Doctoral Thesis in Information and
Communication Technology

Transport Solutions for Future Broadband Access Networks

MOZHGAN MAHLOO

Stockholm, Sweden 2015

TRITA-ICT-COS-1501
ISSN 1653-6347
ISRN KTH/COS-15/01-SE
ISBN 978-91-7595-450-9

KTH Royal Institute of Technology
School of Information and Communication Technology
Department of Communication Systems
SE-164 40 Stockholm, Sweden

Akademisk avhandling som med tillstånd av Kungliga Tekniska Högskolan framlägges till offentlig granskning för avläggande av teknologie doktorsexamen måndagen den 13 april 2015 klockan 10:00 i Sal B, Electrum, Isafjordsgatan 26, Kista, Stockholm.

Tryck: Universitetsservice US AB, Stockholm, 2015

Abstract

"Connected society" where everything and everyone are connected at any time and on any location brings new challenges for the network operators. This leads to the need of upgrading the transport networks as the segment of Internet infrastructure connecting the fixed users and mobile base stations to the core/aggregation in order to provide high sustainable bandwidth, as well as supporting a massive number of connected devices. To do this, operators need to change the way that access networks are currently deployed. The future access network technologies will need to support very high capacity and very long distances, which are the inherited characteristics of optical transmission. Hence, optical fiber technology is recognized as the only future proof technology for broadband access.

Capacity upgrade in the access networks can lead to a huge capacity demand in the backbone network. One promising solution to address this problem, is to keep the local traffic close to the end users as much as possible, and prevent unnecessary propagation of this type of traffic through the backbone. In this way, operators would be able to expand their access network without the significant capacity upgrade in the higher aggregation layers. Motivated by this need, a comprehensive evaluation of optical access networks is carried out in this thesis regarding ability of accommodating local traffic and amount of possible saving in the backbone by implementing locality awareness schemes.

Meanwhile, next generation optical access (NGOA) networks have to provide high capacity at low cost while fulfilling the increasing reliability requirements of future services and customers. Therefore, finding cost-efficient and reliable alternative for future broadband access is one of the most important contributions of this thesis. We analyzed the tradeoff between the cost needed to deploy backup resources and the reliability performance improvement obtained by the proposed protection mechanism.

Among different NGOA architectures, hybrid time and wavelength division multiplexing passive optical network (TWDM PON) is considered as a proper candidate providing high capacity and large coverage. Therefore, this approach is further analyzed and several tailored protection schemes with high flexibility are proposed to statisfy different requirements from the residential and business users in the same PON. The work carried out in the thesis has proved that TWDM PON can also offer high reliability performance while keeping the network expenditures at an acceptable level. Considering some other advantages such as low power consumption and high flexibility in resource allocation of this architecture, it has high potential to be the best candidate for NGOA networks.

Moreover, new deployments of radio access networks supporting the increasing capacity demand of mobile users lead to the upgrade of the backhaul segment as a part of broadband access infrastructure. Hence, this thesis also contributes with a comprehensive techno-economic evaluation methodology for mobile backhaul. Several technologies are investigated in order to find the most cost-efficient solution for backhauling the high capacity mobile networks. Finally, a PON-based mobile backhaul with high capacity and low latency has been proposed for handling coordinated multipoint transmission systems in order to achieve high quality of experience for mobile users.

Keywords: Capital expenditures (CAPEX), Operational expenditures (OPEX), Mobile backhaul, next generation optical access network, protection, passive optical network, reliability, techno-economic, total cost of ownership, wavelength division multiplexing.

Sammanfattning

"Det hopkopplade samhället" där allt och alla är förbundna oavsett tidpunkt och plats skapar nya utmaningar för nätverksoperatörerna. Det leder till behovet av ständiga uppgraderingar av transportnätet. Detta utgör det segment i Internets infrastruktur som binder ihop användarna och mobila basstationer med kärnnätet i syfte att ge hög kontinuerlig bandbredd samtidigt som många ska kunna betjänas. För att lösa detta behöver operatörerna förändra det sätt på vilket accessnäten byggs ut. Framtida teknologier för accessnät kommer att behöva understödja mycket hög kapacitet över mycket långa avstånd, något som är tydliga egenskaper hos optiska transmissionssystem. Optisk fiberteknologi är hittills identifierad som den enda framtidssäkra tekniken för bredbandsaccess.

En utökad kapacitetsuppbyggnad i accessnäten kommer att leda till ett enormt kapacitetsbehov i kärnnätet. En lovande lösning för att hantera detta problem är att hålla lokal trafik nära slutanvändarna i så hög grad som möjligt för att således undvika onödig transport av denna trafik genom kärnnätet. På detta sätt kan operatörer utöka sina accessnät utan signifikanta uppgraderingar i de högre aggregationslagren. Motiverad av detta behov har vi i denna avhandling genomfört en omfattande utvärdering av optiska accessnätverk utifrån deras möjlighet att hantera lokal trafik samt undersökt möjliga besparingar i kärnnätet som kan uppnås genom att implementera scheman som är platsmedvetna.

Samtidigt måste nästa generations optiska accessnät (NGOA) tillhandahålla hög kapacitet vid låg kostnad och detta med de ökade krav på tillförlitlighet som ställs av framtida tillämpningar och användare. Ett av de viktigaste bidragen i denna avhandling är därför att finna kostnadseffektiva och tillförlitliga alternativ för den framtida bredbandsaccessen. Vi har analyserat avvägningen mellan kostnad att tillföra ytterligare back-up resurser och den förbättring i tillförlitlighet som erhålls genom att utnyttja den föreslagna skyddsmekanismen.

Bland de olika NGOA arkitekturerna så utgör hybrid-tid våglängsmultiplexerade passiva optiska nätverk (TWDM PON) lämpliga kandidater för att ge stor kapacitet och stor täckning. Av denna anledning är denna teknik särskilt analyserad och flera skräddarsydda skyddsmekanismer med hög flexibilitet föreslås i syfte att tillfredsställa olika krav från privatanvändare och företagskunder vilka delar samma PON. Arbetet har visat att TWDM PON kan erbjuda hög tillförlitlighet samtidigt som kostnaderna kan hållas inom acceptabla gränser. Även med tanke på andra egenskaper såsom låg effektförbrukning och hög flexibilitet i resursallokeringen så är denna teknik potentiellt den bästa kandidaten för NGOA nätverk.

Utbyggnaden av nätverk baserade på radioaccess för att hantera det ökade kapacitetsbehovet från mobila användare leder till behovet att uppgradera även det mobila förbindningsnätet som utgör en del av bredbandsinfrastrukturen. Avhandlingen bidrar således också med en övergripande tekno-ekonomisk utvärderingsmetod för sådana mobila förbindningsnät. Flera olika teknologier undersöks i syfte att finna den mest kostnadseffektiva lösningen för att förbinda mobila högkapacitativa nätverk. Slutligen föreslås ett PON-baserat mobilt förbindningsnät med hög kapacitet och låg fördröjning för att hantera koordinerade "multipoint" transmissionssystem i syfte att erhålla hög upplevd kvalitet för de mobila användarna.

Acknowledgements

There are a number of people without whom this thesis would have been impossible to be written and to whom I am greatly indebted.

First and foremost, I would like to express my deepest gratitude to my supervisor, Professor Lena Wosinska, for offering me the opportunity to continue as a PhD student in her team, for helping with the improvement of my scientific writing and finally for giving me the confidence to grow. Without her excellent supervision, my Ph.D. study would not go forward.

I would also like to extend my sincere thanks to Dr. Jiajia Chen, another supervisor of mine, for guiding me through the years of my Ph.D. study and her endless research advice. All the lessons she has taught me, especially the work attitude, are so precious.

I would like to express my appreciation to Dr. Carmen Mas Machuca for her advice and support. My technical visit to her group at the beginning of the study has been inspiring me all these years.

My gratitude goes to all the co-authors of my publications for their valuable collaborations and intellectual inputs. I am also grateful to all the partners in the OASE project for sharing their knowledge and fruitful discussions.

Furthermore, I would like to thank the following people who have contributed to my professional and personal time at the optical networking laboratory (ONLab), in no particular order:

- Amornrat Jirattigalachote, for her help and support in every aspect during first years of my study.
- Pawel Wiatr, for sharing the office with me, and for not hesitating to help with anything varying from technical discussions to simple life related issues.
- Adriana Rosa, for being an energetic colleague and lovely friend, for fruitful chats during office hours.
- Paolo Monti, for his support and guidance both in regards to scientific recommendation and administrative related tasks.
- Professor Robert Forchheimer, for translating my thesis abstract to Swedish.
- Lech Wosinski, for delicious barbecue, and his unlimited hospitality every summer.
- Members of ONLab family, for their happy and positive attitude during these years, for building a very joyful work environment, and for all the fun we have had during last 4 years, in particular, Jawwad Ahmad, Kun Wang, Marilet De Andrade, Marija Furdek, Matteo Fiorani.
- Eva Andersson and Sarah Winther, for managing the administrative and economic issues.

I am also grateful towards my beloved friends, Maryam Olyaei, Serveh Shalmashi, Arash Shakoei, Zargham Baghchesaraei, Forough Yaghoubi and Ali Yavari, for sharing the lunch breaks with me, as well as for their practical and emotional supports during my study.

Living abroad very far from home and for a long time has its difficulties, and I am grateful to all my friends, because of whom this has become a lot easier, in particular, Ramona Kaviani, Mariam Jarahnejad, Mahsa Mashoof, Mohammadreza Asadi, Kiumars Kamyabnejad, Sepideh Abolhassani, Amin Vali, Farshad Naghibi.

Most importantly, my deepest gratitude belongs to the ones who have supported me unconditionally, by all means, during my lifetime and taught me to believe in myself, although they had to live a continent apart, for years; thus, my special thanks belong to my mother and my sister, who have cherished with me every exciting moment and supported me when I needed. To my mother who has been a source of encouragement and inspiration throughout my whole life.

Mozhgan Mahloo
Stockholm, Sweden
March 2015

Table of Contents

List of abbreviations

AON	Active Optical Network
Av	Availability
AWG	Array Waveguide Grating
BBU	Base Band Unit
BS	Base Station
BW	Bandwidth
CAN	Central Access Node
CAPEX	Capital Expenditures
CF	Cash Flow
CO	Central Office
CoMP	Coordinated Multipoint
DF	Distribution Fiber
DSL	Digital Subscriber Line
eNB	evolved Node B
E-to-E	End to End
EPON	Ethernet Passive Optical Network
FF	Feeder Fiber
FIF	Failure Impact Factor
FR	Failure Reparation
FSAN	Full Service Access Networks
FTTB	Fiber to the Building
FTTH	Fiber to the Home
Gbps	Gigabit per second
GPON	Gigabit capable Passive Optical Network
HetNet	Heterogeneous Network
HPON	Hybrid Passive Optical Network
ISP	Internet Service Provider
LMF	Last Mile Fiber
LTE	Long Term Evolution
MAC	Multiple Access Control
Mbps	Megabit per second
MIMO	Multiple Input and Multiple Output
MO	Mobile Operator
MTBF	Mean Time Between Failures

MTTR	Mean Time to Repair
NGOA	Next Generation Optical Access
NGPON	Next Generation Passive Optical Network
NP	Network Provider
NPV	Net Presented Value
NS2	Network Simulator 2
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPEX	Operational Expenditures
PIP	Passive Infrastructure Provider
PON	Passive Optical Network
PtP	Point to Point
PtMP	Point to Multi Point
P2P	Peer to Peer
RN	Remote Node
RRU	Remote Radio Unit
SLA	Service Level Agreement
STB	Set-Top Box
SP	Service Provider
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TV	Television
TWDM	Time/Wavelength Division Multiplexing
UDWDM	Ultra Dense Wavelength Division Multiplexing
UnAv	Unavailability
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
3GPP	3rd Generation Partnership Project
5G	5th Generation

List of Publications

Publications included in the thesis:

Paper I: **M. Mahloo**, A. Gavler, J. Chen, S. Junique, V. Nordell, and L. Wosinska, "Offloading the Aggregation Networks by Locality-Aware Peer-to-Peer Based Content Distribution", IEEE/OSA/SPIE Asia Communications and Photonics Conference and Exhibition (ACP), 2011.

Paper II: **M. Mahloo**, J. Chen, and L. Wosinska, "PON versus AON: Which is the Best Solution to Offload Core Network by Peer-to-Peer Traffic Localization", Elsevier Journal of Optical Switching and Networking (OSN), vol. 15, no. 1, pp. 1–9, 2015.

Paper III: C. Mas Machuca, **M. Mahloo**, J. Chen, and L. Wosinska "Protection Cost Evaluation of Two WDM-based Next Generation Optical Access Networks", IEEE/OSA/SPIE Asia Communications and Photonics Conference and Exhibition (ACP), 2011.

Paper IV: **M. Mahloo**, C. Mas Machuca, J. Chen, and L. Wosinska, "Protection cost evaluation of WDM-based Next Generation Optical Access Networks", Elsevier Journal of Optical Switching and Networking (OSN), vol. 10, pp. 89–99, Jan. 2013

Paper V: A. Dixit, J. Chen, **M. Mahloo**, B. Lannoo, D. Colle, and M. Pickavet, "Efficient Protection Schemes for Hybrid WDM/TDM Passive Optical Networks", IEEE International Conference on Communications (ICC), New Trends in Optical Networks Survivability, 2012.

Paper VI: **M. Mahloo**, A. Dixit, J. Chen, C. Mas Machuca, B. Lannoo, D. Colle, and Lena Wosinska, "Towards Reliable Hybrid WDM/TDM Passive Optical Networks", IEEE Communications Magazine (ComMag), vol. 52, no. 2, pp. s14-s23, 2014.

Paper VII: **M. Mahloo**, P. Monti, J. Chen, and L. Wosinska, "Cost Modeling of Backhaul for Mobile Networks", IEEE International Conference on Communications (ICC), Fiber-Wireless Integrated Technologies, Systems and Networks, 2014.

Paper VIII: **M. Mahloo**, F. Farias, P. Monti, J. C. Weyl, L. Wosinska, and J. Chen, "Techno-Economic and Business-Feasibility Modeling of Mobile Backhaul", submitted to IEEE Communications Surveys and Tutorials, March 2015.

Paper IX: **M. Mahloo**, L. Wosinska, and J. Chen, "Efficient Mobile Backhaul Architecture Supporting Coordinated Multipoint Transmission", submitted to IEEE Communications Letters, March 2015.

Publications not included in the thesis

Paper 1: A. Dixit, **M. Mahloo**, B. Lannoo, J. Chen, L. Wosinska, D. Colle, and M.Pickavet, "Protection Strategies for Next Generation Passive Optical Networks-2", IEEE International Conference on Optical Network Design and Modeling (ONDM), 2014.

Paper 2: C. Mas Machuca, M. Kind, K. Wang, K. Casier, **M. Mahloo**, and J. Chen, "Methodology for a Cost Evaluation of Migration towards NGOA Networks", IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 5, no. 12, pp.1456 – 1466, 2013.

Paper 3: J. Chen, **M. Mahloo**, and L. Wosinska, "Reducing the Impact of Failures in Next Generation Optical Access Networks", IEEE/OSA/SPIE Asia Communications and Photonics Conference and Exhibition (ACP), 2012.

Paper 4: C. Mas Machuca, J. Chen, L. Wosinska, **M. Mahloo**, and K. Grobe, "Fiber Access Networks: Reliability and Power Consumption Analysis," International Conference on Optical Networking Design and Modeling (ONDM), 2011.

Patent: COMP backhauling solutions via PON (Filed at 9 September 2014 with number PCT/SE2014/051029)

Chapter 1

Introduction

The future information society and the requirements of having a connected world along with new concepts such as information centric networks [1], network function virtualization [2] and cloud computing [3] services bring the need of upgrading the Internet infrastructure. The growing number of connected devices, radical changes in the user behavior (always on), emerging new applications, such as ultra-high definition television (4K TV), machine-to-machine (M2M) communications, are bringing new challenges for the network providers, such as offering very high capacity per user, as well as reliable and low-latency end-to-end connectivity for a massive number of devices in a cost- and energy-efficient manner. In this thesis, the segment of the Internet infrastructure between core/aggregation network and both fixed users and mobile base stations is considered and referred to as transport network.

Problem statement

To address challenges of the future transport networks, this thesis provides a comprehensive guidance to find the best alternatives for the capacity upgrade of the fixed and mobile broadband networks in the 2020 time frame. The main objective of this work is to find the solutions which are able to fulfill the following criterias to support variety of Internet applications [4]:

- Capacity of higher than 10 Mbps for mobile user
- Sustainable capacity per residential user of 300 Mbps
- Business user capacity demand of 10 Gbps and higher
- Low cost and energy consumption
- High end-to-end resilience
- Low end-to-end latency

In this regard, we focus on the design and performance assessment of cost-efficient and reliable architectures for the future fixed broadband access and mobile backhaul networks. This goal is achieved by proposing new topology and architectural designs, proper protection schemes for various user profiles, cost and business models as well as new reliability performance metrics. This thesis highly focuses on the access technologies for the fixed broadband network. Meanwhile, the mobile backhaul networks are also studied as a part of access networks.

1.1 Background and motivation

To address some of the challenges related to the future high capacity transport networks, this thesis mainly focuses on three major areas (i.e., impact of traffic locality on the network infrastructure, cost versus reliability of future access networks and cost-efficient mobile backhaul technologies) where the background and motivations are described in the following sub-chapters.

1.1.1 Optical access networks

Although the optical transmission technology is widely deployed in the core/aggregation networks, it is still considered expensive for the last mile broadband access. However, optical access networks are the only viable solution to be deployed in the last mile segment, due to their potential to offer very high capacities and long reach [5][6]. Therefore, this thesis focuses on the technologies based on the optical transmission in order to find the suitable architecture that is able to meet various requirements of future broadband access networks.

Recently a large number of studies have been done aiming to propose a good candidate for the next generation optical access (NGOA) network with an emphasis on passive optical networks (PONs) [7][8]. In [7], several time division multiplexing (TDM) PON architectures such as XGigabit capable PON(XGPON) [9] and 10G Ethernet PON (10G-EPON) [10] are introduced as the candidates for future access networks. However, the bandwidth provided by these technologies are not high enough for the NGOA networks. Reference [8] introduces several alternatives for the next generation PONs including some variants of time and wavelenght devision multiplexing PON referred to as hybrid PON (HPON). But the study is not able to select a single architecture suitable for the high capacity access networks. A number of European projects involving partners from both academia and industry (e.g. photonic integrated extended metro and access network (PIEMAN) [11], multi-service access everywhere (MUSE) [12]) have also 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. Another European large scale integrated project, i.e., optical access seamless evolution (OASE) [13], addressed fiber-to-the-home (FTTH) solution within a multi-disciplinary approach to provide a set of technological candidates for the NGOA networks. Each of the proposed in the literature architectures has their own pros and cons. However, there is still lack of a successful approach that can meet a variety of technical and economical criteria. Therefore, finding an appropriate network architecture, which can take advantage of the high transmission capacity offered by optical fiber while being feasible from the cost perspective is still an important research problem to be solved.

1.1.2 Impact of peer-to-peer applications on the network infrastructure

One of the key requirements of future optical access networks is to provide high sustainable bandwidth per-user in a scalable way. However, the capacity upgrade in the access networks may lead to a huge traffic demand increase in the core/aggregation networks [14]. Consequently, in the near future the core segment may become the bottleneck for the bandwidth upgrade per user. One way to address this problem is to keep the local traffic in the access network area as much as possible. It would prevent “feeding” the core network with the data belonging to the users in the same geopgraphical locations and help to mitigate the increase of the capacity demand in the core/aggregation networks caused by the development of the access segment.

Based on the study presented in [15], the sum of all types of video traffic including TV, client-server based video downloads and peer-to-peer (P2P) have exceeded 60 percent of the global consumer traffic by 2014. Therefore, we try to remove the bottleneck from the core network by keeping the video traffic inside the access network as much as possible. This is done via putting the micro cashes close to the end users or using P2P protocols which allows users to access the content available in their vicinity. The P2P technology has shown its potential as an efficient solution for transferring the bulky Internet files such as videos. In the recent years, there has been an increase in the number of data sharing applications which are designed based on the P2P techniques. A good example of this can be Spotify [16], which is a famous company providing commercialized music streaming services with around 40 million users over the world. Spotify started to use P2P application to complement their client-server based services in order to save both on the storage and processing devices and the network resources. Skype [17] is another successful story of the large world class enterprises employing P2P techniques for their application. In addition to the traditional file sharing applications, there is also a growing interest on using P2P for the Internet TV channels. PPLive [18] is one example of the online TV channels, employing the P2P for live streaming.

