (BW) is around 2.5 Gbps, thus using a 1:32 power splitter gives around 80 Mbps per-user, which does not meet the NGOA networks’ requirement of 1Gbps sustainable bandwidth per-user. Even in case of XGPON or 10GEPON [15] that are standardized as the intermediate step towards NGOAs, the bandwidth is not sufficient considering high demand for client count in the future access networks. Furthermore, passive reach in TDM PON is relatively short due to the high power loss of the splitters in the RN.

![Figure 2.4. Schematic view of a TDM PON.](image)

### 2.2.2 WDM PON

WDM PON uses either power splitter or wavelength multiplexer/demultiplexer (e.g. array waveguide grating, AWG) in the RN. Having AWG improves the passive reach compared to the approach with power splitter in the field, since it typically has an obviously lower optical power loss than the splitter. In WDM PON, each user is assigned its own wavelength. Therefore, in logical layer it has a virtual P2P connection, whereas the fiber topology is still P2MP.

This architecture is able to offer high data rate per-user over tens of kilometers, while the number of ONUs connected to the same FF is limited by the number of available wavelength channels. Except some part of Korea, there are not many WDM PONs
deployed yet [14]. But it is one of the strongest candidates for the next generation optical access networks offering at least 1Gbps bandwidth per-user. WDM PONs are divided into several variants, depending on the type of device used in the RN. The architecture with the power splitter in RN is called broadcast and select WDM PON, while the variant with wavelength multiplexer/demultiplexer is referred to as wavelength split or wavelength routed WDM PON. Figure 2.5 shows the general architecture of a wavelength routed WDM PONs.

![Figure 2.5. Schematic view of a wavelength routed WDM PON.](image)

### 2.2.3 Hybrid PON (HPON)

As it was mentioned in the previous sub chapters, both TDM PON and WDM PON have some advantages and drawbacks and can partly meat the NGOA requirements. Combining these two technologies makes it possible to come up with a more powerful candidate for the future access networks, namely hybrid WDM/TDM PON. Generally, the hybrid PON (HPON) can be a mixture of any two multiplexing techniques and it is not limited to aforementioned ones. For example the hybrid orthogonal frequency division multiplexing (OFDM) and WDM PON systems is also categorized as the HPON. But in this thesis we use the general term of HPON for the network with combined time and wavelength multiplexing capabilities (see Figure 2.6).

The advantage of having WDM is the increase of spectrum utilization, while the advantage of TDM is the high scalability and flexibility on bandwidth allocation. This architecture has also a tree topology where the OLT is at the root. The OLT is connected to the RN1 where its output ports are connected to the power splitter at the RN2. Each output of the power splitter in RN2 is dedicated to one ONU.

![Figure 2.6. Schematic view of a simple HPON.](image)

One of the most common variants of hybrid WDM/TDM PON has an AWG in the first remote node, which routes a dedicated wavelength to each RN2. In this approach all ONUs connected to the same RN2 share one wavelength using TDMA technique.
Chapter 3

Evaluation methodology

Deployment of any new technology and infrastructure may need a huge investment cost and hence, prior to network deployment a comprehensive techno economic study is necessary to get an estimation of the required investment cost. The cost assessment allows providers to calculate their revenues and to be able to judge if it is worth to migrate towards new technologies or architectures. In addition to the cost some other aspects, i.e. survivability, energy consumption, etc., may also play an important role for network design and/or deployment. Therefore some analytical models can be helpful to assess the cost or other performance capabilities of access technologies before the deployment. This chapter presents the models and formulas used for the cost and resiliency studies in this thesis. Some parameters such as connection availability are already known for years, while some other metrics like FIF are counted as the contributions of this thesis.

3.1 Total cost of ownership (TCO)

Total cost of the network can be divided into two parts, namely as capital expenditures (CAPEX) and operational expenditures (OPEX).

Capital expenditures (CAPEX):

In this thesis CAPEX represents the required initial investment cost to deploy the access network and is calculated by adding three following expenses together.

- **Network equipment**: cost of purchasing the required equipment all the way from the OLT up to the ONU.
- **Equipment installation**: a product of the total time needed to install the equipment including the travel time to/from the components location and the number of required technicians and their salaries. Fiber splicing expenses are also counted as a part of
Chapter 3 Evaluation methodology

installation cost. The installation expenditure can differ between the specific cases due to the technicians’ salaries variation. This cost is usually high and cannot be ignored.

• **Fiber infrastructure**: All the fiber/cable related expenditures are considered as the infrastructure cost, which includes the fee of purchasing the fibers and cables, in addition to the expenses of digging and burying the ducts and cable installation. This value is highly related to the network design, fiber layout, population density and some other aspects.

The CAPEX per-user is defined via dividing the calculated total value by the number of ONUs served in the area.

**Operational expenditures (OPEX):**

OPEX has been shown to be a very important factor of the TCO for the network operators [16]. This cost covers the expenses related to the network operation during its life time that is the period when the network is operable till it is replaced by a new technology. OPEX could also be calculated per yearly basis. The OPEX considered in Paper I, II and III consists of the expenditures presented below.

• **Failure reparation (FR)**. The FR cost depends on the number of expected failures in the network during its operational time. Mean lifetime and mean time to repair (MTTR) of each network component determine the total reparation time per year, which is multiplied by the number of technicians required and their salaries in order to calculate the yearly FR cost. MTTR is the average time between occurrence of a failure and the moment when the reparation is finished [17].

• **Power consumption**. This cost is calculated by multiplying the price of a unit of electrical energy by the sum of the energy consumption associated with all the active components used in the network during an operational time period.

• **Penalties (P)**. The service interruption penalty is the fine specified in the service level agreement (SLA) between operators and customers. If the service interruption time is higher than a threshold mentioned in SLA, the operator has to pay a fee depending on the interval that the service is unavailable. This cost also depends on the penalty rate (e.g. cost unit/hour) and the percentage of users signing the SLA in the area. Nowadays mainly business users would pay the extra cost for higher reliability, but it is expected that in the future some residential users may also want to spend more to have lower service interruption time.

• **Floor space**: The equipment in the OLT side are placed in the racks located in the central office. The rental fee of these offices corresponds to the floor space cost. This expenditure is a product of the space required to place all the racks and equipment in the OLT side and the yearly rental fee per square meter. In the model presented in Paper III, each rack contains up to four shelves with 20 slots in each. The number of users that can be covered by one shelf depends on the architecture, and size of its equipment. So the number of racks is calculated via dividing the number of users
served by each CO by the number of ONUs that can be served by each rack. The total space per rack is equal to the sum of its bottom area (0.6 m * 0.3 m) and required work space for the technician to stand in front of it (0.6 m * 1.0 m) that is shown in Figure 3.1 [18].

![Floor space required for a rack including the working space](image)

Figure 3.1. Floor space required for a rack including the working space [43].

### 3.2 Reliability performance parameters

Two reliability parameters are taken into account in this thesis namely, connection availability and failure impact factor (FIF). The former one shows a user perspective, while the latter one is more important from an operator point of view.

#### 3.2.1 Component and connection availability

The probability that a component/fiber is operable in an arbitrary point of time defines the component availability. Availability of the equipment can be calculated using Equation 3.1 [19].

\[
Av = 1 - \frac{MTTR}{MTBF}
\]  

(3.1) \hspace{1cm} MTTR = \text{mean time to repair} \hspace{1cm} MTBF = \text{mean time between failures}

MTBF and MTTR of each component/fiber are defined by the device vendors. Connection availability corresponds to the probability that all the components and fiber segments between the OLT and ONU are operational. In some cases connection unavailability (UnAv) is used to present the probability of being disconnected from the service and it can be calculated via equation 3.2.

\[
UnAv = 1 - Av
\]  

(3.2)

To analyze the reliability performance of a connection, all the components in the path should be considered. Some equipment is connected to each other in series from reliability point of view, meaning that in order to have an operational system all components in series configuration should be working. Equation 3.3 presents an approximate model for calculating the unavailability of the serial configuration

\[
UnAv_{\text{serial}} = \prod_{i=1}^{n} \left(1 - Av_i\right)
\]  

(3.3)
Chapter 3 Evaluation methodology

assuming that $UnAv_i$ are very small. Components/fibers with same functionality that are protecting each others are considered as parallel blocks when calculating the reliability performance of the system. In case of parallel configuration a system is unavailable when all the blocks fail and the unavailability can be calculated by formula 3.4.

$$UnAv_{series} = UnAv_1 + UnAv_2 + ... + UnAv_n \quad (3.3) \quad n = \text{No. of components connected in series}$$

$$UnAv_{parallel} = UnAv_1 \times UnAv_2 \times \ldots \times UnAv_n \quad (3.4) \quad n = \text{No. of components connected in parallel}$$

Formulas 3.1 could be used to define the fiber availability per kilometer. Then the total availability of a fiber link can be obtained by the series combination of several one kilometer fiber segments.

### 3.2.2 Failure impact factor (FIF)

FIF is a new reliability performance parameter reflecting the operators’ point of view. This metric was introduced in Paper V of this thesis. Distinct components’ breakdowns have different influence on the network operation. The failure of an OLT impacts all the connected customers whereas the crash of an ONU affects just one user. Compared to availability, FIF can be a better measure to reflect the different impact of failures of various network segments, and can be calculated for each component using equation 3.5.

$$FIF_{component} = CAF \times UnAv \quad (3.5) \quad CAF = \text{number of customers affected by a failure}$$

The FIF of end-to-end connection consisting of a sequence of components can be evaluated by:

$$FIF_{EtoE} = \sum FIF_{component i} \quad (3.6)$$

Lower FIF means a smaller risk that a huge number of end users are experiencing the service interruption simultaneously due to a single failure in the shared parts of the access network.

### 3.3 Network planning tools

To gain a general idea regarding the network investment cost or its reliability performance an average length for the fibers and trenching should be considered as a starting point. But a more detailed model is needed to have a complete and accurate assessment of the TCO and reliability performance. For example the user distribution in the area can affect the fiber layout of the network, amount of required cables and ducts and possible portion of sharing resources. To consider these effects proper network dimensioning models are needed. Most of the studies done till now are either
3.3.1 Geometric models

Several geometric models can be found in the literature to estimate the amount of required infrastructure, while calculating the investment cost of access networks. These models are normally based on a uniform distribution of the nodes such as buildings, cabinets, etc. Triangle model [20] is a very old geometric model that is polygon-based proposed for the estimation of the fiber and trenching lengths. This model considers the shortest fiber path between physical locations of network without any possible sharing of the resources. This is not practical for the dense urban areas, but it might be good for the rural area with large distances between the houses. In this model the amount of required fibers and trenching is equal, which is not true in real deployments.

Simplified street length (SSL) [21] model is another existing geometric model with customers uniformly distributed over a squared area. Each home (customer) is represented by a small square, which is connected to the central office or cabinet via one fiber. In dense urban areas several apartments are located in the same buildings, making it possible to share cables and trenching by the customers living in the same building. But SSL model is not considered this sharing factor and hence, it is not a suitable tool for modeling dense urban areas.

Manhattan network is another classical geometric model, which is used in this thesis. Apart from the area of Manhattan in New York city, the Manhattan model is also well mapped into the parts of some big European cities such as the Eixample district (see Figure 3.2) in Barcelona. This makes Manhattan model suitable as a dimensioning tool for the dense urban scenarios, and it is the reason why we used this model for our studies.