P2P applications are highly scalable and efficient for large volume content distribution, but its traffic can be very expensive for Internet providers due to the lack of a standard way to keep it locally. Based on the study presented in [19], in

2013 the total localized P2P video content exceeded 20 Exabyte per month. Therefore, there is a huge potential to save network resources in the core/aggregation networks by applying locality-aware P2P schemes for video streaming. In this way the next generation access networks can be deployed without strong implication on the core network.

The benefits of resource saving in the existing access networks using locality of traffic have been shown in [20] and [21]. However, the suitability of various optical access network architectures for accommodating the P2P traffic may depend on the network architecture, which can affect the efficiency of the resource utilization in different network segments. Thus, it is important to study the performance of each optical access architecture in this regard.

By deploying a proper architecture in the access segment along with an efficient traffic locality-aware strategy, the extra investment and capacity upgrade of the expensive core network resources needed to support the future traffic expansion can be minimized. Pushing the Internet traffic towards the end users can be used as a short-term solution to reduce the need of upgrading core network. This issue is addressed in Chapter 4 of this thesis.

1.1.3 Cost versus reliability performance of the optical access networks

One of the key objectives of the conducted research regarding NGOA networks is to find a candidate which is economically viable, considering the growing gap between the operator's expenditures and the revenues. Access network is generally 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 realistic approach needs to be cost-efficient. Consequently, the required investment for the deployment and operation of the access network turns to an important assessment criteria of each NGOA candidate.

Next generation optical access networks are expected to cover large areas [4] in order to reduce operational expenditure per user [22][23]. 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). However, this concept might lead to a less reliable network as a result of longer fiber paths. Expanding size of the service areas as well as users demand for highly available connections turns network reliability performance of the access networks to a new challenge for the operators. A higher number of clients served by one central office (CO) increases the failure penetration range, since more customers can be affected simultaneously via a single breakdown in the network. In addition, customers in their daily lives are more and more dependent on an uninterrupted access to the Internet services and in the future they will not be able to tolerate long service unavailability. As a result, it becomes vital to offer an acceptable level of reliability performance in emerging NGOA.

It should be mentioned that there is always a tradeoff between expenses related to providing the backup resources and level of network reliability. Operators would like to minimize the impact of failures but are not willing to pay a lot of extra investment for protecting the individual users. Therefore, cost-efficient and reliable NGOA architecture should be developed to fulfill the requirements of both customers and operators. In this regard, any NGOA candidate should be assessed in terms of ability to offer an acceptable level of reliability with minimum extra capital expenditures (CAPEX) and operational expenditures (OPEX) in order to be considered for deployment. Consequently, any proposed resilience mechanism for these NGOA alternatives should be further assessed regarding the additional expenditures needed for protection. Recently many studies have been concentrated on developing a cost-efficient and reliable access network by proposing new resilience mechanisms. In [24][25][26], 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 connecting 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 [27]. In this way, the large amount of investment cost for burying redundant distribution fibers to each user can be saved and, consequently, the CAPEX can be reduced. In [28], 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 extensive studies on proposing the cost-efficient protection mechanism for each access technologies, confirm the importance of this research topic, which also motivates some of the contributions presented in this thesis.

1.1.4 Mobile backhaul architectures

In addition to the fixed broadband users, the number of mobile subscribers is rapidly growing. Based on a study presented by Ericsson [29] the data traffic from mobile devices is expected to have a-8-fold increase between 2014 till 2020. This means that a large part of broadband access will be served by the wireless networks. High performance fixed and radio networks are expected to co-exist and support each other in various scenarios. Hence, the fixed and mobile network convergence turns to an important research topic in the recent years. Several large scale projects are funded by European Union, which are trying to address the fixed and mobile convergence as well as proposing the high capacity radio networks such as convergence of fixed and mobile broadband access/aggregation networks (COMBO) [30]. COMBO aims to propose and investigate new integrated approaches for fixed and mobile converged broadband access and aggregation networks for different scenarios (dense urban, urban, rural).

Future transport networks should be able to fulfill the requirements of various customers' profiles at the same time. One of the most important customers for the fixed network providers can be the mobile operators who need backhaul connectivity for their radio access network (RAN) in order to be able to serve their customers. The backhaul segment is considered as a part of the transport network. Therefore, it is important to have the right technology supporting both fixed and mobile users when the convergence is considered in the transport network. Consequently, this thesis also evaluates the performance of mobile backhaul architectures as a part of the broadband access segment.

The mobile traffic and control data are transferred from the RAN to the mobile core network via backhaul network. Operators select a suitable combination of backhaul technologies, according to their needs in terms of capacity, reliability, cost and deployment time. The mobile backhaul technologies are mature and well established for the current mobile deployments. However, a rapid increase of the mobile data which leads to the introduction of high capacity mobile technologies such as long term evolution (LTE) [30] and the fifth generation (5G) [31] brings new challenges for the design of the backhaul network. Increasing the radio network capacity is not possible without having high capacity backhaul links for sending data back towards backbone network. Moreover, introducing new wireless deployment solutions such as heterogeneous network (HetNet) [32] increases the importance of backhaul technologies which are able to support large number of small cells offering capacity where needed [33], co-existing with the low number of macro cells providing the coverage.

Basically, cost of backhaul can be as significant as the RAN [34] and cannot be neglected while deploying a new mobile technology Therefore, finding a high capacity and cost-efficient solution for backhauling mobile networks should be addressed while designing future radio access networks.

Another new aspect which sharply changes the design of future mobile transport networks is the introduction of techniques such as massive multiple inputs multiple outputs (MIMO) [35] and coordinated multipoint transmission (CoMP) [37] with the goal of increasing the cell throughput specially in the network edges. These techniques require backhaul links with very high capacity and low latency.

Moreover, new cellular architectures such as cloud-RAN (C-RAN) [38] are introduced to further improve the performance of future mobile broadband access networks. In C-RAN, the base band units (BBUs) which are responsible for processing the signals coming from user's handsets are moved from the cell site towards several centralized locations. This reduces the expenditures and the footprint of wireless deployment as well as the operational complexity of the mobile networks. In order to benefit from implementation of the C-RAN, links with data rates of several Gbps referred to as fronthaul are required to transfer signal received by remote radio units (RRUs) to the centralized BBUs (see Figure 1.1).

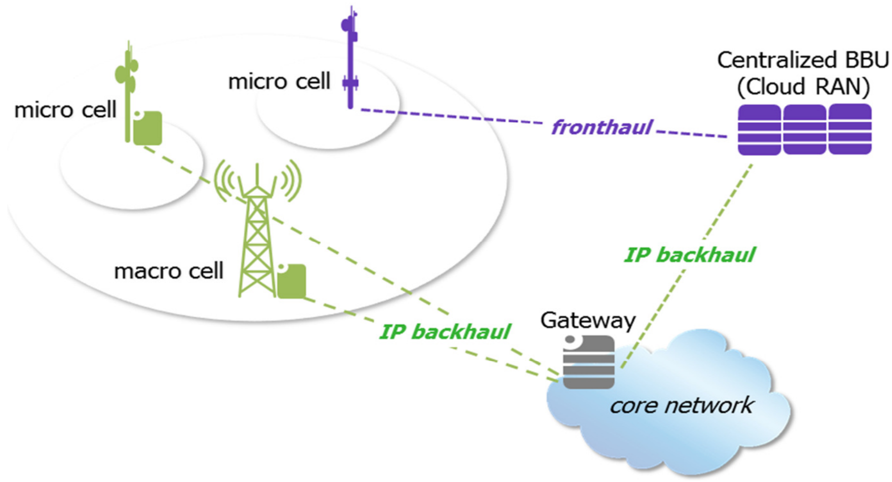

Figure 1.1. Example of mobile fronthaul and backhaul structure [39]

The fronthaul network in combination with the backhaul that is responsible for transmitting data from centralized or distributed BBUs towards core networks constitutes the mobile transport segment (see Figure 1.1)[39].

1.2 Overview of the contributions of the thesis

This sub-chapter briefly describes the contributions presented in each paper included in the thesis.

1.2.1 Optical access network considering traffic locality

As it was mentioned before due to the growing traffic demand, deployments of new access technologies are inevitable. However, without proper planning, the capacity upgrade in the access network may lead to the need of adding a lot of new resources to the core. Therefore, Chapter 4 of the thesis focuses on proposing a suitable solution in order to prevent the need for upgrade of the core and aggregation networks as a result of increase in the user's traffic demand. This may help operators to put their investment only in the access networks without need for the expansion of higher aggregation layers.

Paper I quantitatively analyses the possible resource saving and benefits of using locality-aware algorithms for the video traffic distributions on the networks. We have developed a tailored network simulator based on network simulator 2 (NS2) in order to evaluate video distribution applications such as catch-up TV, P2P and client-server based applications. Moreover, we have proposed and applied an efficient locality-aware scheme to improve locality of video distribution for P2P applications. The results confirm that a huge bandwidth saving is possible in the aggregation and core network by pushing the Internet data towards end users as much as possible. This study is further extended in **Paper II** by analysing the efficiency of supporting locality-aware P2P video distribution algorithm in three main types of optical access network architectures, i.e., active optical networks (AON), wavelength division multiplexing passive optical networks (WDM PON) and hybrid time/wavelength division multiplexing PON (TWDM PON or HPON). **Paper II,** for the first time, compares performance of these architectures with respect to the traffic distribution in different aggregation levels, power consumption taking into account sleep mode functionality at the user premises, and required switching capacity in the network nodes. To simulate the dynamic behavior of video traffic in the access networks, we have extended our home-made simulator used in **Paper I**, by adding the time division multiple access (TDMA) protocol. This allows us to measure the amount of traffic in each network's link for various architectures, and translate the results to model network power consumptions and switching capability of the nodes. This paper provides important design guidelines for the next generation broadband access architectures, while minimizing the need for the core network upgrade.

1.2.2 Reliable optical access network architectures

Chapter 5 is based on the contributions presented in **Papers III**, **IV**, **V** and **VI**, where objective is to find a cost-efficient and reliable optical access architecture which is able to fulfill the requirements of both residential and business users with a focus on the WDM-based PON technologies. According to the outcomes of **Papers I** and **II**, passive optical networks based on WDM show good performance considering energy consumption, resource usage and accommodating local traffic while offering high bandwidth per users and long passive reach.

The reliability performance and total cost of ownership considering protection of the shared part of the network for two WDM-based NGOA candidates, i.e. HPON and ultra-dense WDM PON are evaluated in **Papers III** and **IV**. We have proposed a suitable fiber layout for the feeder fiber section aiming to minimize the cost of protection in the dense urban areas. Moreover, the influence of various splitting ratio and client counts per PON is assessed in **Paper IV,** by proposing efficient remote node positioning and fiber layout.

According to the results presented in **Papers III** and **IV**, HPON can satisfy all the NGOA requirements such as high capacity per-user, long reach and large client counts as well as requiring low investment cost. Hence, in **Papers V** and **VI,** we have 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 resilience for various user profiles. Firstly, **Paper V** has identified the most important parts to be protected in the network aiming to minimize the impact of any single failure. We have introduced a new reliability performance parameter referred to as failure impact factor (FIF) in order to measure the impact of each single failure in the network. This parameter can be used along with the connection availability to give a comprehensive view of the architecture reliability performance. Based on these results two novel protection schemes have been proposed in **Paper V** in order to efficiently improve the resilience of HPON. According to the outcome of this paper, 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 VI** a cost-efficient end-to-end protection scheme has been proposed, which can flexibly upgrade the reliability performance of some selected users. Furthermore, this paper includes a comprehensive techno-economic study along with the sensitivity analysis for our protection schemes.

1.2.3 Cost efficient mobile backhaul

The backhaul expenses have been always an important cost factor for the mobile operators, and its impact is more crucial considering new mobile broadband technologies and architectures targeting the increase of the user capacity demands. Therefore finding a cost efficient backhaul solution turns to an important research question in the recent years, which is addressed in Chapter 6. To this date, there is no complete cost model or business analysis that can be used for the cost assessment of backhaul networks, especially considering the heterogeneous network (HetNet). To address this, in **Paper VII,** we have proposed a comprehensive cost model for calculating the total cost of ownership for backhauling solutions based on fiber or microwave technologies. The cost model includes both CAPEX and OPEX occurred during network life-time.

Estimating the total cost of ownership for any technology can give an idea on how expensive is to deploy and run the network. However, it is not saying anything about the profitability of the new technology, as the market success is related to many other factors such as yearly revenues, user penetration rates, number of competitors in the area, regulations, etc. Hence, **Paper VII** is extended by proposing a complete techno-economic evaluation method along with a comprehensive business viability assessment for future mobile networks considering both RAN and backhaul segments. The overall methodology and the related case studies are presented in **Paper VIII**. This paper also includes a sensitivity analysis on the important cost factors of the backhaul network in order to assess the impact of the assumptions and input values used in the business study.

Chapter 6 also contains a novel low-latency and cost-efficient backhaul architecture based on PON supporting the coordinated multipoint (CoMP) transmission. The material presented in this sub-chapter is based on a filed patent in collaboration with Ericsson as well as contributions presented in **Paper IX**.

In general, backhaul and fronthaul segments can be very similar from technological and architectural points of view except their requirements regarding capacities, reliability, latency, etc. It should be noted that most of the concepts and models introduced in this thesis related to the backhaul network are also valid for the fronthaul. In this thesis, we focused our analyses and case studies on the backhaul. Most of work could also be applied for fronthaul.

Chapter 2

Broadband Access Technologies

In this chapter we introduce the broadband technologies related to the access networks for fixed customers users as well as the ones used for as well as the ones used for backhauling of radio access networks. As described in the previous chapter, 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 architectural options currently deployed or being standardized, which can be used as a basis for further development of the NGOA networks. This chapter briefly introduces both the existing optical access architectures as well as the future candidates of the NGOA networks.

Mobile backhaul networks are also considered to be a part of the transport networks, and hence are studied in this thesis. Several technologies are known to be suitable for the mobile backhaul based on copper, fiber, and microwave. Figure 2.1 presents the current and expected share of each technology in the backhaul networks worldwide [32].

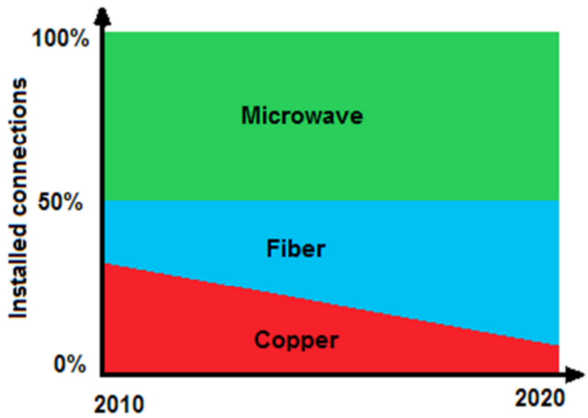

Figure 2.1. Projected changes in backhaul technology [32]

Microwave represents nearly 50% of all backhaul deployments, and it is expected that it will maintain the same share in the coming years. Copper-based backhaul amounts approximately up to 20% among all three technologies in 2014, and it will be gradually replaced by fiber-based backhaul network in the future. It should be mentioned that recently several new technologies such as free space optical (FSO) [40] and millimeter-wave (mm-Wave) [41] are introduced to be used as the short range backhaul solutions. These technologies are mostly suitable for small cells as they offer Gbps capacity in the range of tens of meters with low footprint. However, as these technologies are not standardized yet, they are not the focus of this thesis. Based on the aforementioned assumptions, fiber and microwave technologies will be the two main candidates for backhauling of the future mobile networks, which will be shortly discussed in this chapter.

2.1 Microwave based backhaul

Microwave links are relatively fast to deploy with a moderate installation cost compared to the fiber networks. However, the power consumption and footprint of the microwave antennas increase the operational expenses for microwave-based backhaul.

Typically, microwave-based backhaul network consists of a number of point-to-point (PtP) or point-to-multipoint (PtMP) microwave links, with antennas in both sides of the links. The links can be installed with a topology of the tree, star, ring or any combination of these topologies. Mobile data related to each base station is sent to the antenna located at the cell side via a switch. This data is then received by another antenna on the other side of the link that is connected either to a switch at the first aggregation point of the backhaul infrastructure (i.e., in the case of a multistage backhaul) or directly to a switch at the central office. When several microwave antennas are co-located in one place, a tower mast needs to be installed which is referred to as the microwave hub. Figure 2.2 shows an example of multi-hop microwave backhaul with PtP links. Ethernet switches are added to the sites with several antennas in order to aggregate data coming from all the antennas.

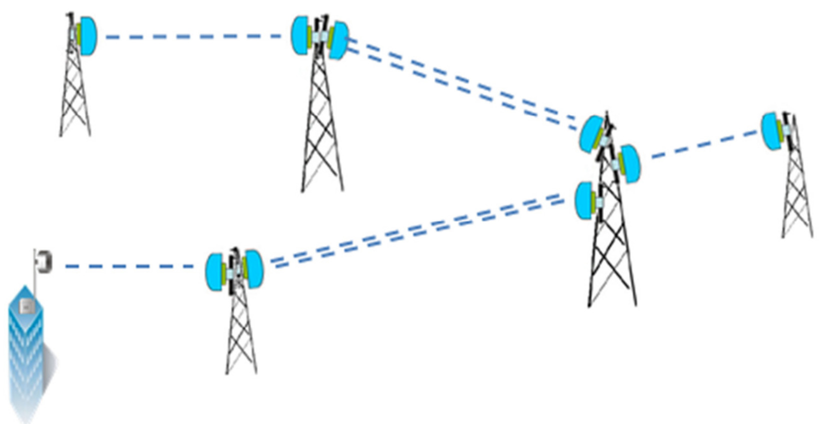

Figure 2.2. Example of multi-hop microwave backhaul with PtP links

Nowadays, microwave links can offer up to 1Gbps capacity over several kilometers [42] and therefore they can fulfill the capacity requirements of backhaul networks.

2.2 Fiber technologies

Fiber-based networks offer very high capacity over long distances. However, it is relatively expensive and slow to deploy in the areas where no fiber infrastructure already exists. However, the widespread penetration of fiber, mostly replacing existing copper-based infrastructures, can be expected in the coming years, since fiber has been recognized as the future-proof technology for broadband access. The main requirements of next generation optical access networks considered in this thesis are listed below [4].

a) Sustainable bandwidth of 300 Mbps per residential user (Residential BW)
b) Business, backhaul (fixed, mobile) peak date rate up to10 Gbit/s (Business BW)
c) Supporting more than 256 users per feeder fiber (Client count)
d) Supporting passive reach up to 60 km (Passive reach)

Figure 2.3 gives an overview of the access network node locations as considered in this thesis. Optical access network consist of three main parts: (a) central office (CO) or central access node (CAN) where the optical line terminal (OLT) is located, (b) one or more intermediate nodes refer to as the remote nodes, (c) optical network unit (ONU) responsible for terminating the optical signal at the user side.

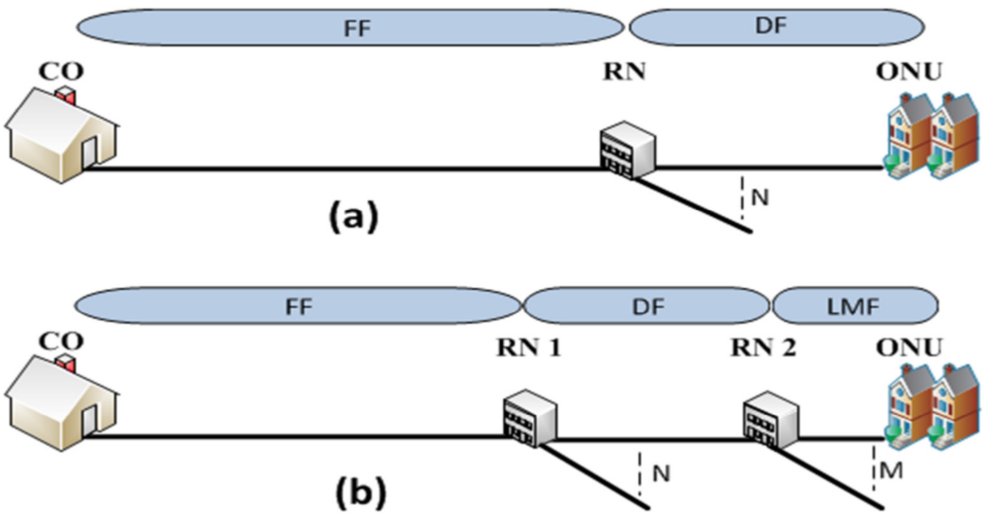

Figure 2.3. Physical connection points and fiber segments in optical access networks

Most of the deployed optical access networks nowadays have a tree-based fiber topology with OLT connected to multiple ONUs located either at the end users premises or close to the users (e.g. in a street cabinet). The OLT is responsible for terminating optical signal in the operator side. The network infrastructure consists of fibers and remote nodes (RNs) where either splitting or switching devices are placed. The OLT 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 2.3(a)).