![Figure 3.2. Aerial view of the Eixample district in Barcelona [22].](image)
In Papers I, II and III the ONU placement is according to the Manhattan network model. The users are grouped in blocks of buildings separated through the parallel streets in both vertical and horizontal directions. In each block side, 8 customers are considered leading to 32 ONUs per block. Central office is located in the center of the first vertical street on the left hand side of the service area (see Figure 3.3).

The number of buildings covered by one CO depends on the maximum reach of the considered access network technology and is calculated using formula 3.7, where maxReach denotes the maximum reach for a given configuration of a certain network architecture. The Blocksize represents the length of one block side in kilometers, \( V_{\text{block}} \) and \( H_{\text{block}} \) denote the number of vertical and horizontal blocks respectively.

\[
\frac{\text{maxReach}}{\text{Blocksize}} > (H_{\text{block}} + \frac{V_{\text{block}}}{2}) \tag{3.7}
\]

Several RNs are normally co-located at the junction of some streets to cover nearby ONUs. The exact place of RNs and fiber layout may vary depending on the network architecture and its client count. It should be noted that this model is typically considered for the urban areas and it is not suitable for modeling the rural network infrastructure.

### 3.3.2 Geographical network planning tool

There are several homemade or commercial network planning tools, which take as the input the real geographical data of an area and give as the output the optimal fiber and trenching layout as well as the number of RNs needed to cover the whole service area. The geographical information of the buildings and streets are extracted from publicly available data sets i.e. either from commercial applications such as Google map, or open source tools such as Openstreetmap [23].
Given a geographical area with location of buildings and CO, specific technology, number of splitting steps, maximum reach, etc, clustering algorithms are used to categorize buildings connected to each RN. The routing design to find a suitable fiber path between customer premises and RNs as well as the route between RNs and CO could be done via modified versions of the Dijkstra algorithm [24][25]. Figure 3.4 shows an example output of a geographical planning tool. Logical model of an access network based on PON is shown in Figure 3.4(a), while the real fiber path and the distances between different nodes corresponding to this logical topology are shown in Figure 3.4(b).

![Logical model of a PON](image1)

![Geographical model of the same PON](image2)

**Figure 3.4.** (a) Logical model of a PON (b) Geographical model of the same PON in a real environment [26].

Although these models usually deliver more precise results than geometric ones, they are specific per region and hence it is not easy to gain a general and broad view. Moreover, they are usually more complex and need more time to be executed and obtain results than the geometric models, especially in case of large service areas.
Chapter 4

Techno-economic study: cost versus reliability

Optical access networks are being widely deployed by cause of their high capacity. Fiber-based technologies make it possible to cover large service areas since they can offer long reach due to the low attenuation and signal distortion compared to copper-based transmission lines. High client count per feeder line is another benefit of optical access network, though it increases the risk of service disconnection for large number of end users by a single failure compared to the conventional copper-based architectures. In addition, as time goes customers rely more and more on the internet connection in their daily lives and cannot tolerate long service interruption as they do today. Currently, penalties are paid to business customers when the service interruption time is longer than the agreed value at the service level agreement (SLA) by the operator. However, the number of users requesting penalty tends to be increasing. Therefore, according to the aforementioned highlights, resilience in NGOA becomes an important aspect to be considered.

Network reliability performance 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 users being affected by a single fiber cut or a hardware problem. But there is a tradeoff between the deployment cost and the level of protection provided in the network. For example, adding backup resources in the access network can be too expensive considering the fact that access networks are very cost sensitive. Therefore, the extra expenditures needed to offer resiliency should be carefully evaluated.

Recently many studies have been concentrated on various protection schemes in PONs and their reliability performance. In late 90’s, four standard resilience mechanisms, referred to as schemes type A, B, C and D, were defined by ITU-T [27]. In the schemes A and B, part of the network, which is shared among all the users is duplicated, so the impact of a single failure significantly decreases. However the
connection availability of individual customers may be still not satisfactory because of the unprotected segments of the network. In type C full duplication of PON resources is leading to low connection unavailability, but unfortunately may result in high CAPEX. Type D offers the possibility of having full duplicated resources for some users, while rests of the customers are only protected partially in the shared parts of the network.

In [28], the standard resilience schemes are compared in terms of reliability performance and cost of protection. According to the results, type C and D can achieve very high availability by paying twice of the CAPEX of an unprotected network, which makes them unfeasible for cost sensitive access networks.

Aforementioned protection schemes do not give the best outcome in combination with the network expenditures. Therefore many research efforts have been put to develop a cost efficient reliable access network by proposing new resilience mechanisms.

In [29][30][31] some novel reliable architectures are proposed for TDM PON, WDM PON and hybrid WDM/TDM PON. Two neighboring ONUs protect each other via interconnection fibers between them. This method allows reusing the available distribution fibers belonging to the other user premise in the vicinity for protection. Another proposal is to use a ring topology instead of conventional tree-based one in order to connect ONUs to the OLT [32]. In this way, the large amount of investment cost for burying redundant DFs to each user can be saved and, consequently, the CAPEX can be reduced compared to the standard schemes C and D. In [33], a new mechanism is proposed for the improvement of reliability performance in WDM-based access networks with slightly modified ONU structure. ONUs are protected via connection to their adjacent ONUs through a ring using dual fibers.

The cost efficient method to protect a network is very dependent on the component technology, physical topology, fiber layout, and customers’ density in the service area. As confirmed by the previous studies [34], trenching expenses are usually the most costly part of the network deployment. Therefore a suitable design of fiber layout could significantly decrease the protection expenditures, but this effect has not been widely investigated for resilience studies of NGOAs.

Moreover, the migration strategy an operator follows toward a resilient network is another important aspect influencing the cost and/or design of protected architecture. The amount of available infrastructure from already existing networks such as copper-based technologies is also important while calculating the investment expenses. For example in some areas where the xDSL is available (Brownfield), the amount of required new trenching are much lower compared to a Greenfield scenario without any available resources.
Thus, in Papers I, II and III, we introduced different protection upgrade strategies and fiber layout design aiming to maximize utilization of the available infrastructure, which leads to a considerable saving in the CAPEX. Afterwards, based on the proposed network structure, an intensive assessment for several optical access networks (current and next generation) was carried out in terms of their reliability performance and protection cost. The results of analysis presented in Papers I, II and III, helped us to find a suitable candidate for NGOA network as the basis for our future studies. This chapter covers the contributions published in Papers I, II and III.

4.1 Assessment of optical access network architectures

In Paper I, the CAPEX and OPEX required to offer resiliency for different upgrading strategies toward a protected access network has been compared for several optical access architectures (TDM PON, WDM PON, AON and Home run) described in Chapter 2. Moreover, an analysis of the power consumption per-user per year has been provided based on the present and estimated future input values.

Paper I considers deployment in dense urban service areas, where the user density is high and the distance to the OLT is short. Customer replacement is based on the Manhattan network [35], which is a well-known geometric network planning model (more information regarding Manhattan model can be found in chapter 3). According to this model, users are distributed in blocks separated by parallel streets. We assumed that each of the blocks contains 32 buildings (see Figure 4.1). Fibers are placed along the streets and terminated in each building. Fiber and trenching layout are varying according to the map of the region and user density. In considered dense area, we proposed two different simple fiber connection strategies to see the influence of fiber layout on the protection cost.

Figure 4.1. Schematic view of Manhattan network model.
An operator can follow various strategies to migrate towards a survivable access network (see Figure 4.2). Starting from the Greenfield scenario, the operator either directly plans for a protected access network, or deploys a network without any resiliency in the first step. The design of an unprotected access network can be done without taking into account future protection upgrade (U1). But it might be more beneficial to define the unprotected architecture considering an easy migration towards a reliable network in the future (U2). Operators need to decide whether to offer duplicated resources up to the RN (Prot1 scenario) or all the way up to the end user (Prot2 scenario), based on the regulation, requirement of availability, etc. Therefore, in Paper I, three schemes have been evaluated keeping in mind various upgrading options (see Figure 4.2); unprotected, protected up to the RN and full protection up to the customer.

The results presented in Paper I, show considerable improvement in connection availability for the protected architectures compared to the unprotected one. WDM PON with protection up to the RN is shown to be the most efficient alternative among the considered options, while the most expensive architecture is the home run. It can also be observed that due to the high service interruption penalty, having duplicated resources for protection in dense areas decreases the total expenditure, considering fiber layouts proposed in Paper I. This might encourage operators to protect the last mile section of their network. Considering availability and cost figures calculated in Paper I, PON-based architectures show better performance compared to active star and home run.
4.2 Assessment of WDM-based NGOA architectures

Paper I demonstrates that PONs are more cost-efficient than the active approaches, but the variants studied before didn’t take into account all the requirements of future access networks. Therefore we extended our work to find appropriate PON architectures that are able to offer higher bandwidth capacity per-user as well as larger coverage. Several NGOA alternatives were proposed in [36], which are further explored in this chapter keeping in mind some key aspects such as cost, reliability, flexibility, etc.

In Papers II and III, we investigated the capital and operational expenditures for two of the WDM-based NGOA architectures in dense urban area with and without protection. In Paper II one simple case of each candidate was considered. Then this study was further extended in Paper III by presenting a comprehensive techno-economic study taking into account 3 variants of each architecture. The aim of these two papers was to evaluate the impact of providing protection on the total cost of ownership as well as comparing two considered NGOA architectures: ultra-dense WDM PON (UDWDM PON) and hybrid WDM/TDM PON (HPON).

UDWDM PON

This architecture (see Figure 4.3) is able to deliver at least 1 Gbps data rate per channel over tens of kilometers and thus, it can guarantee the capacity requirement of NGOAs in [5]. UDWDM PON has an OLT as the root of the tree and the ONUs as the leaves. The OLT is connected to a waveband splitter based on AWG, located at the first remote node (RN1). Each RN1’s output port goes to a second remote node (RN2), which includes a power splitter. Every output of the power splitter is connected to an ONU, so that each user premise has to ultimately select its dedicated wavelength from the received waveband.

HPON

The considered HPON (see Figure 4.4) combines the TDMA and WDM technology. This architecture also has a tree topology with the OLT at the root. The OLT is connected to an AWG located in RN1. One separate wavelength reaches to the power splitter’s input in RN2 from each of AWG’s output port, which is further broadcasted to all the ONUs connected to the same power splitter. Thus, all customers connected to the same RN2 are sharing the same wavelength using TDMA.
In **Paper III**, three variants (See table 4.1) of both architectures have been studied and compared regarding their cost and reliability performance in dense urban area. The expenses include both capital and operational expenditures. The CAPEX consists of the fees related to the network equipment, installation and the infrastructure, while the OPEX covers the charges for the network operations containing the failure reparation, penalty of service interruption, power consumption and rental of the central offices.