In some cases, the physical infrastructure may consist of more than one splitting point between the CO and the ONUs (see Figure 2.3(b)) in order to increase the number of users connected to each OLT (referred to as client count). 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 between RN1 and RN2 is called DF and the one between end user and RN2 are connected through last mile fiber (LMF) (see Fig. 2.3(b)).

Next generation access networks are going to expand towards the backbone in the way that they also include the current aggregation network segments, connecting the last miles directly to the core network. Elimination/reduction of the aggregation network is possible using the long reach capabilities of the optical transmission technologies which allows co-locating several conventional COs in one place namely central access node (CAN). This concept is also referred to as node consolidation and offers a great potential to minimize the deployment and operational cost. The degree of node consolidation is defined as the ratio between the number of the CANs and old COs. Figure 2.4 shows an example of conventional and consolidated optical access network, where 3 COs are replaced by a CAN covering much larger service area. In this example, the ratio of node consolidation is 1:3.

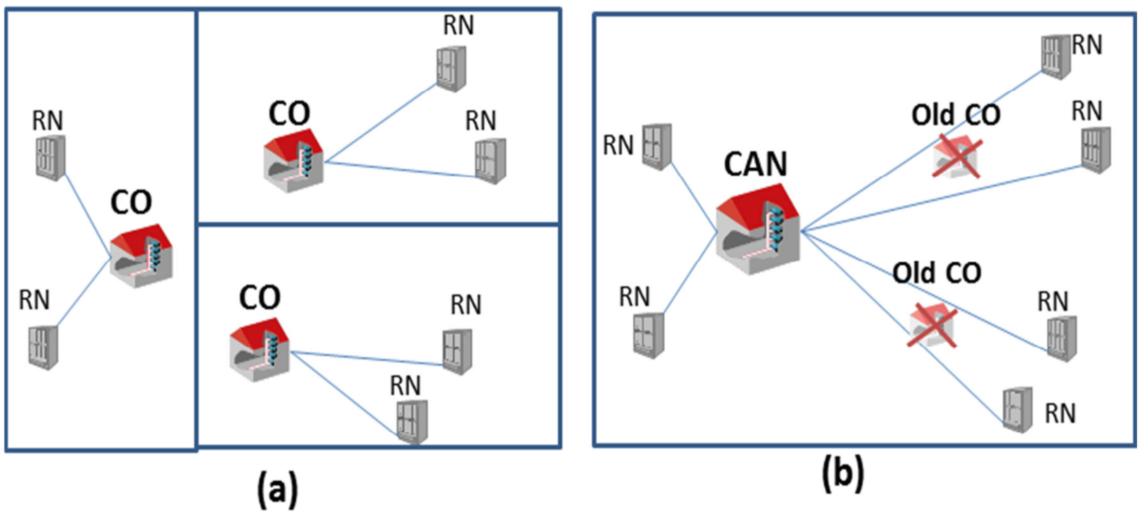

Figure 2.4. Optical access network (a) without node consolidation,(b) with node consolidation.

One way to categorize optical access networks is based on the types of devices located in the field, which they can be either passive (i.e., no need of power supply in the field) or active.

Another widely used classification is related to the physical topology connecting the OLTs and the ONUs. Two typical categories are referred to as PtP and PtMP. When there is a dedicated fiber or wavelength connection directly from the OLT to the ONU, it is defined as PtP, whereas using a multiplexing technique that leads to sharing the resources (e.g. feeder fiber) among multiple end users is categorized as PtMP.

Fiber to the X (FTTX) is a generic term for access network architectures where all or parts of the existing copper-based infrastructure is replaced with fiber technology. The "X" can represent "home", "building", "curb" or "cabinet" based on the location that terminates optical signal in the access network. In this thesis, we are considering the fiber to the home (FTTH) [43] 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 gives a complete view regarding different classes of optical access architectures.

2.2.1 Active optical network (AON)

Currently, AONs use Ethernet as a service carrier between active components and the data is switched over in the electrical domain. So both the data plane and the control plane need to be electronically processed in the remote node. Currently two common last mile fiber topologies deployed in case of AONs as described in the following sub-chapters. AONs are mostly deployed in European countries such as Sweden and Denmark [44], due to the low user density in these places.

a) Active star

In this architecture, a single fiber is connected from an aggregation switch at the CO to an active Ethernet switch located at RN, which implies the need of power supply in the outside plant (see Figure 2.5). 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 an Ethernet switch without going back to the OLT if not needed. AONs are capable of offering high capacities due to the availability of commercial 10Gbps Ethernet interfaces. They can also offer service over long distances up to 100 km, as a result of signal regeneration during optical to electrical (OE) conversions.

Feeder fiber (FF) is considered as a shared medium meaning that this architecture has a PtMP 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.

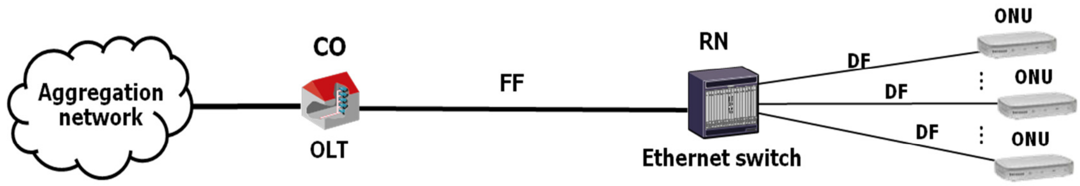

Figure 2.5. A schematic view of the active star architecture

b) 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 2.6). 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). However, it has the 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. This architecture is also capable of offering up to 10Gbps per user for very long distances of up to 100 km.

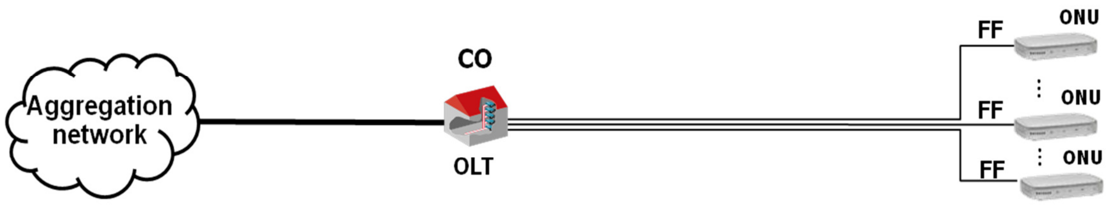

Figure 2.6. A schematic view of the home run architecture

2.2.2 Passive optical network (PON)

PON is the promising candidates for the future access networks due to its simplicity, transparency, reduced footprint and low power consumption. This architecture can 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 PtMP architecture in the fiber topology. In case of PONs both data and control planes remain optically transparent. 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.

It should be mentioned that in some cases reach extenders are used in the remote node to increase the passive reach which implies the need of power supply and optical to electrical signal conversion. In these cases, the architectures might consider as semi-passive. However, in this thesis we consider both passive and semi-passive architectures as PONs, since the data plane is still optical. PONs can be divided to several subclasses according to the end-to-end transmission and multiple access techniques used for sharing the common resources such as FFs.

a) 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 one or more power splitters at RN (see Figure 2.7), leading to a less secure connection as everyone receives the information of all other users. The ONU transceivers need to support the aggregated bandwidth of the PON which is the total bandwidth of all the ONUs connected to the same OLT.

This type of PON is already deployed widely using the standardized TDMA protocols namely gigabit-capable passive optical network (GPON) [45] and Ethernet passive optical network (EPON) [46]. GPON is mostly deployed in North America and small parts of Europe while Asia-Pacific countries (such as Japan) have EPON enabled TDM PON installed in their access networks [44].

In TDM PON, the bandwidth per ONU is limited by the fact that a single wavelength is shared by all users connected to the same OLT. In the 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 in average per-user, which does not meet the NGOA networks' requirement of several hundred Mbps sustainable bandwidth per-user. It also supports up to 20 km of passive reach.

The data rate of TDM PONs are enhanced by introducing the XG-PON [9] and 10GEPON [10], supporting up to 10Gbps in the downstream directions as well as passive reach of 60 km and 20 km, respectively. These TDM PON based systems are standardized as the intermediate step towards NGOAs. According to the standard, 10GEPON is capable of supporting up to 32 ONUs per feeder fiber while this number can increase up to 128 in case of XG-PON.

Figure 2.7. A schematic view of a TDM PON

The maximum bandwidth of 10Gbps is still not sufficient considering high demand for client count in the future access networks. Furthermore, passive reach in TDM PON is relatively short and cannot satisfy the requirements of future access networks.

b) 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 ONU is assigned individual wavelength. So this architecture can provide higher bandwidth per user and ONUs can work at the individual data rate rather than the aggregated one. Moreover, the security and the network integrity are enhanced compared to TDM PON. WDM PON has a PtP connection in the wavelength layer, whereas the fiber topology is still PtMP.

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. This architecture 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 types of devices used in the RN. The architecture with the power splitter in RN is called broadcast and select WDM PON where fixed or tunable WDM filters at the ONU select their own dedicated wavelength. The passive reach of this variant decreases with an increase in the splitting ratio of the power splitter. Another variant with wavelength multiplexer/demultiplexer in the RN is referred to as wavelength-split or wavelength-routed WDM PON which leads to a much simpler ONU and longer reach with the drawback of lower flexibility in the wavelength assignment. Figure 2.8 shows the general architecture of a wavelength-routed WDM PONs.

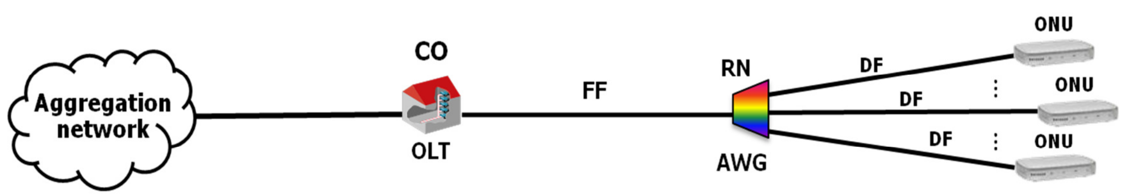

Figure 2.8. A schematic view of a wavelength-routed WDM PON

Another important variant of WDM PON is the ultra-dense WDM (UDWDM) system with very small channel spacing. This requires the coherent detection with high sensitive receivers, especially in the configurations with very high fan-out (theoretically up to 1000 wavelengths are possible considering 3GHz spacing). This architecture (see Figure 2.9) can deliver at least 1 Gbps data rate per channel over tens of kilometers and thus, it can guarantee the capacity requirement of NGOAs in [22].

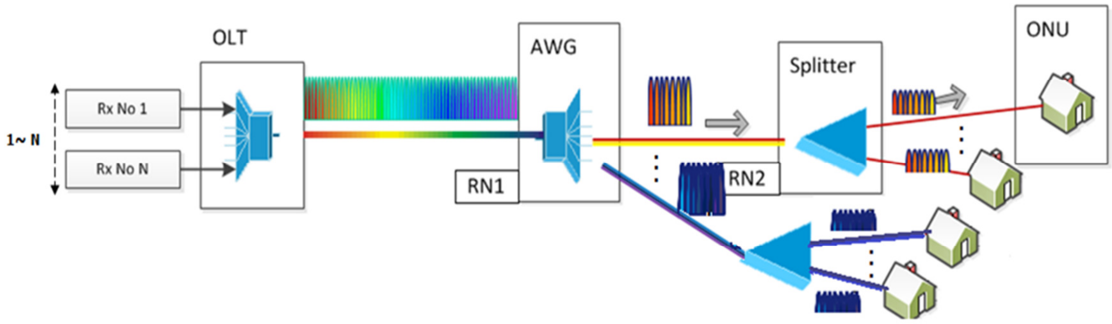

Figure 2.9. A schematic view of UDWDM PON architecture [Paper IV]

As you can see, 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 ultimately to select its dedicated wavelength from the received waveband. Using a combination of band filter and power splitter, passive reach of 60 km [47] is possible for this architecture.

c) Hybrid PON (HPON)

Hybrid PON is another candidate in order to achieve very high client count and capacity per user basis. As it is mentioned in the previous sub-chapters, both TDM PON and WDM PON have some advantages and drawbacks and can partly meet 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 or TWDM PON for the network with combined time and wavelength multiplexing capabilities. 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. Figure 2.10 shows a schematic view of one of the common variants of HPON. This architecture also has a tree topology where the OLT is at the root. The OLT is connected to an AWG located in RN1. One separate wavelength reaches 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.

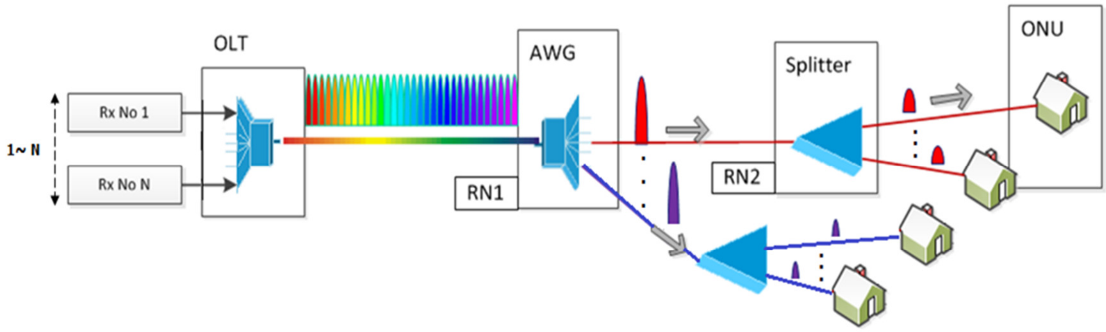

Figure 2.10. Considered HPON architecture [Paper IV]

In this thesis, three HPON variants are considered (see Figure 2.11) with different types of components located in RN1 (all of them have power splitter placed in RN2).

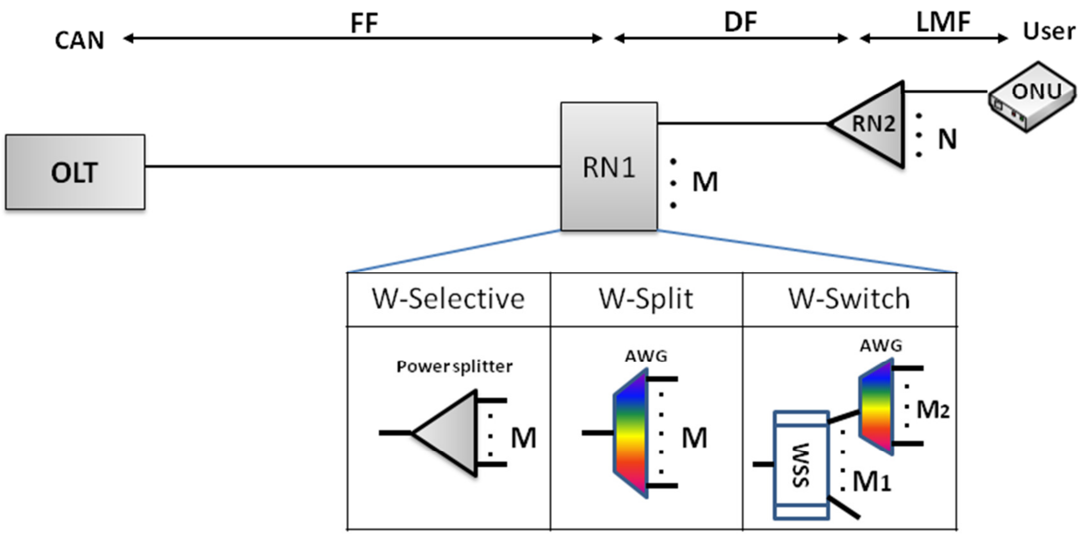

Figure 2.11. Three HPON variants [Paper V]

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, by using fixed or tunable WDM filters and an appropriate multiple access control (MAC) protocol. This solution has a serious security threat as the content of all the wavelengths is available to all ONUs. It also suffers from high power loss due to having two stages of power splitting in the field.

Wavelength-split (W-Split) HPON contains an AWG at RN1. In this way, one dedicated wavelength is routed to each RN2. So the security and power budget are enhanced compared to the previous variant. However, the flexibility in the wavelength domain is restricted.

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. Usage of WSS allows some degree of flexible and dynamic wavelength assignment. Moreover, the security concern is improved in comparison to the W-Selective HPON. The required link power budget is also in the middle of two other variants.

2.2.3 Summary of optical access networks performance evaluation

Table 2.1 summarizes the capabilities of the aforementioned optical access architectures in fulfilling the NGOA requirements. The table is used as a guide to find the suitable candidates for further investigations in the next chapters of this thesis.

Table 2.1. Summary of optical access architectures assessment considering NGOA requirements

Architecture	Residential BW	Business BW	Client count	Passive reach
EPON/GPON	Yes	No	No	No
10GE/XG-PON	Yes	Yes	No	No
Active star	Yes	Yes	Yes	Yes
Home run	Yes	Yes	No	Yes
WDM PON	Yes	Yes	No	Yes
UDWDM PON	Yes	Yes	Yes	Yes
HPON	Yes	Yes	Yes	Yes

As you can see from the table, except the TDM PON variants and home run, all of the other optical access architectures can fulfill the NGOA requirements up to an acceptable level. Therefore, we focus on several main categories of the aforementioned architectures in this thesis.

It should be noted that fiber-based backhaul networks can be based on any of the aforementioned optical access network technologies. Backhaul segment can share the same infrastructure of the optical access networks offering broadband services to the residential and business customers. In the case of backhaul networks, ONUs are located in the cell site gathering mobile data from antennas and base stations to send over optical fibers towards the core network or centralized BBUs.

Chapter 3

Evaluation Methodology

This chapter describes the evaulation methodology we used in this thesis to assess different aspects of the studied topics.

The typical life cycle of any network consists of following phases: planning, initial installation, operational phases, and teardown. Deployment of any new technology 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 and business viability of the project. This is done in the planning phase of the project. The initial planning phase helps operators to evaluate the profitability of any new project considering uncertainties on the user penetrations, revenues, and market convergence. Moreover, a comprehensive techno-economic study comparing available technologies helps operators to narrow down the technological options and choose the most cost efficient technology which is able to fulfill all the user requirements. The business 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 deployment. Therefore, some analytical models can be helpful to assess the project business viability, cost or any other performance capabilities of various technologies before the deployment. This chapter presents the models and formulas used for the techno-economic and resilience studies in this thesis. Moreover, the methodologies used to define network scenarios and topologies for the case studies are presented in this chapter. Some parameters such as connection availability are already known for years while some other metrics like failure impact factor (FIF) are counted as the contributions of this thesis.

3.1 Techno-economic evaluation framework

To have a comprehensive techno-economic evaluation and risk analysis, a complete framework is required. Figure 3.1 shows the techno-economic framework proposed in **Paper VIII** of this thesis. This framework defines the relation between various models affecting the network planning, such as the market model, topology model, architecture model, etc. and their input and output parameters. It should be noted that this structure is general enough to be used for any network.

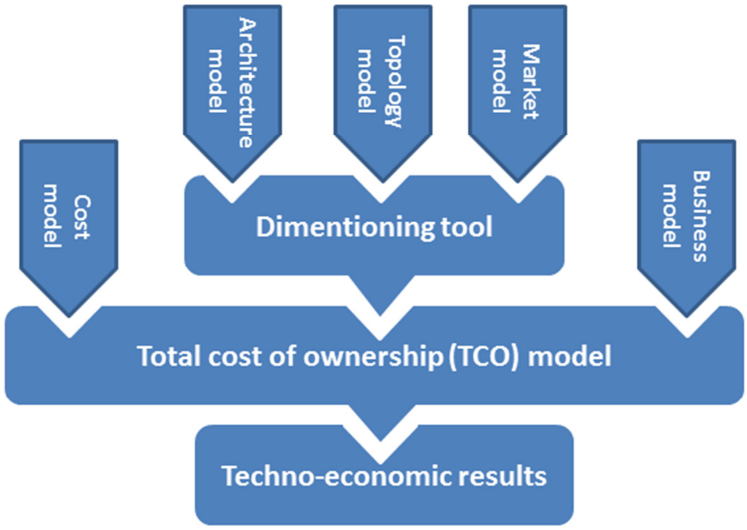

Figure 3.1. Techno-economic evaluation framework

3.1.1 Architecture model

Normally operators have more than one technology alternative to deploy in their network. Finding suitable technologies or architectures, which meet service requirements, as well as determining the location and volume of equipment/device for different technologies, is done via the architecture model. This allows operators to compare cost efficiency of various technology options in order to decide which way to go. For example, in case of WDM PON, the OLTs are located in CO, splitters or AWGs are placed in the RN and ONUs are installed at the user premises, all connected via fibers. Operators use techno-economic analysis as a method to compare the cost efficiency and the benefits of various technology options in order to decide which way to go.

3.1.2 Topology model

The structure in which various components of each technology are connected to each other is referred to as topology of the network. Network topology can be based on the ring, star, tree, mesh, etc. The demographical data of the area under study is also an important part of this model. Number of buildings, user density, size of the area, existing infrastructure, such as available ducts and many more parameters are also input for the topology model. The number of network nodes (e.g. CO, RN, cabinets, etc.) and their location, distances between the nodes and the type of equipment which should be located in each location, are the output data of this model. These parameters are fed to the network dimensioning tool.

3.1.3 Market model

Estimating the market related parameters such as user penetration and churn rates, operator's market share, area throughput, quality of service (QoS), etc., is very important step in the planning phase. These variables are used as the input for the market model, which in turn estimates the possible revenues and number of the connected users per year.

3.1.4 Network dimensioning tool

Dimensioning tool calculates the amount of required new infrastructure (fibers, ducts, hubs, etc.) and the volume of each component in various network locations in a yearly basis for any defined scenarios. The calculations are based on the results of aforementioned models (i.e. architecture, topology and market models). Moreover, operational parameters related to the human resource activities such as the traveling time of technicians or the installation time of the equipment are also calculated using this tool. All mentioned parameters are added to a file which in this thesis is referred to as the shopping list. This file is used as the input for the TCO model.

3.1.5 Cost model

The price of each component or the service fee is defined in this model that is used for calculating the total cost of ownership for any network. When estimating the price of equipment or human related resources, cost erosions must be considered. The price of components usually follows a declining trend due to the mass market production and increase of the market purchase, as well as the matureness of the technology. On the other hand, the human related services such as technicians' salaries are increasing per yearly basis. The price variation of the equipment in the time domain can be calculated via learning curve that is used in the industry to predict the reduction of the product cost. However, finding the right learning curve for each product is not an easy task [48]. Therefore, a linear model based on the Equation 3.1 can be used to include the impact of price erosion while calculating the total cost of ownership in order to simplify the calculations.

$$P_i = P_0 + \alpha P_{i-1} \qquad (3.1)$$

Where P_i represents the price in year i during network life cycle and P_0 is the initial price in year zero of the project. The coefficient of α denotes the cost change factor in time. This parameter has a negative value when calculating the hardware prices and a positive value for parameters such as energy cost or salaries. In reality α might vary in time, however in this thesis it is considered as a constant value during the network lifetime.

3.1.6 Total cost of ownership (TCO) model

This sub-chapter presents the proposed cost classification considered for the TCO calculations in this thesis (see Figure 3.2). The model includes all the costs incurred during the network life cycle, i.e., from the huge upfront investment required at the network deployment phase (capital expenditures), up to all the cost related to each operational process (operational expenditures). Some of the categories shown in the Figure 3.2 such as spectrum and fiber leasing are valid for calculating the TCO related to mobile applications (e.g., back/fronthaul) and are not needed for the fixed broadband access technologies.

In the following sub-chapter, we briefly introduce each cost factor shown in Figure 3.2. The equations proposed for calculating each cost element is presented in detail in **Paper VIII** of this thesis.

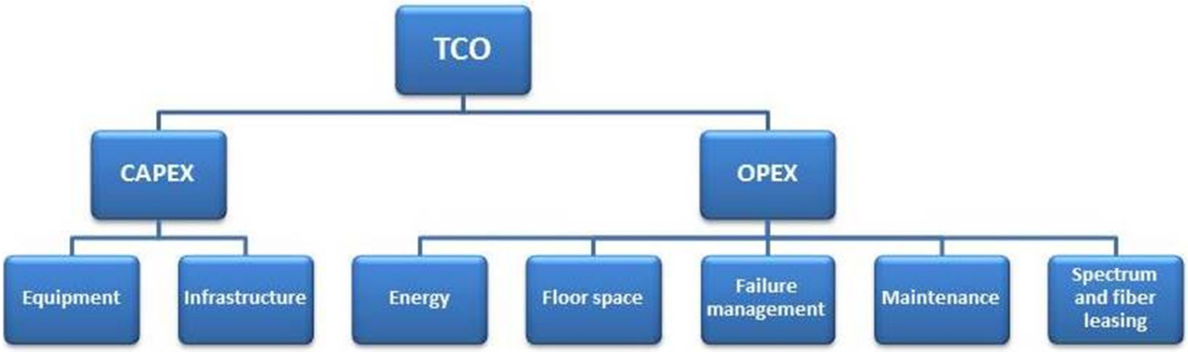

Figure 3.2. Total cost of ownership (TCO) cost classification

a) Capital expenditures (CAPEX):

CAPEX represent the required initial investment cost to deploy the access networks and are calculated by adding three following expenses together. The equipment cost in Figure 3.2 consists of two subcategories, namely "network equipment" and "equipment installation".

- *Network equipment*: This cost includes all the expenses related to purchasing the required equipment that is calculated based on the shopping list.
- *Equipment installation:* This element is a product of the total time needed to install the equipment including the travel time to/from the components location, the number of required technicians and their salaries. In the case of optical networks, fiber splicing expenses are also counted as a part of installation cost. The installation expenditure can differ a lot based on the various scenarios (e.g.

geographical locations) due to the technicians' salaries variation. This cost is usually high and cannot be ignored.

- *Infrastructure*: All the fiber/cable related expenditures in case of optical networks as well as tower mast installation for mounting the macro cells and microwave antennas for wireless deployments are considered as the infrastructure cost. This cost element includes the fee of purchasing the required infrastructure such as cables, in addition to the expenses of digging and burying the ducts and tower installation. This value is highly related to the network topology, amount of existing infrastructure, population density and some other aspects. In the cases where the operator leases the fiber instead of deploying its own infrastructure, a one-time initial fee is also considered as a part of this cost category.

The CAPEX per-user per year is defined via dividing the calculated yearly CAPEX by the number of connected customers on that year.

b) Operational expenditures (OPEX):

OPEX has been shown to be a very important factor of the TCO for the network operators [49]. This cost covers the expenses related to the network operation during its life time that is the period when the network is operable (the network lifetime is ended till it is replaced by a new technology). OPEX are usually calculated per yearly basis. The OPEX considered in **Paper I**, **II** and **III** consists of the expenditures presented below.

- *Failure Management* (FM). The FM 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 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 FM cost. MTTR is the average time between the occurrence of a failure and the moment when the reparation is finished [50].
- *Energy consumption.* The yearly energy consumption 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 the year.
- *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*: Any expenses related to yearly rental fee paid for placing the active equipment in the network or infrastructures such as microwave hubs is considered in this cost. For example, the equipment in the OLT side is placed in the racks located in the central office. The rental fee of these offices corresponds to the floor space. This expenditure is a product of the space required to place all the racks in the OLT side and any other network node by 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 with one shelf depends on the architecture and size of its equipment. So the number of racks is calculated via dividing the number of users associated to the CO by the number of users that can be served by each rack. The total space per rack (see Fiure 3.3) is equal to the sum of its bottom area (0.6 m * 0.3 m) and the required work space for a technician to stand in front of it (0.6 m *1.0 m) [51].

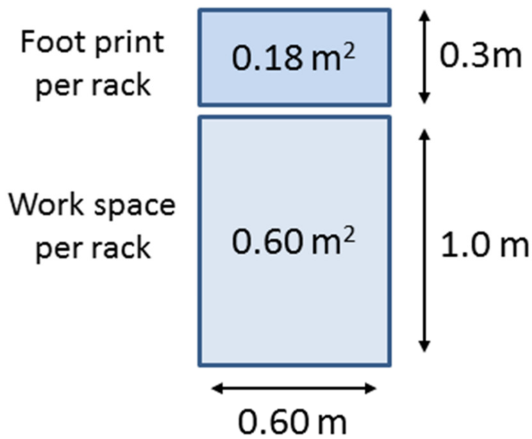

Figure 3.3. Floor space required for a rack including the working space [53]

In **Papers IIV** and **IIIV**, a fixed area is considered for each cabinet located in the field and hubs, which is multiplied with the yearly rental fee to calculate the floor space.

- *Spectrum and fiber leasing:* When calculating the cost of microwave-based backhaul networks, the yearly leasing fee for renting the spectrum per link is an important part of the TCO that is considered in this cost element. Moreover, in some cases operators might want to lease the fiber instead of deploying the infrastructure. In that case operators pay a one-time initial fee as well as a yearly cost for the maintenance and fault management of leased infrastructure. The yearly price of leasing is considered as part of this category. However, one-time initial fee is added to the infrastructure part of the CAPEX. This part of cost is mainly considered to support mobile networks.

- *Maintenance:* A regular maintenance routine is needed to keep the network up and running. This includes monitoring and testing the equipment, updating the software (including renewing licenses when needed), and the renewal of supporting components such as batteries, etc. All the expenses related to the aforementioned tasks are added together to calculate the maintenance fee.

3.1.7 Business model and scenario

This model describes the business environment such as various actors and the cooperation models between them. . Business actors can be categorized as passive infrastructure provider (PIP), network provider (NP), service provider (SP) and mobile network operator (MNO). For example, it is possible that the PIP deploys all the fiber infrastructure in a specific region, and then different NPs might lease the dark fiber and install its own network equipment. On the other hand, it is possible that the operator deploys its own infrastructure instead of renting it from other actors. Other important business related factors are the market share of each operator, open access model if any, regulations and the political restrictions, etc.

3.1.8 Techno-economic evaluation results

The feasibility of any projects can be decided using the static techno-economic analysis including cash flows (CF), net presented value (NPV), etc. OPEX and CAPEX calculated by using the presented TCO model, only show the pure expenses, where the possible income of the project is not considered. Cash flow refers to the amount of cash received (revenues) and spent during the network lifetime. After calculating the cash flows, we can estimate the NPV that is a standard parameter for analyzing the feasibility of a long-term project [52] and can be calculated via Equation 3.2. NPV indicates the amount of gain that a project brings to the invested money. If the NPV is negative, the project is typically recommended to be rejected in the planning phase to avoid financial loss.

$$NPV = \sum_{i=0}^{L_n} \frac{CF_i}{(1+r)^i} \quad (3.2)$$

Where, L_n, CF_i and r, denote network lifetime, cash flow in year i and the discount rate, respectively.

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 later 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 is defined as component availability. Availability of the equipment can be calculated using Equation 3.3 [53].

$$Av = 1 - \frac{MTTR}{MTBF} \qquad (3.3)$$

Where MTBF is the mean time between failures, which is equal to a sum of mean lifetime and mean time to repair MTTR (mean lifetime >> MTTR). MTBF (approximately = mean lifetime) of each component/fiber is defined by the device vendors while MTTR is an operator related parameter. Connection availability (Av_c) corresponds to the probability that the connection between the two end nodes of the network (in our case between the OLT and ONU) is operational. In some cases, connection unavailability ($UnAv_c$) is used to show the probability that a user loses its access to the network due to a failure and it can be calculated via Equation 3.4.

$$UnAv_c = 1 - Av_c \qquad (3.4)$$

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 the reliability point of view, meaning that in order to have an operable system all components in series configuration should be working. Equation 3.5 presents an approximate model for calculating the unavailability of the serial configuration assuming that $UnAv_i$ are very small. In the cases where there are backup components/fibers which are able to protect each other, connection unavailability can be calculated via Formula 3.6. This is referred to as a parallel connection from the reliability point of view and a parallel system is unavailable when both working and backup components/fibers fail.

$$UnAv_{series} = UnAv_1 + UnAv_2 + \ldots + UnAv_n \qquad (3.5)$$

$$UnAv_{parallel} = UnAv_1 \times UnAv_2 \times \ldots \times UnAv_n \qquad (3.6)$$

Formula 3.3 could be used to define the fiber availability per kilometer. Then the total availability of a fiber link can be obtained via equation 3.7, where Av_i and L denote the fiber availability per kilometer and the length of the fiber link in kilometers, respectively.

$$Av_{fiber} = (Av_i)^L \qquad (3.7)$$

3.2.2 Failure impact factor (FIF)

FIF is a reliability performance parameter reflecting the operators' point of view. This metric was introduced in **Paper V** of this thesis. Distinct components' breakdowns can 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 for the case of FTTH. Compared to availability, FIF can be a better measure to reflect the impact of failures of various network segments, and can be calculated for each component using equation 3.8.

$$FIF_{component} = CAF \times UnAv \tag{3.8}$$

Where the CAF denotes the number of customers affected by a single failure in the network. The FIF of the end-to-end connection consisting of a sequence of components can be calculated by:

$$FIF_{EtoE} = \sum FIF_{component\ i} \tag{3.9}$$

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

3.3 Network planning tools

To gain a general idea regarding the network investment cost and the other network performance (e.g., reliability) an average length for the fibers and trenching can be considered for the preliminary assessments. However, a more detailed model is needed to have a complete and accurate evaluation of the TCO and other network performance parameters. For example, the user distribution in the area can affect the fiber layout of the network, amount of required cables and ducts and possible sharing portion of resources. To consider these effects, proper network dimensioning models are needed. Most of the available studies use either the geometric models or the geographical planning tools. A brief description of the available geometric models and geographical network planning tools can be found in the following sub-chapters.

3.3.1 Geometric models

Several geometric models can be found in the literature for estimating the amount of the required infrastructure while analyzing the various network performance parameters in the access networks. These models are normally based on an uniform distribution of the nodes such as buildings, cabinets, etc. Triangle model [54] 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 infrastructure. This method 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 always true in real deployments.

Simplified street length (SSL) [55] model is another existing geometric model with customers uniformly distributed over a square 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 many European cities such as the downtown district (see Figure 3.4) in Barcelona in Spain. This makes Manhattan model suitable as a dimensioning tool for the dense urban scenarios, and it is the reason we used this model for our studies on dense urban areas.

Figure 3.4. Aerial view of the Eixample district in Barcelona [58].

In **Papers III** and **IV,** 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, eight 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 3.5).

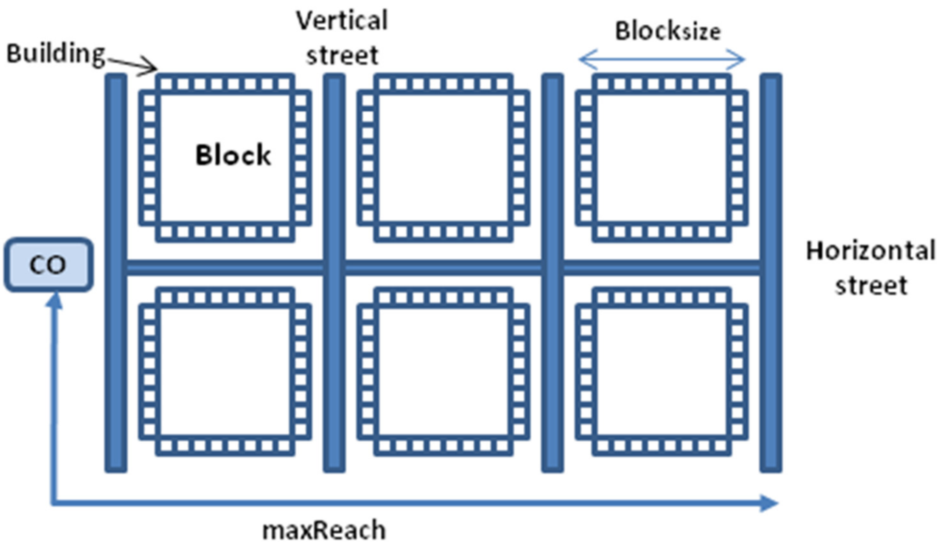

Figure 3.5. A schematic view of the considered Manhattan model

The number of buildings covered by one CO depends on the maximum reach of the considered access network technology, and it is calculated using Formula 3.10. The maxReach denotes the maximum reach for a given configuration of a certain network architecture. The $Block_{size}$ represents the length of one block side in kilometers, V_{block} and H_{block} denote the number of vertical and horizontal blocks, respectively.

$$\frac{maxReach}{Block_{size}} > (H_{block} + \frac{V_{block}}{2}) \tag{3.10}$$

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. A similar methodology is used for building placement in **Papers IIV** and **IIIV** to define the parameters for the case study.

3.3.2 Geographical network planning tool

There are several homemade or commercial network planning tools, which take the real geographical data for a certain area as the input and give the optimal fiber and trenching layout as well as the number of RNs needed to cover the whole service area as its output. The geographical information of the buildings and streets can be extracted from the available data sets e.g. either from commercial applications such as Google map or open source tools such as Openstreetmap [57].

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. Finding a suitable fiber path between customer premises and RNs as well as the cable route between RNs and CO could be done via modified versions of the Dijkstra algorithm [58][59]. Figure 3.6 shows an example output of a geographical planning tool. Logical model of an access network based on PON is shown in Figure 3.6(a), while the real fiber path and the exact location of the nodes corresponding to this logical topology are shown in Figure 3.6(b).

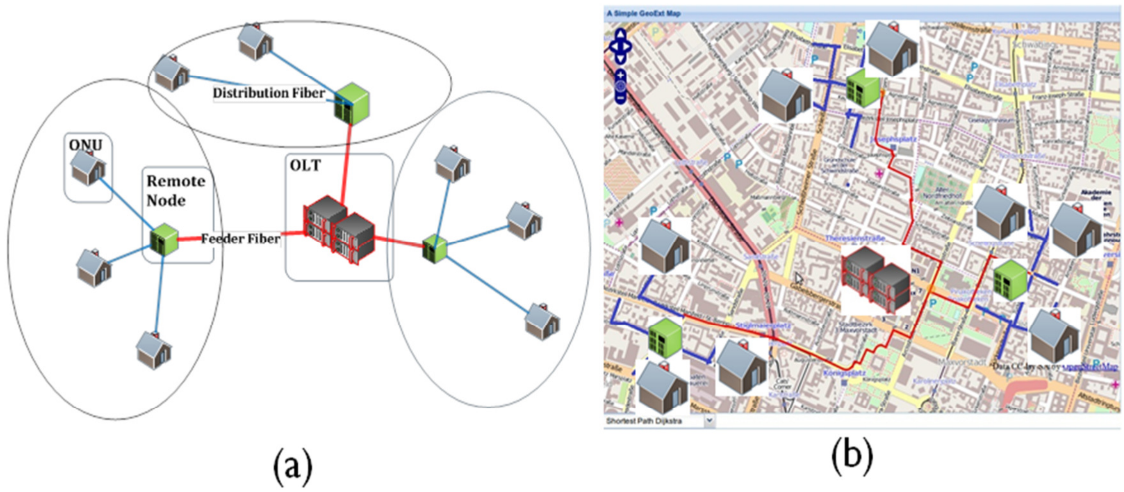

Figure 3.6. (a) Logical model of a PON (b) Geographical model of the same PON in a real environment [62]

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 the case of large service areas.

3.4 Network simulator 2 (NS2)

In **Papers I** and **II,** we investigated the performance of various optical access technologies by running simulations in the packet level. To do this, we developed a tailored simulation tool based on network simulator 2 (NS2) which let us quantitatively evaluate the efficiency and scalability of the proposed methods and compare various architectures.

NS2 is an event-driven and real-time network simulator which makes it possible to simulate the dynamic behavior of flow and congestion control scheme at packet level [61]. It is one of the most popular simulators used in academia as it is an open source simulator, and it’s constantly updated by a large user base. NS2 based simulator allowed us to process dynamic traffic distribution and hence accurately measure bandwidth usage on each link in any arbitrary short period of time. Tha packet level simulations enables us to see the influence of layer two (L2) protocols on the network resource usage that is not possible to obtain by the simple flow based simulators (such as the one used in [14]). NS2 is based on two languages (see Figure 3.7); an object oriented simulator, written in C++, and an OTcl interpreter, used to execute users command scripts.