<table>
<thead>
<tr>
<th>Architecture variant</th>
<th>Number of AWG output ports in RN1</th>
<th>Number of splitter output ports in RN2</th>
<th>Number of ONU per FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPON 1:40/1:8</td>
<td>40</td>
<td>8</td>
<td>320</td>
</tr>
<tr>
<td>HPON 1:40/1:16</td>
<td>40</td>
<td>16</td>
<td>640</td>
</tr>
<tr>
<td>HPON 1:80/1:16</td>
<td>80</td>
<td>16</td>
<td>1280</td>
</tr>
<tr>
<td>UDWDM 1:40/1:8</td>
<td>40</td>
<td>8</td>
<td>320</td>
</tr>
<tr>
<td>UDWDM 1:80/1:8</td>
<td>80</td>
<td>8</td>
<td>640</td>
</tr>
<tr>
<td>UDWDM 1:20/1:32</td>
<td>20</td>
<td>32</td>
<td>640</td>
</tr>
</tbody>
</table>

**Papers II and III** are also based on the Manhattan network model, similarly to **Paper I**. Different RNs distribution has been considered depending on the splitting ratio of AWGs and power splitters. For example, in scenario with 1:8 power splitter in RN2, one block side is covered by one splitter, meaning that 8 RN2s are co-located in a street cabinet as depicted in Figure 4.5. There are two levels of splitting points leading...
to three fiber segments referred to as FF, DF and LMF. Since network operators typically want to offer protection down to RN1, which is used to avoid the high risk of the large number of ONUs affected by a single failure, in our study FF was duplicated. The proposed FF layout and RNs replacement aimed to minimize the length of required feeder fibers (see Figure 4.5).

![Figure 4.5. An example of network model and proposed fiber layout for 1:40/1:8 variants [Paper III].](image)

The working FF connects the OLT to RN1 through the shortest path and the FF protection uses an available disjoint duct, which just requires blowing new dark fiber. Using considered trenching approach extra trenching investment for backup paths can be avoided.

The total cost per building for a network operational time of 20 years was evaluated in Papers II and III. The results show that in dense urban areas the CAPEX is not significantly different for the two considered PON architectures and their variants, due to the high sharing of the expenses among users. It can be also observed that for unprotected scenario, penalty cost is comparable with the infrastructure expenditure and in some cases it is even higher than the total CAPEX. Moreover, the outcome of Paper III, confirms that with a proper fiber layout design, minor extra investment for protection of NGOA networks can make a significant saving on TCO as a result of a huge decrease in the OPEX.
Chapter 5

Cost efficient protection schemes for HPON variants

Network operators prefer to have a single architecture in their network, due to a variety of reasons. It is profitable from the planning point of view to purchase a large number of components, and have technicians specialized in one certain technology. However, it is not easy to find a single solution that can fulfill all the NGOA requirements at the same time. For example, increasing the client count causes the decrease in the passive reach. Therefore, it might be logical to select an architecture option with several variants, in order to support different types of geographical areas with diverse densities of customers and requested reach. Hybrid WDM/TDM PON (HPON) has this interesting advantage and is considered as a promising NGOA approach.

More importantly, HPON becomes one of the best candidates for the NGOA networks, due to its capability of offering a high splitting ratio and consequently achieving relatively low cost and power consumption on a per-user basis according to the techno-economic studies in Papers II and III. Also the component technology for HPON is more mature than for UDWDM. Therefore, this chapter presents a more detailed study on HPON.

In this chapter, three HPON variants are considered (see Figure 5.1) with different types of components located in RN1 (all of them have power splitter placed in RN2).

- Wavelength selective (W-Selective) HPON has a power splitter in RN1, which implies broadcast and select behavior, since each ONU has to ultimately select its assigned wavelength and time slot.
- A wavelength split (W-Split) HPON contains an AWG at RN1. In this way, one dedicated wavelength is routed to each RN2.
In wavelength switched (W-Switch) HPON, an active optical component requiring power supply and electronic control like wavelength selective switch (WSS) is installed at RN1.

These variants perform different with respect to the cost of deployment, reliability performance and flexibility of resource allocations. Some of them might be suitable for a highly populated area with lots of users but short required reach, while the others fit well to wide region with low client count. For example W-Switch and W-Selective are not feasible for the rural area with high node consolidation degrees due to their reach limitation, while W-Split supports longer reach and can be deployed in such areas. Meanwhile, all HPON variants have nearly similar infrastructure and fiber layout, which allow co-existence of these approaches in the same service area for the various end users requirements and geographical constraints.

Considering the aforementioned highlights, Papers IV and V, focus on three HPON variants presented above as the main candidates for NGOA networks. As mentioned in previous chapter, each NGOA candidate not only should be able to meet the general requirements of future access network such as long reach and high bit rates, but also offer high level of survivability at minimum extra cost. Hence, in Papers IV and V a comprehensive study towards finding the most cost efficient resilience schemes for HPON is presented. In Paper IV, the parts of the HPON with low availability and high impact failure were identified. Leveraging on these findings, Paper IV, was further extended by proposing two resilience mechanisms for HPON considering protection up to the first remote node. This paper also provides evaluation of the resilience architectures in dense urban, urban and rural scenarios in terms of two reliability performance metrics, namely failure impact factor (FIF) and availability. FIF is a new parameter introduced in Paper IV, which indicate the number of users affected by a single failure on the network.
In *Paper V*, we extended this work by adding the cost assessment of the proposed resilience mechanisms, as well as introducing the end-to-end (E-to-E) protection for some selected (business) users. The access network architecture proposed in *Paper V* is able to accommodate different user profiles with various reliability parameters together with a minimum extra cost in return of offered service. In this study the cost of offering protection up to the first remote node for the residential customers and fully duplicated resources for business users is evaluated, taking into account different protection upgrade policies. Cost efficient and smooth migration between the protection upgrade steps was the main concern while designing the fiber layout. *Paper V*, also contains a sensitivity analysis in respect to the CAPEX fluctuations caused by the varied density of enterprises in the area as well as different time for protection upgrades. The contributions published in *Papers IV and V* are summarized in the following subchapters.

### 5.1 Reliability performance assessment

Both *Paper IV and V*, analyze the reliability performance of the proposed resilience schemes in three HPON variants. Two reliability performance parameters that are referred to as unavailability and failure impact factor (FIF) were considered in order to compare the HPON variants (The detailed way to calculate these parameters is presented in Chapter 3).

Unavailability and FIF results for components and fiber segments of the HPON presented in *Paper IV*, demonstrate that the OLT in all cases and RN1 in W-Switch HPON have poor reliability, due to the existence of active components. FF is also a threat for the network resilience, since it is shared among a large number of users. Consequently, main sections of the access network where protection is necessary in order to reach an acceptable level of unavailability and FIF values were defined.

Based on these primary outcomes, two novel protection schemes were proposed and their performance was evaluated in *Paper IV*. Both mechanisms are based on duplicated OLTs and FFs and thus they are identical up to the first remote node. In the first protected scheme shown in Figure 5.2(a), working and backup FFs are directly connected to the RN1 using a 2:M component replacing the 1:M device presented in Figure 5.1. On the other hand, in the second resilience architecture (see Figure 5.2(b)), a 2:2 3dB power splitter is added to the infrastructure, in order to connect FFs and the equipment located at RN1. In this scheme the distribution part of the HPON is divided in two similar parts, each of which has one splitting device in RN1 supporting half of the PON users. However in order to cover the same number of customers as in the scheme shown in Figure 5.2(a), the splitting ratio of the RN2s is divided by two ($2\times M\times N/2= M\times N$).
Chapter 5 Cost efficient protection schemes for HPON variants

Figure 5.2. Proposed reliable architectures for all variants of HPON (a) without 3dB splitter (Wo 3dB) (b) with 3dB splitter (W 3dB) [Paper IV].

Paper IV, deals with three population scenarios; dense urban (DU), urban (U) and rural (R) with high (H) and low (L) node consolidation degrees where 80 and 4 COs are co-located in one CAN respectively. Connection unavailability and FIF values of unprotected (UnProt) and protected architecture with 3dB splitter for all scenarios are presented in Figures 5.3 and 5.4 respectively (the results are similar for Wo 3dB scheme).

Figure 5.3. Connection unavailability for different variants of unprotected and protected HPON.

It should be noted that due to the reach limitation, W-Selective and W-Switch cannot be deployed in a number of scenarios, especially in rural cases. Based on the results shown in both figures, proposed resilience mechanism exhibits a significant gain in
5.1 Reliability performance assessment

terms of reliability performance compared to the unprotected scheme. In general, protected architectures decrease FIF and connection unavailability to an acceptable level for the residential users.

![Figure 5.4. FIF for different variants of unprotected and protected HPON.](image)

W-Switch exhibits the highest unavailability compared with other options. In case of W-Split, there is an obvious increase in unavailability values for longer reach due to the need of reach extender. So, this variant shows better reliability performance in dense urban areas and in scenarios with shorter reach. On the other hand, it is the only possible option for the rural area with high node consolidation degree, though it offers least flexibility regarding the wavelength allocation compared to other HPON architectures.

According to the calculations in Paper IV, protection up to the first remote node cannot satisfy the availability requirement of 4 nines (99.99%) for business users. Therefore, a cost efficient E-to-E resilience scheme for business users is proposed in Paper V, while the rest of customers in the same PON are only protected up to the RN1. It is possible to fully protect all the customers in the network, but not everyone is willing to pay the additional cost for this reliability upgrade. Residential users are able to tolerate some hours of service disconnection during a year without encountering any problem, e.g. financial losses.

To decrease the investment cost in the first year of deployment, operators may provide a network without any resilience. Then as the take rate increases, operators are forced to add protection resources to their network, in order to offer a more robust service. The expenses of this reliability improvement can be decreased by taking into account the future protection upgrade in the initial deployment.
In this regard, in Paper V, we proposed an unprotected HPON architecture with slightly modified infrastructure plant in the distribution part of the access network, which can be smoothly migrated towards the introduced E-to-E resilience scheme with minimum additional cost (see Figure 5.5). The main objective of the proposed architectures is to co-locate the fully protected business users and residential customers with partial protection in the same PON, while minimizing the required extra investment for these resilience schemes.

In Paper V, we focused only on one area type namely dense urban, which typically have high density of both business and residential users. The considered unprotected architecture for HPON is shown in Figure 5.5(a). Dividing the distribution segment of the network into two parallel sections leads to an architecture, which is able to provide a cost efficient resilience mechanism for E-to-E protection of some selected users per PON.

As it was shown in Paper IV, offering resilience up to the RN1 is required to lower down the probability that a large number of users get disconnected by a single failure. Therefore, in Paper V, we used the scheme depicted in Figure 5.5(b) to increase the reliability performance of the access network. The structure is very similar to the one presented in Paper IV, except replacing the 2:2 splitter with two 1:2 splitters (Prot1). In this way the splitter is also protected.

Figure 5.5(c) depicts the proposed E-to-E protection scheme for business users (Prot2). The only extra investment using this mechanism is related to the last mile fiber section shown in green in the figure and the replacement of unprotected ONU by the one with duplicated transceivers. It should be mentioned that several output ports of power splitter in RN2 location are reserved for the protection from the beginning (denoted by “n” in Figure 5.5). Therefore, maximum number of users that can be supported by each OLT is slightly decreased.

When a customer requests an E-to-E protection, the operator adds a fiber path from that user to the RN2 of adjacent distribution segment, which is connected to the disjoint component at RN1 (shown by green in the Figure 5.5(c)). To decrease the additional expenses of new infrastructure, required backup fibers are blown through the available disjoint ducts belonging to the neighboring ONU, where possible. In this way the digging effort can be minimized.
5.2 Protection cost assessment

Using E-to-E protection scheme proposed in Paper V, the connection availability higher than 99.99% could be reached for the business users, which is in line with the requirement of this user profile. The FIF values are not improved significantly via Prot2, since the failure impact of the distribution part of network is low.

**Figure 5.5.** (a) unprotected scheme, (b) protection up to RN1 (Prot1) and (c) E-to-E protection for business users (Prot2), for HPON variants [Paper V].