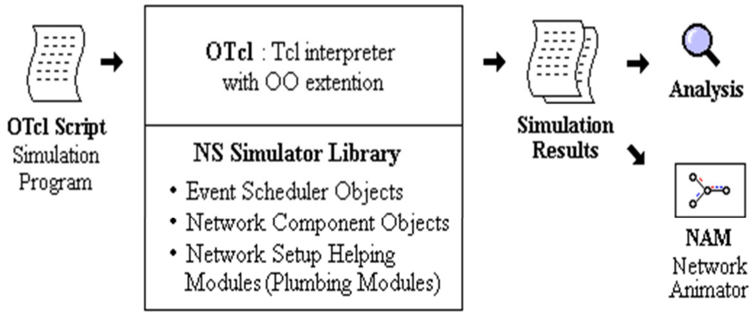

Figure 3.7. Simplified User's View of NS2 [63]

Implementing modules using C++ leads to more efficiency and faster execution time for simulations. On the other hand, OTcl script is used as the user interface in order to define the network topology, and scenarios to be simulated.

As NS2 is an open source tool, each user can add their own module based on their need. Therefore, in **Paper I**, we extend NS2 by implementing several application-level modules in order to simulate video distribution application and user behaviors considering peer-to-peer distribution algorithm. In **Paper II**, we further extend the NS2 based simulator used in **Paper I**, by adding a module supporting TDMA algorithm (based on GPON standard). This algorithm controls the upstream access to a shared medium for TDM based PON to have a collision-free network.

Chapter 4

Traffic Locality in Optical Access Networks

The future upgrade of user capacity in the access network can in turn lead to a huge traffic increase in the aggregation and core segments. Therefore, the core network might become the bottleneck for providing higher bandwidth per user. One way to address this problem is to keep the traffic locally, i.e., in the access network area, as much as possible. It would prevent unnecessary "feeding" the core network with all the local traffic from the access segment. A simple and scalable way for keeping the traffic local is to use peer-to-peer (P2P) technology, instead of traditional client-server based models.

P2P technology can be an efficient solution for the distribution of bulky internet files such as videos with large user interest. In a P2P application, each end user acts both as the server and the client. Hence there is no need to install expensive servers at the operator's side. Also, since every node can provide data, they can serve as backup for each other in case of failures.

P2P applications are highly scalable and efficient for large volume content distribution, but its traffic can be very expensive for Internet providers due to the lack of a standard way to keep it locally. In practice, it happens frequently that P2P data is downloaded or uploaded at high cost over the links of the other Internet providers' networks, despite of its availability inside the end user's own Internet service provider (ISP). To avoid unnecessary transit of P2P traffic among multiple ISPs, different locality–aware content fetching solutions have been proposed [21][63], aiming to enhance the locality of P2P traffic independently from the architecture of the network. However, none of the studies have considered the impact of deploying locality-aware schemes on the network resource utilization and its possible savings occurred in various network architectures.

Based on the aforementioned highlights, P2P traffics will constitute a considerable portion of Internet traffics in the future. Therefore, considering an efficient way to handle this type of traffic while designing next generation broadband access solutions, might lead to a huge saving for the providers in terms of deployment cost especially in the core/aggregation networks.

Thus, this chapter address the challenges regarding the traffic growth in the core/aggregation networks as a result of increasing bandwidth demand per user by keeping the Internet traffic inside the access networks as much as possible. The change of traffic patterns due to employing a locality–aware content distribution scheme can have a very high impact on the architecture of access and metro networks. Highly consolidated architectures with the central access nodes with large capacities located far from the users

may offer a reduction of operational cost, but can have difficulty to handle local traffic in an efficient way and hence cannot off-load the traffic in metro and core network links. On the other hand, utilizing algorithm for localizing the traffic can make it possible to upgrade the access network capacity without the need of increasing the bandwidth in aggregation networks, which has a high potential to bring CAPEX saving. With this in mind, in **Papers I** and **II,** we investigate the benefits of off-loading the aggregation/core networks by using a locality-aware content fetching strategy for different access networks. This helps providers to upgrade user capacity without the need of extra investment for expansion of the aggregation segment. Furthermore, we concentrated on a preliminary set of next generation optical access network architectures and evaluated their capabilities in accommodating P2P video traffic. The contributions of **Papers I** and **II** are summarized in the following sub-chapters.

4.1 Resource saving in core/aggregation network using P2P applications

In **Paper I** of this thesis, we propose a locality–aware content fetching strategy for the P2P applications and investigate the influence of systems utilizing locally stored content on the traffic load distribution between core, aggregation and access networks. The proposed algorithm is based on the cooperation between the P2P application provider and the network operator, where the application has a list of all IP addresses of the nodes and their geographical location. In this way, the network operator can control the P2P traffic and increase the traffic locality while the service provider can offer higher quality of experience (e.g. lower delay) for the users.

Moreover, we quantitatively evaluate the improvement of the resource utilization and possible bandwidth saving in the aggregation/core network segments based on the proposed locality-awareness scheme.

In this work, we simulate an access and aggregation network architecture with four-level of hierarchy for separation of local traffic in different levels (see Figure 4.1). The edge nodes of the core network (point of presence), i.e., edge routers R1-R4, are connected in a ring. Each router is attached to several layer2/layer3 (L2/L3) metro switches. Multiple access switches are associated to each L2/L3 switch and finally at the tree leaf end–users are connected to one of the access switches. The network is divided to four regions, also referred to as the aggregations levels. The peers are in Region 0 (R0) for a given end–user if they are under the same access switch in the first aggregation level. If the peers belong to the same second aggregation level, i.e., L2/L3 switch but via two different access switches, they are in Region 1. The peers connected to the same router but through two distinct L2/L3 switches are located in Region 2 of the source node.

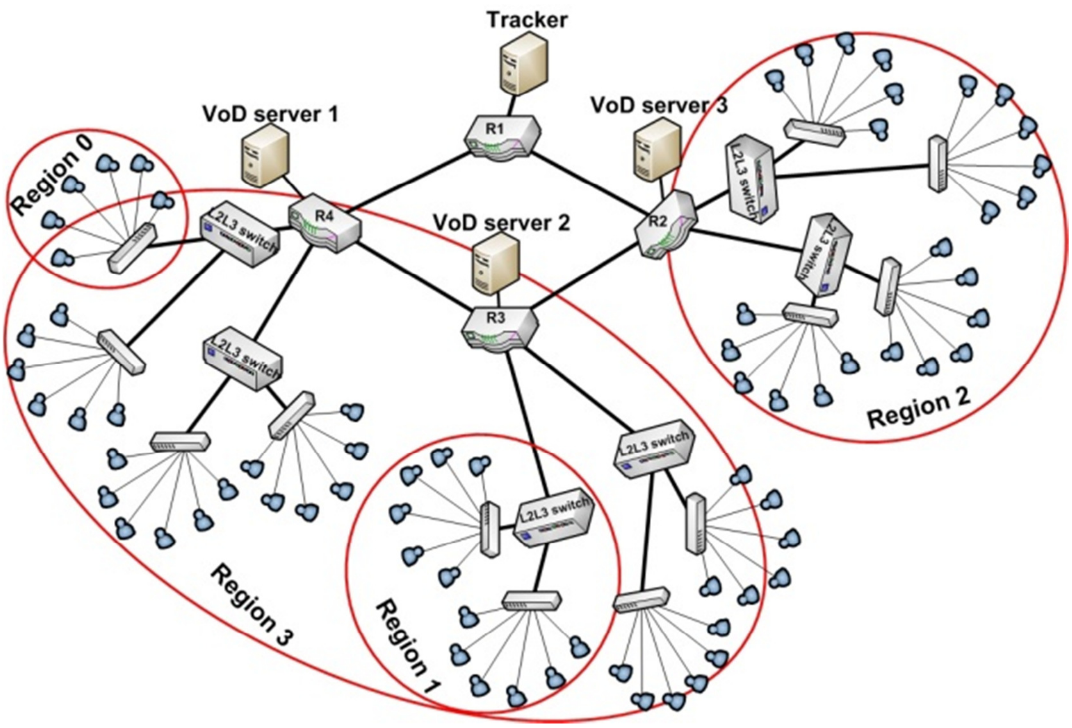

Figure 4.1. Network physical topology including regions

Based on the statistics presented in [15], currently more than 60% of the Internet traffic is related to the video files, and hence we mainly consider video applications for this study. Each user is equipped with a set-top box (STB), which is responsible for downloading and broadcasting the movies on user request. During the simulation time, users randomly start watching videos from a predefined list of movies. Each movie is downloaded to the STB via P2P technique from other users who already have the desired content in their boxes. In order to see the impact of traffic localization on the resource utilization of various network segments, we have implemented a peer selection algorithm in our simulator which is based on the network simulator 2 (NS2). The proposed algorithm considers the geographical location of the peers while selecting the source for downloading in order to keep the traffic local inside the access network. We investigate the relation between the resource saving and the amount of local traffic in the network by comparing two scenarios: Scenario 1 uses random peer selection approach while scenario 2 utilizes the proposed locality–aware peer selection for P2P application.

When a peering query arrives, the tracker sends back a list of IP addresses of peers containing desired content using a recursive search in its database. The tracker has a list of all the active nodes in the network with a list of their content. The peers are chosen randomly in case of Scenario 1, while for Scenario 2 with the proposed locality-aware algorithm they are ordered according to the distance from the requesting node. Here the distance is defined as the number of aggregation nodes in the network that traffic needs to pass between the source and destination nodes. For example, in case of the network topology presented in Figure 4.1, nodes located in Region 0 have a distance of one from each other as they are connected to the same access switch. The goal of this algorithm is to find enough peers in the vicinity of the source node to limit the P2P traffic passing the aggregation/core network as much as possible.

The simulation results presented in Paper I, show that providers can save a considerable amount of capacity on the core network links and off-load the traffic from higher aggregation levels by keeping the local traffic in the access network close to the users utilizing the locality-aware content fetching scheme.

4.2 Performance evaluation of optical access architectures considering locality-aware P2P scheme

As studied in **Paper I**, the network providers can reduce the traffic passing the core and aggregation networks, via an appropriate locality-aware scheme keeping the P2P traffic close to the users. However, the amount of saving can differ according to the network architectures and the number of the aggregation levels between core edge and end users. Various optical access network architectures perform differently in accommodating the P2P traffic. Hence, it is important to study these differences in order to identify the best architecture options for capacity offloading in the core network. By deploying a proper architecture in the access segment along with an efficient traffic locality-awareness strategy, the extra investment for capacity upgrade of the core network aiming to support the future traffic expansion of users can be optimized.

Therefore, in **Paper II**, we analyze the efficiency of supporting locality-aware P2P video distribution algorithm in three main candidates of next generation optical access network architectures, i.e., AON, WDM PON and TWDM PON. In this work, we evaluate the impact of traffic dynamicity of P2P applications caused by the multiplexing techniques such as time division multiple access (TDMA) of various access architectures on the power consumption and network resource utilization.

Our goal is to provide important design guidelines for the next generation broadband access architectures while minimizing the need for the core network upgrade.

The simulation setup regarding video distribution and the user behaviors are the same as the one introduced in **Paper I**. The proposed locality-aware peer selection scheme is used to find the source of download for the users. Therefore, each user downloads the desired movie from its neighbors when possible. Figure 4.2, shows the schematic view of the considered network topologies along with the mapping to the regions shown in Figure 4.1.

In the case of AON, when a user requests to download a movie, the tracker starts the process by searching the peers connected to the same Ethernet switch at the RN for the required content. If it cannot find a sufficient number of peers on this level, the tracker checks the contents at the ONUs connected to the same OLT but to the different RNs. However, as one can see in Figure 4.2, PONs have one less aggregation level compared to the AON, due to the lack of switching capabilities in the RN. So the traffic needs to travel at least up to the central office. More detail on the number of nodes on each level and the simulation scenarios can be found in **Paper II** of this thesis.

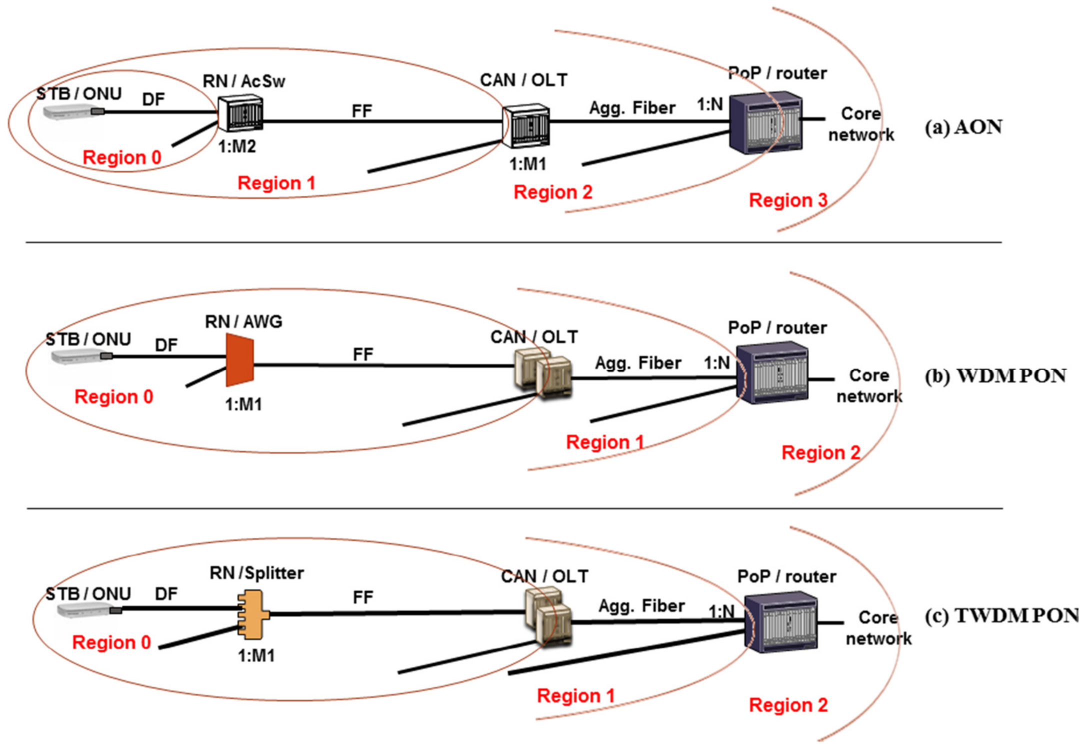

Figure 4.2. Schematic view of (a) AON, (b) WDM PON, (c) TWDM PON, and their mapping to the local regions

The amount of P2P traffic passing each link in one microsecond is logged during the simulation time. The total amount of traffic on the aggregation fiber link is similar in all the three considered architectures, which means that they have almost equal capability to offload traffic in aggregation/core networks by employing P2P applications. However, they perform differently in terms of instant traffic intensity, which significantly affects the energy consumption and required switching capacity in various nodes. It is mainly because of the variations in the topologies and the applied resource sharing mechanisms.

The total required switching capacity for handling peak traffic in different locations of the network is also measured for each architecture**.** Ethernet switches in AON and TDMA protocol in TWDM PON cause that these two architectures have a more steady traffic flow on different links compared to WDM PON. The results show that WDM PON needs nearly three times larger switching capacity to handle the same total amount of P2P traffic compared to the other two architectures. This is a consequence of the large bursts of data that are transmitted in WDM PONs due to dedicated high capacity links per user. As AON has one more aggregation level compared to the other two architectures, its switching function should be also located at RN, which leads to the higher operational complexity due to the active components in the field.

Based on the results related to the instant traffic on the links, there are some time slots during the transmission of P2P traffic in which the links are idle, offering the possibility to turn off the transceivers on the user side if an energy efficient scheme is applied. Therefore, we evaluate the power consumed by the active components in the access network from CAN down to the ONUs to carry out P2P traffic and investigate the potential energy saving by using low-power mode. Energy consumption became one of the main concerns of the providers and the ICT sector and hence it is one of the key performance parameters of any architecture or technology to be studied.

The power consumption of each active device is divided into two categories: the constant offset power, which is not affected by the traffic, and the power usage that is traffic dependent. The later part can be switched off to save energy when there is no traffic passing the devices or the links. For example the ONU transceivers can be turned off if no data is sent or received by the user. This leads to two modes of operation for each component, namely active and sleep.

The results show that WDM PON could obtain the highest power reduction if the sleep mode is employed, due to the fact that the peers finish downloading their data relatively fast and therefore the transceivers can be in the sleep mode for a longer time. AON has the highest power consumption in the field caused by the active Ethernet switches in the RN. TWDM PON is the most power efficient architecture from the operators' point of view, showing the lowest power consumed in the outside plant.

Table 4.1 summarizes the performance evaluation of three architectures regarding the offloading capability, switching capacity and power consumption based on the results of **Paper II**.

Table 4.1. Performance evaluation summary

	Offloading capability	Required switching capacity	Total power saving	Power consumed by provider
AON	very good	Low	Poor	High
TWDM PON	very good	Low	Good	Low
WDM PON	very good	High	Very good	Medium

Our results reveal that both active and passive architectures have good ability to localize P2P traffic, whereas they show distinct performance with respect to the other aforementioned aspects. Considering the overall performance evaluation, it is shown that PONs are more promising options than AON for the future broadband access, thanks to their low energy consumption and service quality while offering the same capability of bandwidth saving, where locality-aware P2P strategy is applied.

Chapter 5

Reliable Optical Access Network Architectures

Optical access networks are widely deployed because of their high capacity. Fiber-based technologies can cover large service areas due to their 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 a large number of end users by a single failure compared to the conventional copper-based architectures. In addition, customers rely more and more on the Internet connection in their daily lives and have more difficult to tolerate long service interruption. 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 increase. 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 which are shared among many customers 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 resilience should be carefully evaluated and minimized.

The cost efficient method to protect the network is very dependent on the component technology, physical topology, fiber layout, and customers' density in the service area. As the trenching expenses are usually the most costly part of the network deployment, a suitable design of fiber layout could significantly decrease the protection expenditures. However, this impact 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 the 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 some variants of the digital subscriber line (DSL) are available (brownfield), the amount of required new trenching could be lower compared to a greenfield scenario without any available resources.

According to Table 2.1 and Chapter 2 of this thesis, WDM-based PONs are the most energy efficient candidate fulfilling all the requirements of NGOA networks such as high capacity per user, large client count, long passive reach, etc. Therefore, in the first part of this sub-chapter including the contribution of **Papers III** and **IV**, two WDM-based optical access architectures, namely UDWDM and HPON, are evaluated in terms of the cost of offering resilience. This chapter also contains the contributions presented in **Papers V** and **VI** focusing on the HPON as one of the main candidates of NGOA networks. These papers provide a comprehensive study on finding the most cost efficient protection schemes for HPON.

5.1 Cost versus reliability in WDM-based NGOA architectures

In this sub-chapter, the expenses of providing protection on the total cost of ownership for two considered NGOA architectures, namely; UDWDM PON and HPON are presented. The results are calculated for a dense urban area, and they are based on the outcomes of **Papers III** and **IV**. Different protection upgrade strategies and fiber layout design have been introduced aiming to maximize utilization of the available infrastructure, which leads to a considerable saving in the CAPEX.

In order to support large number of clients per feeder fiber, two stages of splitting points are considered for each architecture. Based on the reach requirements and the class of transmitters used in the field various configurations of splitting ratios can be implemented in each remote node for every optical access alternative. To see the influence of client count per FF on the TCO, three variants (See Table 5.1) of each architecture have been studied.

Table 5.1. Considered architecture variants

Architecture variant	Number of AWG output ports in RN1	Number of splitter output ports in RN2	Number of ONUs per FF
HPON 1:40/1:8	40	8	320
HPON 1:40/1:16	40	16	640
HPON 1:80/1:16	80	16	1280
UDWDM 1:40/1:8	40	8	320
UDWDM 1:80/1:8	80	8	640
UDWDM 1:20/1:32	20	32	640

The presented cost results include both capital (CAPEX) and operational (OPEX) expenditures. The CAPEX consists of the fees related to the network equipment, installation and infrastructure. 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.

The placement of the buildings considered for the cost calculations is based on the Manhattan network model presented in Chapter 3. Different RNs distribution has been taken into account depending on the splitting ratio of AWGs and power splitters. For example, in the scenario with 1:8 power splitter in RN2, one block side is covered with one splitter, meaning that eight RN2s are co-located in a street cabinet as depicted in Figure 5.1. There are two levels of splitting points leading to three fiber segments referred to as FF, DF, and LMF. In our study FF is duplicated, since network operators typically want to offer protection down to RN1 in order to avoid the risk that a large number of ONUs would be affected by a single failure. The proposed FF layout and RNs replacement aim to minimize the length of required feeder fibers (see Figure 5.1).

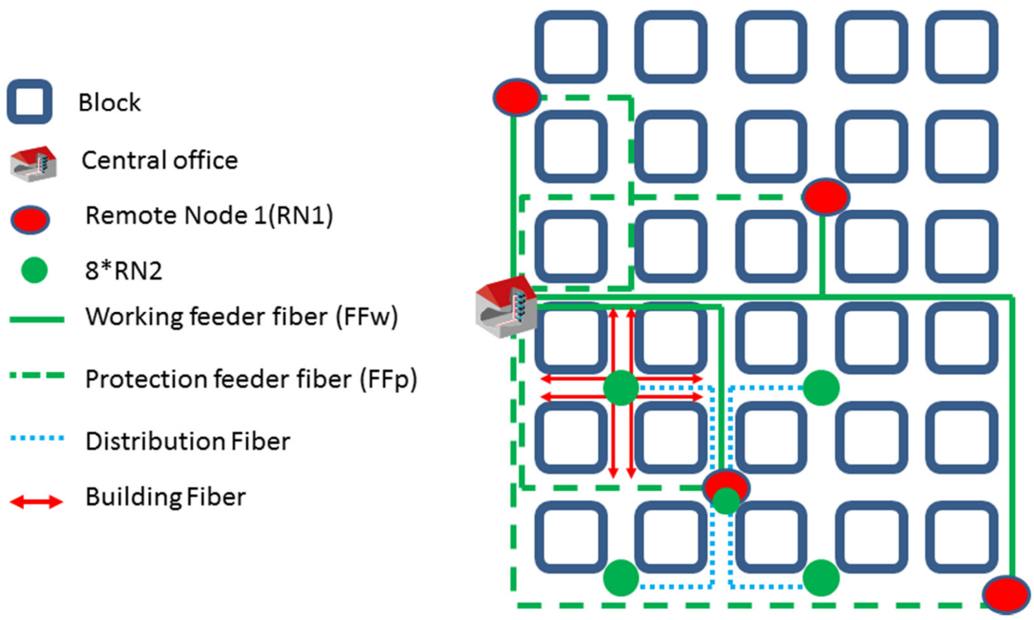

Figure 5.1. Example of proposed fiber layout for 1:40/1:8 variants [Paper IV]

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

The OPEX and CAPEX per building for a network operational time of 20 years considering no protection (UP) and protection up to the FF (P) are shown in Figure 5.2. The results show that in dense urban areas, the CAPEX is not differing significantly for various NGOA technologies and their variants, due to the high sharing cost among users. Moreover, the proposed fiber layout makes it possible to install the protection feeder fibers inside the available ducts, leading to very small increase of CAPEX in case of the protected networks. It can be also observed that the penalty cost for unprotected solutions is one of the most expensive elements of TCO. The penalty cost can be higher than the total CAPEX in some of the scenarios. Our results confirm that with a proper fiber layout design, minor extra investment for protection of NGOA networks can offer a significant saving on failure related operational cost when penalties are considered.

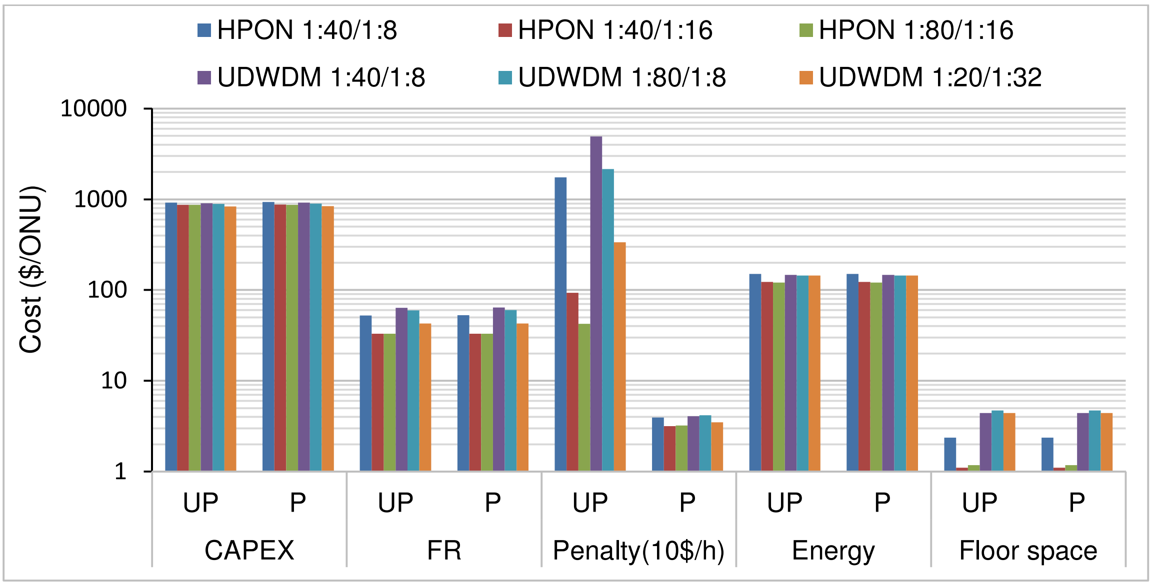

Figure 5.2. Cost elements of TCO [$/ONU] for a network operational time of 20 years

Figure 5.2 also shows that the impact that failure reparation has on the total cost per customer is rather low. The reason is that in a dense urban area, a large number of users are covered with a few kilometers of optical cables and hence, the failure reparation is highly shared. Finally, it can be seen that providing resilience does not affect the other parts of OPEX such as the expenses related to the energy consumption and the floor space.

5.2 Cost-efficient protection schemes for HPON variants

For several reasons network operators prefer to have a single technology in their network. 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, WDM-PON offers long passive reach but the connected number of clients per feeder fiber is limited to the amount of available wavelengths. 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 in addition to being cost and energy efficient. All these benefits make this architecture a promising NGOA candidate.

In **Papers V** and **VI**, three HPON variants which are presented in Chapter 2 of this thesis, namely wavelength selective (W-Selective), wavelength split (W-Split), and wavelength switched (W-Switch), are analyzed.

These variants perform differently with respect to the cost of deployment, reliability performance and flexibility of resource allocations. W-Switch and W-Selective are not feasible to be deployed in the rural areas 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 allows co-existence of these approaches in the same service area to meet the various end users requirements and geographical constraints.

In the first part of this sub-chapter**,** the segment of the HPON with low availability and high impact failure are identified. Leveraging on these findings, the study is further extended by proposing two resilience mechanisms for HPON considering protection up to the first remote node. Then the proposed resilience architectures are evaluated in the 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 this paper, which indicates the impact of a single failure on the network reliability and correlates with the number of affected users. More details on how to calculate FIF and unavailability can be found in Chapter 3.

This study is then extended 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 proposed access network architecture is able to accommodate different user profiles with various reliability performance requirements while offering a minimum extra cost. The additional expenses needed to offer 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 is the main concern while designing the fiber layout. As the cost studies are highly dependent on the considered values and the assumptions, sensitivity analysis may be useful to assess the impact of variations in the input parameters on the cost results. Thus, this sub-chapter also includes a sensitivity analysis in respect to the CAPEX fluctuations caused by varied density of enterprises in the area.

5.2.1 Proposed reliable architecture

Due to the high cost of providing backup resources it is not feasible to offer end-to-end protection for all users. Therefore, the first step towards designing a cost-efficient reliable architecture is to identify the most risky parts of the network that should be protected in order to provide an acceptable level of service availability to the customers. In this regard, this study begins with calculating the unavailability and FIF for every component and fiber segment of the access network for all tree considered HPON variants. The initial results demonstrate that the OLT in all cases has poor reliability as it is an active component, and it is shared among many users. Feeder fiber that is normally longer than several kilometers even in dense urban area, is also a threat for the network resilience, since it is shared among a large number of users. Consequently, feeder sections of the access network (including OLT and feeder fiber) are identified as the most critical parts where the protection is essential in order to reach an acceptable level of unavailability and FIF values.

Based on these primary outcomes, two novel protection schemes are proposed in order to decrease the impact of a single failure in the network (see Figure 5.3).

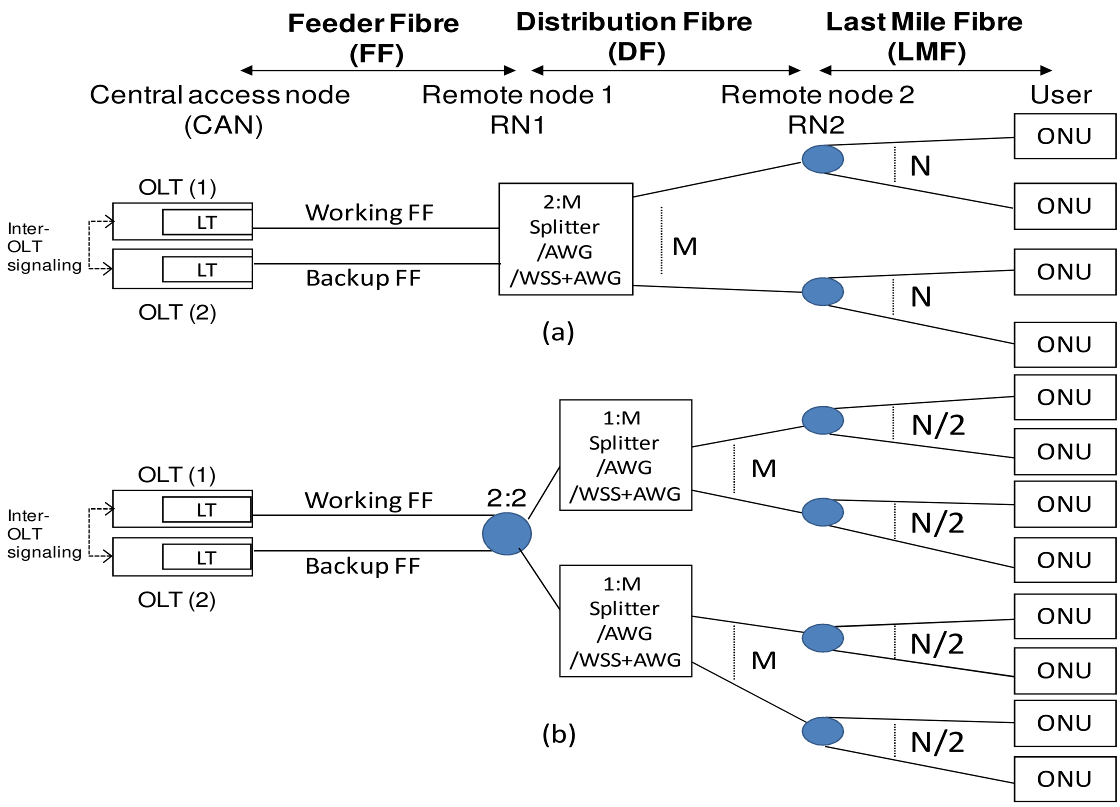

Figure 5.3. Proposed reliable architectures for all variants of HPON (a) without 3dB splitter (Wo 3dB), (b) with 3dB splitter (W 3dB) [Paper V]

Both mechanisms are based on duplicated OLTs and FFs. Thus they are identical up to the first remote node. In the first protected scheme (see Figure 5.3(a)), working and backup FFs are directly connected to the RN1 utilizing a 2:M component replacing the 1:M device used as the first splitting points in unprotected network. In the second resilient architecture (see Figure 5.3(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 into two parallel segments, each of which has one splitting device in RN1 supporting half of the PON users. However, in order to cover the equal number of customers with the same OLT in both protection schemes, the splitting ratio of the RN2s in the second scheme is divided by two (2×M×N/2= M×N).

In order to see the reliability improvements of the proposed schemes, the FIF and connection availability are then calculated for different scenarios, i.e., dense urban, urban and rural. The results demonstrate that adding protection up the first remote node decreases the FIF with at least one order of magnitude, in all the cases. However, the reliability performance of the HPON variants differs slightly based on the components located in the remote nodes and the considered scenario.

In general, protected architectures based on both proposed schemes are able to provide an acceptable level of FIF (lower than 0.1) and connection availability (> 99.95%) for the residential users. Typically, this type of users can tolerate some hours of service disconnection during a year without encountering any significant problems. On the other hand, large enterprises who rely on the uninterrupted Internet access in their businesses normally have much higher availability requirements than residential customers. Hence they are willing to pay extra to get more reliable service.

According to the reliability performance calculations of the proposed resilience schemes protection up to the first RN cannot offer high connection availability, e.g., 4 nines (99.99%). To provide a good reliability performance to business users, a straightfoward way is to provide a dedicated disjoint point-to-point connection realizing end-to-end (E-to-E) protection. This solution has the drawback of very high deployment cost. Besides, it requires running two separate access infrastructures for business and residential users, resepectively.

To address this issue we propose an architecture (see Figure 5.4) with the objective of co-locating the fully protected business users and residential customers with partial protection in the same PON, while minimizing the required extra investment for protection upgrade. Using our proposed scheme, it is possible to upgrade the connection availability of any user based on their request if they are willing to pay extra.

The unprotected HPON architecture is slightly modified in the distribution part of the access network (Figure 5.4(a)).

Dividing the distribution segment of the network into two parallel sections leads to an architecture, which can provide a cost efficient resilience mechanism for E-to-E protection of some selected users per PON (Figure 5.4).

As it is aforementioned, offering resilience up to the RN1 is required to lower the probability that a large number of users get disconnected by a single failure. Therefore, we used the scheme depicted in Figure 5.4(b) to increase the reliability performance of the access network for all the users. The structure is very similar to the one presented in Figure 5.3, except replacing the 2:2 coupler with two 1:2 couplers (Prot1) in order to remove it avoiding a single point of failure.

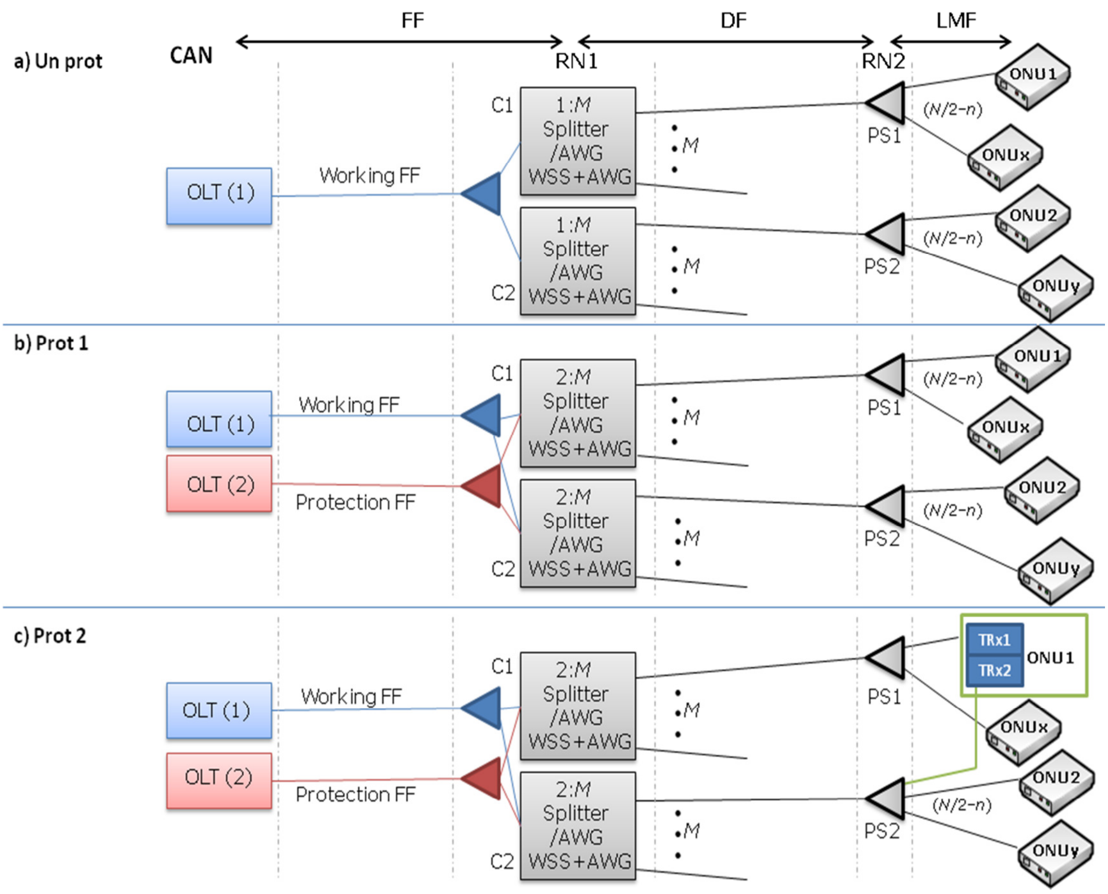

Figure 5.4. (a) unprotected scheme, (b) protection up to RN1 (Prot1) and (c) E-to-E protection for business users (Prot2), for HPON variants [Paper VI]

Figure 5.4(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. 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. The splitter in the secondary RN2 (e.g. PS2 in Figure 5.4) should be connected to the disjoint component at RN1 (shown by green in the Figure 5.4(c)). In order 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 effort of digging fibers can be minimized.

The reliability performance of the proposed architectures is then assessed in a dense urban area, which typically have high density of both business and residential users. The result shows that the connection availability higher than 99.99% can be reached for the business users, utilizing proposed E-to-E protection scheme, which is in line with the requirement of this user profile.

5.2.2 Protection cost assessment

As the money invested in the access network should be affordable for the residential users and small/medium sized enterprises with limited budget, the cost efficiency of protection schemes turn to an important design factor. Hence, minimizing the extra investment for offering resiliency is another criteria considered in the design of proposed protected architectures (Prot1 and Prot2).

In order to show the cost efficiency of our schemes, the aforementioned HPON variants are further evaluated, regarding the extra expenses of providing protection considering different reliability upgrade roadmaps.

Various network upgrade paths can be considered towards the proposed reliable architectures, depending on the conditions and regulations, which impact the investment cost. The influence of migration strategies on the cost while implementing the proposed reliable architectures, are evaluated considering three protection upgrade approaches starting from greenfield, referred to as A1, A2 and A3 (see Figure 5.5).

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 failure. Afterwards, with appearance of business users who require a more reliable connection and are willing to pay for the extra cost, Prot2 scheme can be deployed (A1:S3 in Figure 5.5).

In some occasions, it is more beneficial to deploy the protection resources 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 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 two (A2) and upgrade the network on per-user basis when requested (A2: S2).

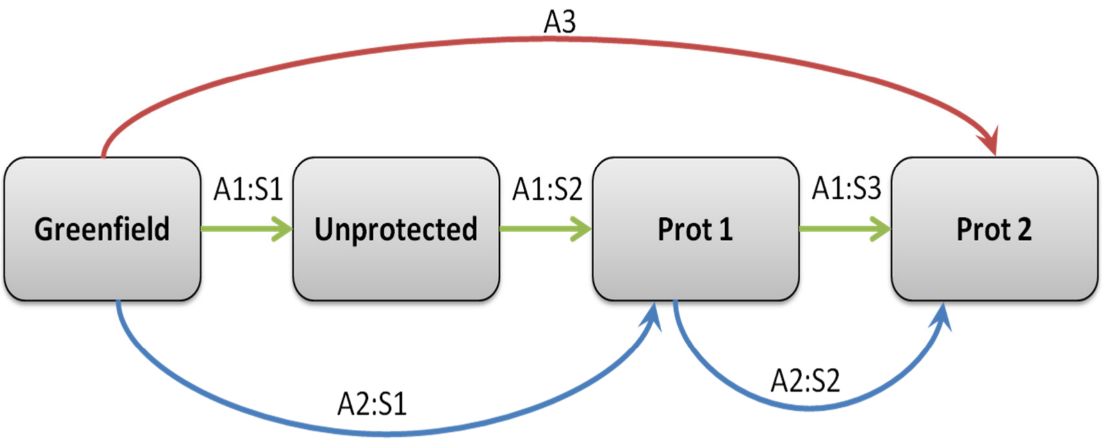

Figure 5.5. Protection upgrades paths

The required investment cost (CAPEX) for business and residential users following the aforementioned planning approaches for the HPON variants is presented in Figure 5.6. The results are based on the cost unit (CU), which corresponds to approximately 50 Euro.