In Paper V, we further evaluated the aforementioned HPON variants regarding the extra expenses of providing protection considering different reliability upgrade road maps. Generally access networks are too sensitive to the expenditures. Therefore the proposed protection schemes should be cost efficient enough for the residential users and small/medium sized enterprises with limited budget.

Different network upgrade paths can be considered towards a reliable access network, depending on the conditions and regulations, which impact the investment cost. For example, if the operator decides to move its customers at once from an old, copper-based technology to the fiber-based architecture, it is more logical to directly deploy the protected network (Prot1 or Prot2). Otherwise, if the take rate is too low in the area,
and the operator needs to wait several years to reach a satisfactory number of customers in the region, it might be worth to deploy an unprotected network to have a lower investment at the beginning. Then the protection could be added in the later stage with increase of the revenues. **Paper V** considers three protection upgrade approaches (see Figure 5.6), in order to investigate the influence of various migration strategies towards the proposed reliable architectures presented in Figure 5.5.

![Figure 5.6: Protection upgrades paths [Paper V].](image)

Starting from Greenfield, an operator may deploy an access network without any protection (A1:S1). Later the increasing number of customers in the service area may motivate operators to add backup resources to the shared part of their network (A1:S2), in order to reduce the impact of a failure. Afterwards with appearance of business users that require a more reliable connection and are able to cover the extra cost, Prot2 scheme can be deployed (A1:S3 in Figure 5.6).

In some occasions, it is more beneficial to deploy the whole network at once in order to avoid the need of expensive civil work on the infrastructure in the later stage. It should be also mentioned that it might not be possible to dig the ground at any time due to the municipality’s regulations in densely populated areas. Therefore, under such conditions the best solution would be the direct deployment of Prot 1 (A2:S1), or Prot 2 (A3). It should be mentioned that it is not always possible to follow approach 3 (A3), since the business customers requesting the reliability upgrade, may appear in the region in the later phases. In this case, operators have to follow approach 2, and upgrade the network on per-user basis when requested (A2: S2).

The required investment cost for business and residential users following the aforementioned planning approaches, is presented in **Paper V** for the HPON variants. According to the results, the amount of extra investment cost per-user needed for offering resilience up to the RN1 is negligible in comparison with the CAPEX per-user. This outcome certifies the cost efficiency of protecting the shared part of access network in order to prevent large number of customers experiencing service interruption simultaneously. CAPEX is nearly doubled for business users by adding a disjoint backup path in the distribution part of network, as a result of the high digging
costs, which is shared among few customers. Regarding the protection upgrade paths, the techno-economic outcomes from Paper V, shows that more number of steps in the network deployment slightly increases the initial deployment cost for each user. A3 gives the minimum total CAPEX among all the considered approaches, though a larger investment is needed in the beginning.

Paper V, also includes a sensitivity analysis of the variation of the deployment cost for HPON, considering different values of input parameters. The duplicated fiber route in the distribution segment of Prot 2, is partly shared among several business users. Therefore the density of enterprises in the service area may influence the protection cost. This effect was studied in Paper V, by varying the percentage of business customers per PON. The results confirm the dependency of the investment required for providing full backup resources on the business users’ population, i.e., by increasing the number of enterprises, the protection cost per business user decreases considerably.

Another parameter studied in Paper V, is the time between two consecutive steps in the network upgrade process. As time passes, the price of equipment such as ONU decreases due to the maturity of the technology. On the other hand the salary of technicians increases each year leading to the increase in the digging expenses. These variations were considered in Paper V, in case of A1 and A2, as they could affect the total deployment cost for these two approaches. According to the outcome of the sensitivity analysis, the investment cost for E-to-E protection of users increases for both approaches, as the times between steps is growing. This means that the personal salaries are more dominant than the components cost, while calculating the network investment expenses.
Chapter 6

Conclusions and future directions

This thesis focused on finding the cost-efficient and reliable solutions for the next generation of optical access networks that are able to fulfill the basic NGOA requirements such as providing high sustainable bandwidth per-user as well as covering large service areas. The considered architectures were evaluated regarding the cost of deployment as well as the required operational expenses during their life time. Furthermore, the thesis has addressed the resiliency issue of the access network, which becomes one of the important aspects of future architectures and should be treated carefully for any NGOA candidate.

In this context, we had first investigated the potential technologies that are able to meet the requirements of future access networks. It was found that WDM-based PON has obvious advantages over all the other evaluated architectures, leading us to divert our focus on this technology.

Therefore, we analyzed the performance of two WDM-based NGOA candidates, namely UDWDM PON and HPON, in terms of total cost of ownership during their operational time with and without protection. The results have shown that with a very small increase of investment to offer feeder fiber protection, network providers can prevent a simultaneous service disconnection of large number of users. This outcome justifies the network providers’ tendency of protecting their network up to the first remote node, which is shared among many customers. We also observed that both UDWDM PON and HPON are very similar regarding the investment cost and resiliency performance, but the former one needs much more complex optical components supporting the coherent receivers that most likely will not be available in the market soon.

Based on the highlights of studies mentioned above, we concentrated on the HPON. A further assessment was done by considering three variants of HPON, in order to evaluate and compare their capabilities of providing a reliable access network with minimum extra cost. As the first step, we identified the main segments of the HPON, which need to be protected aiming to reduce the impact of a failure. Consequently,
based on this result, two novel resilience mechanisms were introduced aiming to improve reliability performance of access network by duplicating the resources up to RN1. The calculated connection availability and FIF have shown that a considerable enhancement in reliability performance of all HPON variants was offered by both proposed protection schemes.

Although, the protection till the first RN could significantly improve the reliability performance, the connection availability is still below four nines, which might be not acceptable for the business users. Meanwhile, not all the users would like to pay more to get high connection availability. Therefore an end-to-end protection scheme for some selected users (e.g. business access) was introduced in the thesis. Such an approach enhances flexibility of protection provisioning in HPON, where reliability performance upgrade for certain users can be done upon request and does not affect any other connected customers.

Any resilience mechanism should be economically feasible in order to be deployed in the access network. With this in mind, we also assessed the investment needed for providing different levels of protection for all HPON variants. The results show that protecting the shared part of the access network needs only a small extra cost compared to the overall initial investment. The outcomes of techno economic studies also present that providing full protection could satisfy four nines connection availability requirement of the business users at the reasonable extra deployment cost of backup resources. According to the finding of this thesis, HPON could be one of the promising candidates for NGOA networks considering its high capacity, large coverage, low cost and power consumption as well as its ability to fulfill different reliability requirements of various user profiles.

In terms of future work, we plan to find a cheaper end-to-end protection scheme for optical access network, which is affordable for residential users or small enterprises. As it was presented, typically network operators do not provide a completely disjoint path for each single customer because it is too expensive. Even in case of small and medium enterprises the full protection is not foreseen, since they normally cannot afford the extra investment cost of such protection (nearly twofold of the initial investment is needed according to the results). Thus, we will investigate a simple and cost-effective protection scheme for residential and small business users. The preliminary idea is to use the available wireless internet connection offered by mobile operators as the backup for the optical access network.

Due to the capacity limitation of available wireless connection the offered bandwidth from mobile backup will be limited to several megabits per seconds (Mbps). This makes it hard to use this method for big enterprises that normally require high bandwidth, but it might be enough for small and medium business or residential users. We will evaluate the possibility of the proposed protection mechanism using existing technology and devices. Also the cost of such scheme will be analyzed and compared with the end-to-end protection scheme proposed in this thesis.
Another future direction could be to further explore the HPON variants using a geographical network planning tool. In Paper II and III, we calculated the extra cost of offering protection up to the first splitting point according to a simple geometric model (Manhattan model) in dense urban area. However, the Manhattan model is not suitable for the rural scenarios. Moreover there can be some factors that are ignored in a homogenous geometric model that could make a significant difference in network deployment. For instance, the results received from geometric model cannot reflect the reality in some uneven populated areas where the households are not uniformly distributed. Considering these points, we plan to extend the previous studies using our home made geographical network planning tool to investigate the cost and reliability performance of the considered WDM-based NGOA architectures in dense urban, urban and rural areas, in particular for some cases, where the households are not uniformly distributed.
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Summary of original work

**Paper I:** Carmen Mas Machuca, Jiajia Chen, Lena Wosinska, Mozghan Mahloo, Klaus Grobe, “Fiber access networks: Reliability and power consumption analysis”, in the 15th International Conference on Optical Networking Design and Modeling - ONDM 2011, February 2011, Bologna, Italy.

In this paper, we analyzed the influence of protection on the cost and power consumption for different current optical access technologies (P2P, AON, TDM PON and WDM PON), considering different migration approach towards protected architectures. The evaluation results show that slightly higher investment expenditure to provide protection, can lead to a huge saving in the total cost of ownership.

*Contribution of author:* The model and formula for calculation of power consumption, calculation and evaluating the results related to the energy consumption and the related text.

**Paper II:** Carmen Mas Machuca, Mozghan Mahloo, Jiajia Chen, Lena Wosinska, “Protection cost evaluation of two WDM-based Next Generation Optical Access Networks”, in Asia Communications and Photonics Conference (ACP), November 2011, Shanghai, China.

The cost of protection up to the RN1 is assessed for two WDM-based next generation access networks referred to as the UDWDM and HPON in dense urban area. The proposed fiber layout and RN replacement aimed to minimize the trenching cost needed for the protection. Both technologies show considerable improvement regarding their reliability parameters in protected scenario compared to unprotected one. The cost study shows that with a suitable fiber layout, small extra investment towards a protected network decreases the failure related cost such as service interruption penalties.

*Contribution of author:* The proposed fiber layout and RN placement, all sections related to the CAPEX including calculations of results, graphs, text.


In this paper we investigate the influence of different client counts and splitting ratios on the CAPEX and OPEX considering protection up to RN1 for two WDM-based NGOAs; UDWDM and HPON. Fiber and trenching layouts are designed according to the RNs splitting ratio to reduce the extra investment cost needed for the protection.
According to the results, higher client count or higher splitting ratio of RN2 will lead to less cost per-user, since more number of users is sharing the same resources.

*Contribution of author:* The proposed fiber layout and RN replacement, all the CAPEX related calculations and analysis, the power consumption and floor space related parts of the paper, the first draft of manuscript


In this paper we are analyzing the availability and FIR for various components and fiber segments of three HPON variants to define the most important part of the access network to protect. Based on these results, we propose some novel protection schemes and evaluate their reliability performance in dense urban, urban and rural areas.

*Contribution of author:* The protection of CAN, the results and some text related to the wavelength selected HPON, contributing on the protected architecture design.

**Paper V:** Mozghan Mahloo, Abhishek Dixit, Jiajia Chen, Bart Lannoo and Lena Wosinska, “Towards End-to-End Reliable Hybrid TDM/WDM Passive Optical Networks”, Manuscript was submitted to IEEE communication Magazine.

In this paper we propose a cost-efficient end-to-end protection mechanism for some selected business users for three HPON variants. Then we evaluate the investment cost needed for providing different degree of reliability for residential and business users considering various protection upgrade paths. Moreover, some study is done to assess the influence of input parameters such as business customers’ density in the area, or the protection upgrade time of the network, on total investment cost of a reliable access networks.

*Contribution of author:* The proposed unprotected and protected schemes, all the calculations and analysis related to the reliability parameters and cost, the first draft of manuscript.