According to the calculated 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 a large number of customers experiencing service interruption simultaneously. Moreover, Figure 5.6, represents that the CAPEX is nearly doubled for business users by adding a disjoint backup path in the distribution part, as a result of the high digging costs, which is shared among few customers. However, the total cost is much lower compared to the conventional dedicated connections for enterprises, as both residential and business users are sharing the same access network.

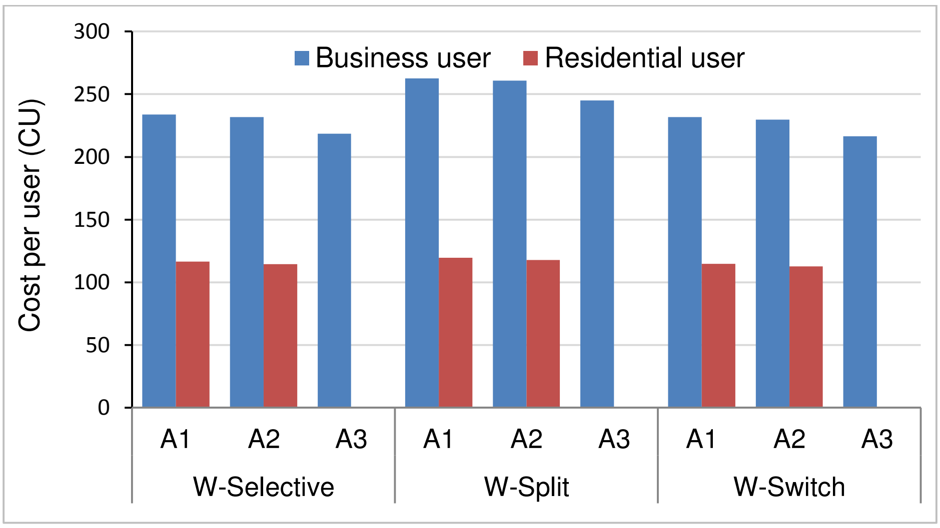

Figure 5.6: CAPEX for protected HPON architectures considering three migration approaches.

Regarding the protection upgrade path, the cost study shows that more number of steps in the network deployment slightly increases the cost for each user. A3 gives the minimum total CAPEX among all the considered approaches, though a larger investment is needed in the first year.

As the cost of proposed end-to-end scheme might depend on the density of business users, we have also done a sensitivity analysis of the variation in the deployment cost cuased by the changes in the percentage of business users in the area. The results shown in Paper VI of this thesis confirm the high dependency of the investment cost 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.

Chapter 6

Cost Efficient Mobile Backhaul

As mentioned in the previous chapters, access networks are serving various user profiles with different requirements (i.e., residential, big enterprises and small/ medium companies). One of the main customers of the access network providers are the mobile operators in order to backhaul their radio access networks (RANs). Therefore, in this chapter we focus on the design and evaluation of cost efficient mobile backhaul architectures supporting high-capacity wireless networks.

In the recent years the exponential growth of mobile traffic, mainly driven by an increase in the demand for video services and number of mobile devices, brings new challenges for mobile network operators (MNOs). Operators can apply various solutions to address the capacity crunch of mobile networks. One of the promising solutions is to migrate from a homogeneous network architecture to a heterogeneous network (HetNet) deployment which is more cost and energy efficient [35]. In HetNet deployments the expensive and high power macro cells are used to provide the coverage while the small cells are added where the more capacity is needed or for improving the signal quality indoor.

However, the introduction of small cells has an impact on the backhaul networks, which are responsible for collecting data traffic from the base stations (BSs) and sending it to the metro/aggregation network. In case of HetNet, a large number of backhual links is required to transfer the data traffic of each small cell to the mobile core. These links are expected to provide a peak rate of hundreds of Mbps per cell and even beyond in future. These rates cannot be guaranteed with legacy copper-based infrastructures (i.e., particularlly over long distances). Thus, mobile operators need to invest on upgrading their backhaul networks to avoid the potential bottlenecks. However, the extra cost of the backhaul network might limit the possible savings from the radio segment of the HetNet deployment. Therefore, it is important to find cost-efficient backhaul architecture while deploying the heterogeneous wireless networks. In this regard, **Papers VII** and **VIII** of this thesis, present for the first time a detailed techno-economic evaluation methodology to compute the TCO of mobile backhaul networks along with business viability analysis. The proposed model helps MNOs to identify the most critical cost drivers of any technology used for the backhaul networks and to have a better understanding of the TCO dynamics of their network. Moreover, it helps to find the most cost-efficient backhaul technology for each wireless deployment scenario with the goal of minimizing total expenditures of MNO.

Although the HetNet deployment is an efficient solution for increasing the mobile network throughput, it is still not enough to address the growing capacity demand of mobile users in the coming years. Therefore, several new technology advancements such as multiple-input and multiple-output (MIMO) [36], coordinated multipoint (CoMP) transmission systems [37] are introduced to improve wireless network performance along with the HetNet deployments. However, none of the aforementioned techniques can reach their ultimate potential without high capacity backhual links. Coordinated multipoint transmission and reception technique is recently introduced in the LTE-Advanced framework due to its potential for improving the network throughput and spectral efficiency. The LTE evolved nodes B (eNBs) exchange the cell information and user data among a cluster of adjacent nodes through mobile backhaul networks. Therefore the quality of the user signal, especially in the border of the cell area (cell edges), is highly dependent on the CoMP backhauling solutions. Depending on the coordination technique used in CoMP, backhaul latency requirements may vary between 0.5 till 10 milliseconds [64]. This condition is hardly fulfilled using the PON architectures introduced in the previous chapters. Therefore, in **Paper IX** of this thesis that is based on a filled patent, we have proposed a low-latency and cost-efficient backhaul network for CoMP transmissions compatible with the PON architecture.

This chapter focuses on finding the suitable backhual options for the future high capacity wireless deployments where the contributions of **Papers VII**, **VIII** and **IX** are presented.

6.1 Techno-economic model and case study of mobile backhaul networks

Paper VII introduces a comprehensive cost model with a detailed CAPEX and OPEX breakdown for calculating the TCO of mobile backhual networks. The proposed methodology is general enough to be adapted to different backhaul technologies and architectures and it allows identifying the most significant cost factors in the backhaul segment which should be considered in the first place to improve overall network cost efficiency.

While the total cost of ownership is a helpful performance factor for the operators when considering migration to the new technologies, it does not provide enough information about the profitability of a project. For example, if an operator does not invest on provinsioning higher capacity when demanded by the customers in order to keep TCO lower, his customers may move to the competitors who are able to offer better services. Lower number of customers on the other hand will lead to a considerable decrease in the total revenue. On the other hand, if the operator decides to invest on the right technology at the right moment, it can increase the company revenues as well as may attract more customers leading to higher profit. Moreover, it is important to assess the TCO of the mobile operators including both backhaul and radio access networks to have a complete picture regarding the possible benefits of new deployment strategies. The aforementioned highlights are addressed in **Paper VIII** by proposing a comprehensive techno-economic evaluation framework based on the preliminary model presented in **Paper VII.**

The techno-economic evaluation framework is presented in Chapter 3 and the detailed equations can be found in **Paper VIII**. The model includes all the costs incurred during the backhaul life cycle (i.e., from the network deployment phase, when a huge upfront investment is required, up to all cost aspects related to each operational process) as well as the operator incomes in terms of revenues. It should be mentioned that the introduced methodology and formulas are also valid for the relevant study of the fronthaul segment. The proposed techno-economic evaluation tool is used to analyze the cost efficiency of two major backhaul technologies. In the first part of this study, we calculate the overall cost to deploy and operate a backhaul segment in a small (i.e., 2×2 km) dense urban area of an average European city [65] considering both homogeneous and heterogeneous deployments. In the case of HetNet scenarios, small indoor cells are installed to cover the users inside the buildings while macro cells are serving the outdoor users. The study focuses on the microwave and the fiber-based technologies as two major backhaul candidates.

Based on the cost evaluations of optical access network presented in Chapter 5, the infrastructure cost is the most expensive part of the optical access network's TCO. We analyze the impact of this fact considering two fiber-based scenarios. In the areas where no fiber infrastructure is available the mobile network operator (MNO) needs to deploy (i.e., trench) its own fiber infrastructure (Fi-Tr). However, if there is already fiber infrastructure available, the MNO has the possibility to lease the fiber connectivity from other business actors such as the municipality (Fi-Le).

The calculated TCO results show that the backhaul is much more expensive in the presence of a HetNet deployment which causes an increase in the total cost of the MNO. Moreover, the microwave-based network backhauling the HetNet deployment is the most expensive scenario among all. This outcome confirms the importance of selecting the right backhaul technology in order to maximize the saving benefits of the HetNet deployments.

This study is then extended by evaluating the business viability of mobile network deployments in a larger dense urban area considering the same scenarios.

The TCO and NPV are calculated for both radio access network (RAN) as well as the backhual network, considering the cost erosions and capacity upgrade on yearly basis for a network lifetime of ten years (see Figure 6.1 and 6.2). Operators use the NPV to measure if a specific technology or implementation can bring any profit to the company. A monthly subscription fee of 30 Euros per user and 10 percent discount rate per year are assumed for the NPV calculations. The TCO calculation helps the operators to estimate the required investment for deploying various technologies, and find the most cost-efficient solutions.

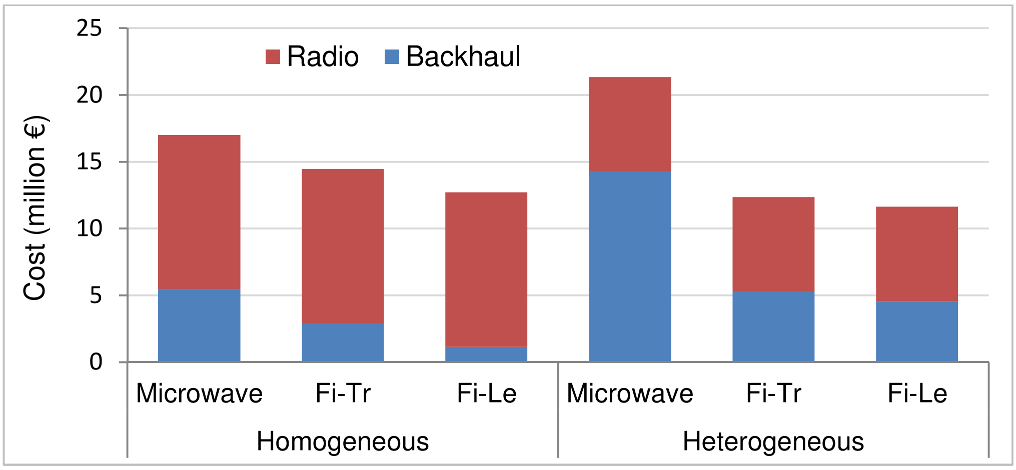

Figure 6.1. Total cost of ownership for a mobile operator during a ten years network lifetime

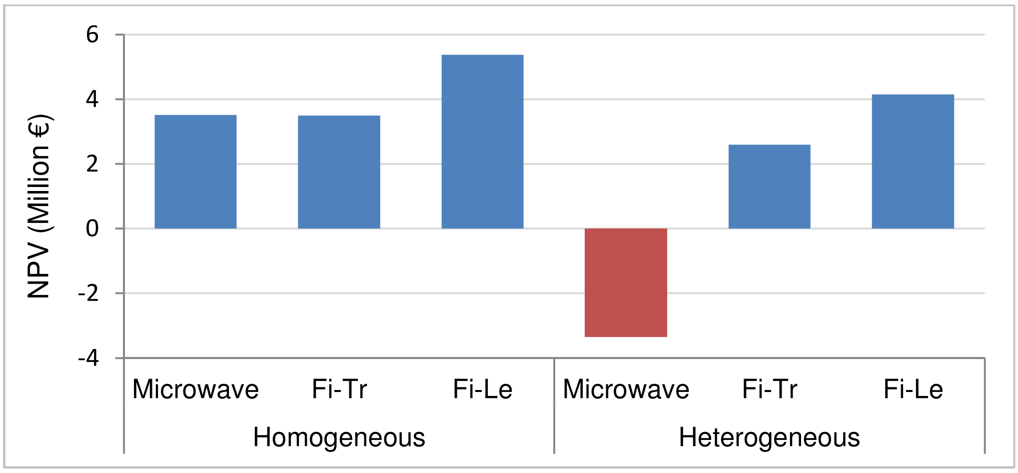

Figure 6.2. Net present value (NPV) for a mobile operator during a ten years network lifetime

Figure 6.2 shows that all the scenarios can have a positive NPV except the HetNet deployment with Microwave-based backhaul. This dictates that, for the monthly subscription fee of 30 Euro or less, backhauling the large number of small cells via microwave leads to a huge money loss for the company. Moreover, the results prove that the fiber-based backhaul scenarios with leasing are the cheapest and most profitable alternative for the high capacity mobile networks. Above figures also show that a lower TCO does not always lead to more benefits (NPV) for the operator. This trend is reflecting the impact of the year that the money is invested. The later the investment is done, the higher the profits can be achieved.

The presented case study shows that by taking the backhual cost in the account HetNet is not always more cost-efficient than the homogeneous cases as claimed in many other studies [66][67]. Therefore, selecting the right backhaul technology is as important as choosing the RAN deployment strategies. It should be considered in the planning phase of upgrading the network capacities.

6.2 Optical access architecture for backhauling of coordinated multipoint transmission

One of the main challenges of large scale implementation of CoMP systems is the strict latency constraint and high capacity requirements of the backhaul link between the neighboring cells. We addressed this challenge by proposing a high-capacity mobile backhaul architecture aiming to minimize the latency of the inter-cell communication where the intermediate electronic processing is removed. Our invention [68] can fulfill the latency constraint of CoMP transmission systems with the minimum extra investment on the network. The proposed architecture is compliant with legacy access networks based on TDM PONs as well as NGPON2 technologies introduced by full service access networks (FSAN) [69].

Besides, the proposed design is highly flexible and can cover areas with various cell densities. It is possible to provide partial or full protection if needed without any significant extra investment.

In the 3GPP standard [70], two logical interfaces are defined for each eNBs referred to as S1 and X2. The former one is responsible for exchanging the data between each cell and the mobile core network while the later one is added to handle the direct communication between the eNBs. In the proposed design, the traffic between X2 interfaces is redirected back at the RN (which is located in a distance from cells lower than 1 km in dense areas, and up to 5km in rural areas [71]) instead of passing through the OLTs and other active nodes. In this way, the end-to-end delay can be reduced using passive interconnection in the last mile segment of the backhaul networks. Based on a study in [72], the mean packet delay will increase linearly with the length of the fiber link. Moreover, using our proposal the processing delay introduced by the active nodes (e.g. approximately 0.1 millisecond per node [73]) can be eliminated.

For interconnection of nodes belonging to different PONs, the end-to-end delay is also dependent on the distance between two OLTs (if located in different COs), the propagation delay in the uplink direction towards aggregation network, and two times of the processing delay at the metro node switches. All these delays can be removed by using our proposed architecture.

The remote radio units (RRUs) that are responsible for exchanging the information between the user's devices and base band units can be grouped togather (as RRU cluster) to improve the area throughput where it is needed. The main benefit of our proposed structure is the possibility of controlling the RRUs dynamically from a centralized baseband unit (BBU) location. This offers the possibility of updating the size and border of RRU clusters with the users movement. Thus, the capacity can be provided in the locations with high density of users at each point of time. Figure 6.3 shows an example of dynamic clustering of RRUs where CoMP is applied.

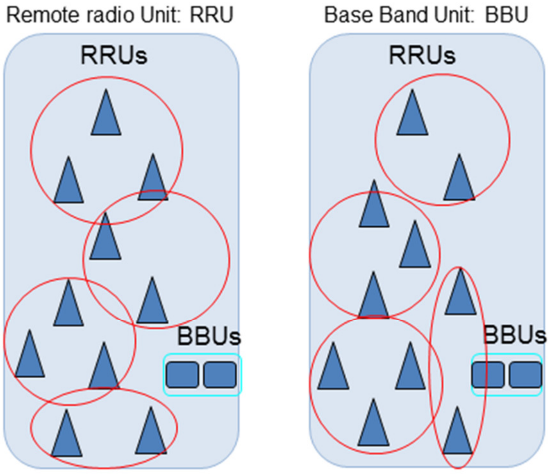

Figure 6.3. Dynamic RRU clustering

In the proposed architecture, each eNB is attached to one ONU, where several ONUs are connected to the splitters in the RN. Main idea here is to broadcast the upstream data from each cell/ONU to all the adjacent eNBs by sending back traffic in the remote node using TDMA (or WDM). This is done via connecting two input ports of the splitter using an isolator (see Figure 6.4) which redirect any upstream signal back to the splitter. In this way, the local traffic does not need to travel all the way up to the OLT. This can also alleviate the amount of traffic passing the central office and the feeder fibers, and hence lead to lower power consumption in active nodes.

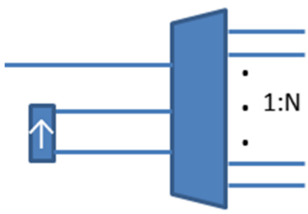

Figure 6.4. Modified structure of the splitter in the remote node

Various backhaul architectures (referred to as Schemes 1-4) are proposed in order to fulfill a variety of connectivity requirements between eNBs and area sizes. In a simple scenario where small numbers of nodes are grouped in predefined clusters to cover some hot spot locations, such as CoMP transmission among central macro cell with processing power and the small cells around it (see Figure 6.5), the scheme shown in Figure 6.6(a) (Scheme 1) can be used.

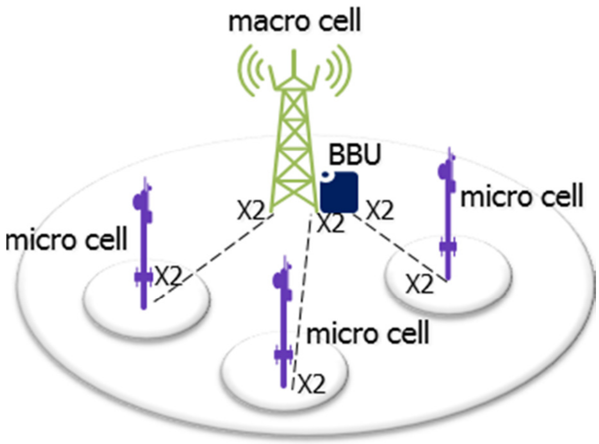

Figure 6.5. Example of CoMP system in a small area where Scheme 1 can be applied

As one can see, any data sent by each ONU not only goes to the OLT but also is broadcasted to all the ONUs connected to the same splitter. Therefore, λ_u that is the wavelength for upstream, can also be used for the interconnection among the eNBs, as well as sending data from ONU to the mobile core center. As the ONU needs to simultaneously receive the wavelength coming from the OLT (λ_d) (broadcasted to all ONUs), along with λ_u used for the CoMP signaling among adjacent cells, two independent receivers (Rx) are required. The tailored structure of the ONU is depicted in Figure 6.6(b).

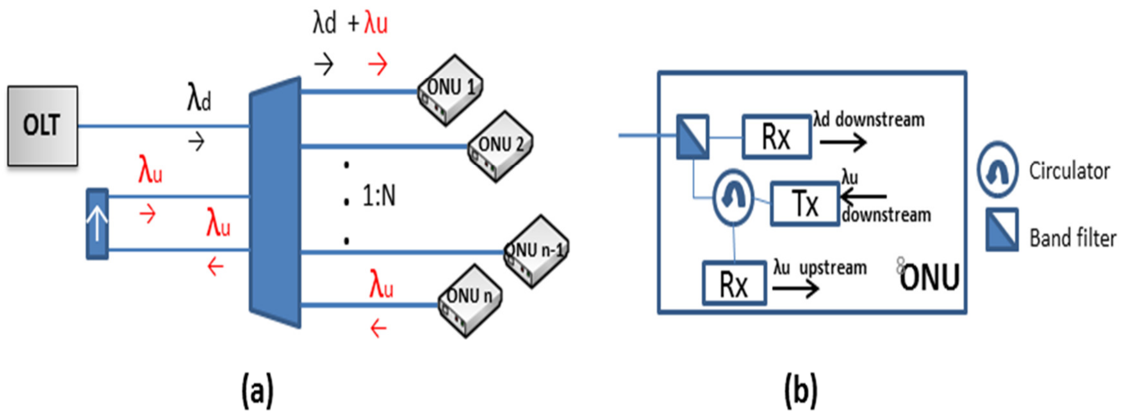

Figure 6.6. (a) Backhaul topology for interconnection of eNBs of the same PON, (b) ONU system architecture (Scheme 1)

Scheme 1 cannot support passive interconnection between the nodes belonging to different PONs, meaning that it is not suitable for the cases with a large number of nodes using CoMP transmission. Therefore, Scheme 2, 3 and 4, are proposed to support any area size and connectivity requirement with or without end-to-end protection. Figure 6.7 shows an example of the area where Scheme 2 is a suitable backhaul architecture supporting CoMP transmission between macro cells.

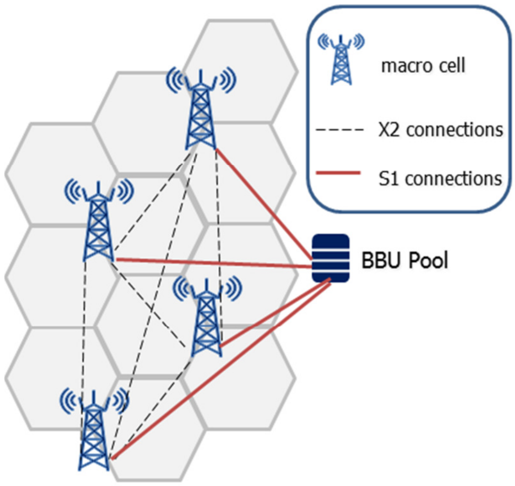

Figure 6.7. Example of CoMP system between large cells with centralized BBUs where Scheme 2 can be used

Figure 6.8(a) (Scheme 2) represents a modified version of Scheme 1 by adding the connection between ONUs of neighboring PONs. The virtual connectivity among X2 interfaces that can be achieved via Scheme 2 is shown in Figure 6.8(b) where each solid circle represents one eNB. The neighboring connectivity can only be extended in one direction, e.g., either vertical or horizontal direction (solid lines on Figure 6.8(b) demonstrate the border of connected backhaul networks). The ONUs in Figure 6.8(a) and their equivalent nodes in Figure 6.8(b) are represented via the same color.

Any data sent from ONU belonging to PON B can be directly broadcasted to all the ONUs connected to its own PON as well as the ones attached to PON A and C shown in Figure 6.8(a). This means that in the case with 4 primarily ONUs per PON (see Figure 6.8) each node can be passively connected to 11 other eNBs in its vicinity, without adding direct links between the cells.

Figure 6.8(c) presents the proposed ONU design for the physical topology related to the Scheme 2. Optical switches and tunable receiver for the downstream wavelength provide the resilience in case of failure. If a failure occurs, the backup OLT can communicate to the ONUs using a different wavelength for downstream and hence ONUs need to be tuned to this new wavelength. Band filters are responsible for separating the downstream and upstream wavebands.

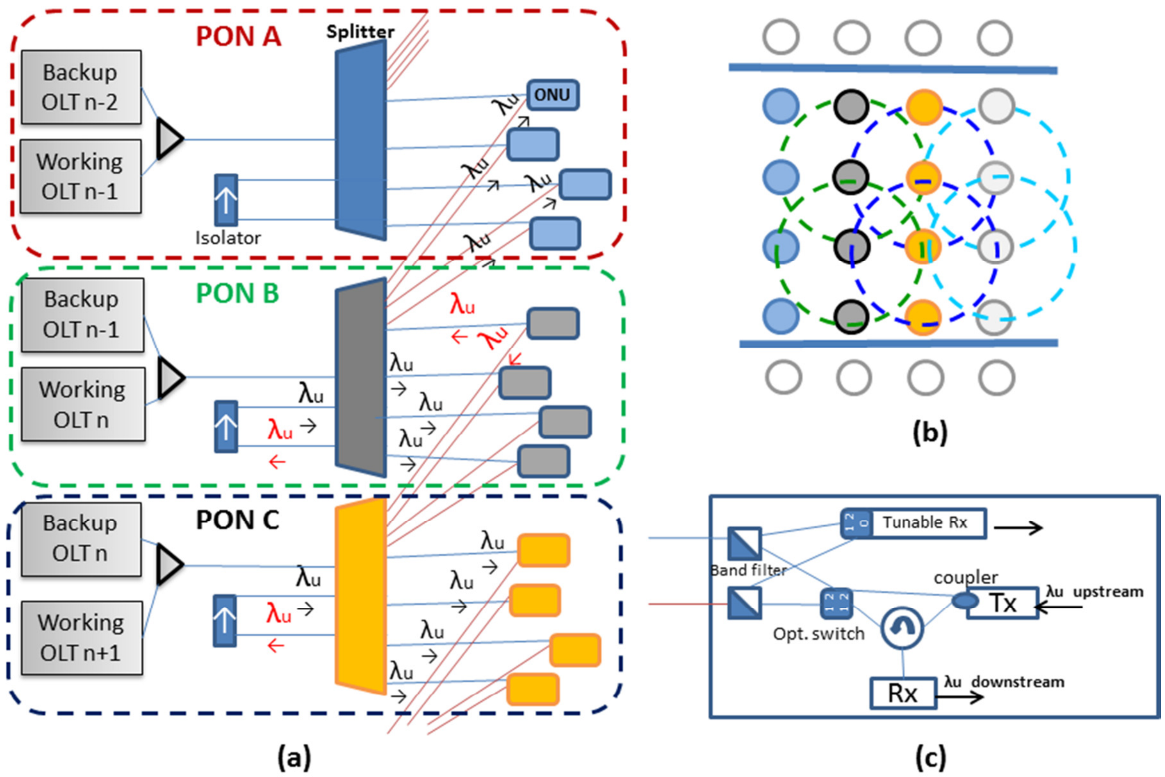

Figure 6.8. (a) Proposed backhaul topology (Scheme 2), (b) virtual X2 topology pattern, (c) ONU system architecture

Although Scheme 2 covers larger areas than Scheme 1, there can still be situations where the inter-BS traffic among neighboring nodes has to pass the OLTs. This occurs for the ONUs separated by the solid lines shown in Figure 6.8(b), as in Scheme 2 virtual X2 topology can be only extended in one direction. To remove this shortcoming and offer a fully connected overlay network among all the cells independently from their locations, Schemes 3 and 4 are proposed. The former one is providing the basic connectivity without any resilience while the later one offers an end-to-end protection from the central office to each eNB.

Figures 6.9(a) and (b) show the physical topology and the virtual connectivity among X2 interfaces in Scheme 3, respectively. Each solid circle in Figure 6.9(b) represents one base station. The neighboring connectivity is extendable in both vertical and horizontal dimensions. A letter written on the splitter denotes the associated PON. Any data sent from ONU belonging to PON E can be directly broadcast to all the ONUs connected to its own PON as well as PON B, D, F and H, where the splitter ports are directly connected to each other.

Figure 6.9(c) illustrates the ONU structure tailored for the physical topology shown in Figure 6.9(a). A separate wavelength (λ_i) is considered for inter-eNB communication that needs an extra transceiver at ONU. The reason for using an extra wavelength is to have enough bandwidth for the communication of S1 interface and separating the traffic of S1 from X2. Band filter is connecting transceivers to the single input port of ONU and is responsible for splitting the inter BS, downstream and upstream wavebands.

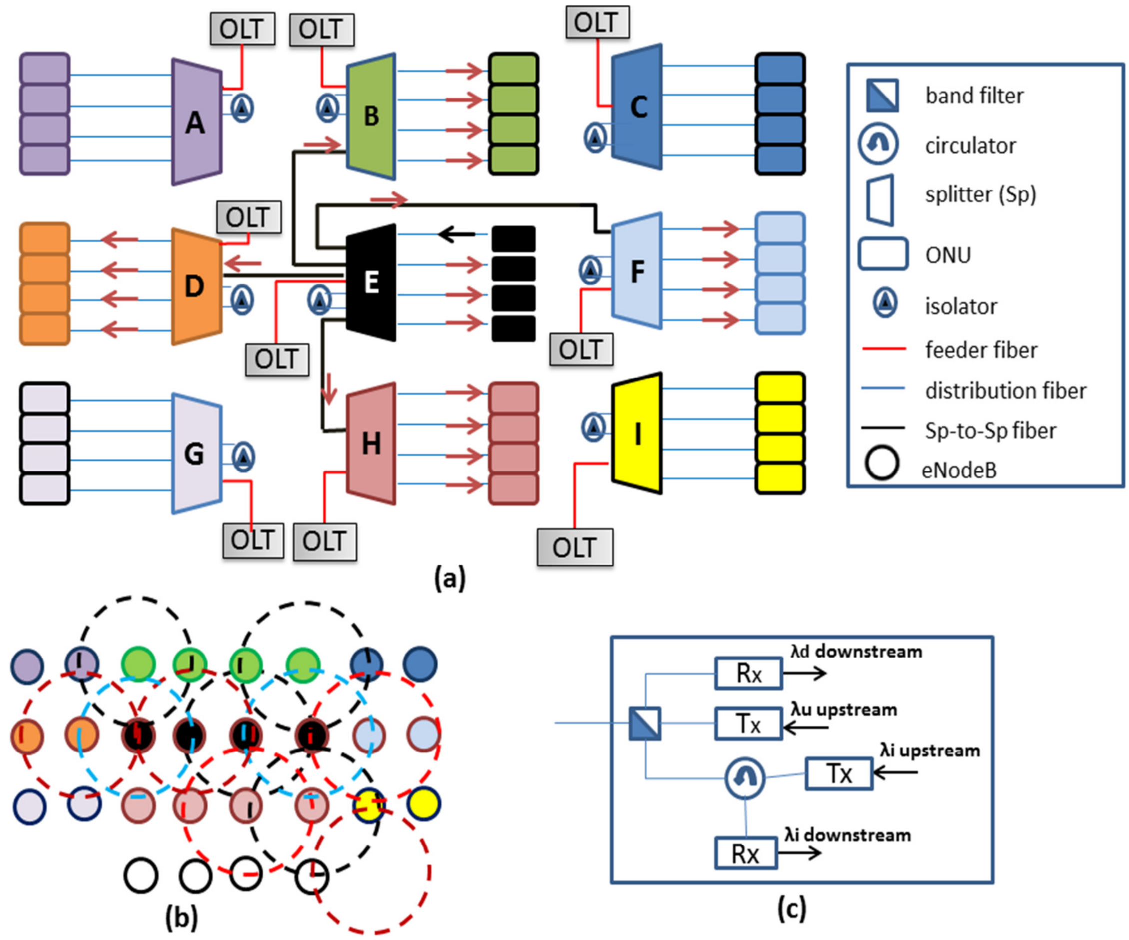

Figure 6.9. (a) Proposed backhaul topology fully extendable without protection (Scheme 3), (b) virtual X2 topology pattern, (c) ONU system architecture

Each eNB serves a large area and hence any failure in the backhaul network might lead to the connection loss for a large number of mobile users which can have a very bad impact on the operator's reputation. This can also bring a huge profit loss if penalties are applied in the service level agreement. Therefore, in Scheme 4, we come up with the backhaul architecture supporting end-to-end resilience up to each eNB while offering all the benefits of Scheme 3. The proposed physical topology and the architecture related to this Scheme are presented in **Paper IX** of this thesis.

It should be mentioned that, all the associated ONUs are designed with the TDMA control access in mind to avoid collisions in direct communication with the neighboring ONUs.

Chapter 7

Conclusions and Future Directions

This thesis addresses the challenges of future internet infrastructure caused by the traffic growth of both fixed and mobile users with a focus on transport solutions for broadband access.

Paper I, has investigated the benefits of implementing locality-aware peer-to-peer schemes for the video distribution. The results of this study show that a considerable reduction of the video related traffic passing the core network can be achieved by keeping the user data inside the access network as much as possible. In this way, telecommunication operators can minimize capacity needed in the higher aggregation layers. However, the capacity savings and benefits of traffic locality depend on the access network technologies and architectures. Therefore, in **Paper II** various types of optical access networks have been assessed regarding their abilities of accommodating local traffic. The results show that WDM-based PONs can offer a considerable bandwidth saving in the core network along with better usage of network resources and energy efficiency. It has been found that WDM-based PON has obvious advantages over all the other evaluated options, leading us to focus on this architecture. Hence, **Papers III** and **IV**, have analyzed the performance of two WDM-based access network architectures (i.e., WDM PON and TWDM PON) in order to find a cost-efficient and reliable solution for the next generation optical access networks that are able to offer high capacity and quality of service from both users' and operators' perspective.

Moreover, **Papers V** and **VI**, have concentrated on three variants of TWDM PON, and assessed their capabilities of providing high reliability performance with minimum extra cost. In **Paper V,** we have identified the main segments of the TWDM PON that need to be protected in order to avoid large impact of any single failure. Based on it, two novel resilience mechanisms have been introduced tailored for all three considered variants of TWDM PON. The results have confirmed that the failure impact is efficiently reduced and connection availability is improved to an acceptable level for residential users.

Although protection of feeder section can significantly improve the reliability performance, the connection availability is still below four nines, which might not be sufficiently high for the business users. Meanwhile, not all the users would like to pay extra to get higher connection availability. Therefore, in **paper VI** we have introduced an end-to-end protection scheme for some selected users (e.g. business access) who request higher availability. Such an approach enhances the flexibility of protection provisioning in TWDM PON, where reliability performance upgrade can be done upon request and does not affect any other connected customers. Moreover, the investment needed for providing different levels of protection has been assessed in **Paper VI**. The results demonstrate that protecting the shared part of the access network can be achieved with a small extra cost while lowering the risk to have large impact of any single failure. The outcomes of techno-economic studies also show that providing full protection can offer four nines connection availability to the business users at a reasonable additional deployment cost of backup resources.

Generally, according to the finding presented in **Papers II**, **III**, **VI**, **V** and **VI**, TWDM PON can be one of the most promising candidates for the next generation optical access thanks to its high capacity, large coverage, low cost and power consumption as well as its ability to fulfill different reliability requirements of various user profiles. This architecture also performs well in terms of resource management and bandwidth saving in the higher aggregation layers when locality of traffic is considered.

Apart from broadband access for fixed users, this thesis also addresses the challenges of mobile backhaul networks aiming to satisfy mobile users' capacity crunch. **Papers VII** and **VIII**, proposed a comprehensive techno-economic evaluation method helping to find the suitable backhaul technology supporting high-capacity wireless networks. The introduced methodology has been applied to case studies for a dense urban area with both homogeneous and heterogeneous wireless network deployment. The business viability of the scenarios where radio access networks are backhauled via either microwave links or fiber solutions has also been assessed in **Paper VIII**. The results confirm that fiber-based backhaul technology (especially where leasing fiber is an option) in combination with the heterogeneous wireless deployment bring the highest profits and increase the cash flow for the mobile operators.

Finally, **Paper IX** has proposed a high-capacity PON-based architecture for backhauling the CoMP transmission system of LTE-advanced. Compared to the conventional PON architectures, the proposed scheme can easily meet strict latency demand of CoMP systems by using its direct links between the cells while minimizing the extra cost and power consumption. This architecture is also able to provide the end-to-end protection up to each cell offering high reliability.

In terms of the future work, in the area of traffic locality, it would be interesting to investigate the benefits of adding small cashes in some relay nodes inside the backhaul network (e.g., co-located with macro cells), and quantify the possible reduction of video traffic passing the backbone generated by the mobile users. Moreover, with the increasing penetration of smart phones and people dependency on being always connected, the reliability performance of mobile services will turn to an important factor for the mobile network operators. Therefore, proper resilience schemes should be considered when designing the backhaul solutions to support high-capacity radio access networks. This can be done, by extending the schemes proposed in **Papers V** and **VI** of this thesis.

New concept of cloud-RAN (C-RAN) as well as radio over fiber using digitalized protocol is only possible to be carried out by ultra-high-capacity fronthaul links (e.g., 10Gbps and beyond). Therefore, finding cost-efficient technologies and architectures for frounhauling solutions in the future is another interesting direction. Moreover, the increasing interest on the smart cities coming with the trend of urbanization, dictates a converged network including various wireless and fixed technologies. Consequently, finding an optimized combination of different technologies, where both high capacity fixed network services as well as X-hauling (including backhauling and fronthauling) are served via fiber infrastructure could be considered as the next step towards high performance broadband access solution.

References

[1] IRTF task force for information-centric networking research, https://irtf.org/icnrg, retrieved 27 December 2014.

[2] "Network functions virtualisation - introductory white paper," https://portal.etsi.org/NFV/NFV_White_Paper.pdf, retrieved 27 December 2014.

[3] "The NIST definition of cloud computing," http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf, retrieved 27 December 2014

[4] FP7 European project, OASE deliverable 2.1, "Requirements for European next generation optical access networks".

[5] T. Koonen, "Fiber to the home/fiber to the premises: What, Where, and When?," proceedings of the IEEE, vol. 95, no. 5, pp. 911-934, 2006.

[6] J. Prat, "Next-generation FTTH passive optical networks," Springer, 2008 [book].

[7] M. D. Andrade, G. Kramer, L. Wosinska, J. Chen, S. Sallent, and B. Mukherjee, "Evaluating strategies for evolution of passive optical networks," IEEE communications magazine, vol. 49, no. 7, pp. 176-184, 2011.

[8] F. Effenberger, H. Mukai, S. Park, and T. Pfeiffer, "Next-generation PON part II – candidate systems for next generation PON," IEEE communications magazine, vol. 47, no. 11, pp 50–57, 2009.

[9] "10-gigabit-capable passive optical networks (XG-PON): general requirements," G.987.1 international telecommunication union, 2010.

[10] "10Gb/s Ethernet passive optical network: IEEE P802.3av task force," http://www.ieee802.org/3/av/, retrieved 27 December 2014.

[11] FP6 European project, photonic integrated extended metro and access network (PIEMAN), http://www.ist-pieman.org.

[12] FP6 European project, multi-service access everywhere (MUSE), http://www.ist-muse.org.

[13] FP7 European project, optical access seamless evolution (OASE), http://www.ict-oase.eu/.

[14] M. Ruffini, E. Di Pascale, and D. B. Payne, "Improving high fidelity multi- media distribution in next-generation optical networks," in proceeding of international conference on transparent optical networks (ICTON), 2013.

[15] "Cisco visual networking index: Forecast and methodology, 2013-2018," http://www.cisco.com/c/en/us/solutions/collateral/service-provider/ip-ngn-ip-next-generation-network/white_paper_c11-481360.html, retrieved 16 December 2014.

[16] Spotify, https://www.spotify.com/se/, retrieved 27 December 2014.

[17] Skype, http://www.skype.com/en/, retrieved 27 December 2014.

[18] S. Spoto, R. Gaeta, M. Grangetto, and M. Sereno, "Analysis of PPLive through active and passive measurements," IEEE international symposium on parallel and distributed processing, 2009.

[19] A. Tanny, "P2P locality awareness architecture in Ethernet passive optical networks," in proceedings of international conference on quality in research (QiR), 2013.

[20] C. A. Chan, A. Wong, and A. Nirmalathas, "Energy savings dependency of IPTV caching systems on similarity in user behavior," in proceeding of European conference on optical communications (ECOC), 2011.

[21] D. R. Choffnes, and F. E. Bustamante, "Taming the torrent: a practical approach to reducing cross-isp traffic in peer-to-peer systems," ACM SIGCOMM conference on data communication, vol. 38, no. 4, pp. 363-374, 2008.

[22] D. Breuer, F. Geilhardt, R. Hülsermann, M. Kind, C. Lange, T. Monath, and E. Weis, "Opportunities for next-generation optical access," IEEE communications magazine, vol. 49, no. 2, pp. 16-24, 2011.

[23] O. Findahl, "Svenskarna och Internet," world Internet institute, digital version 1.1, 2009.

[24] J. Chen, B. Chen, and S. He, "Self-protection scheme against failures of distributed fiber links in an Ethernet passive optical network," Journal of optical networking, vol. 5, no. 9, pp. 662-666, 2006.

[25] T. K. Chan, C. K. Chan, L. K. Chen, and F. Tong, "A self-protected architecture for wavelength division multiplexed passive optical networks," IEEE photonic technology letter, vol. 15, no. 8, pp. 1660-1662, 2003.

[26] J. Chen, and L. Wosinska, "Analysis of protection schemes in PON compatible with smooth migration from TDM PON to Hybrid WDM/TDM PON," Journal of optical networking, vol. 6, no. 5, pp. 514-526, 2007.

[27] C.H. Yeh, and S. Chi, "Self-healing ring-based time-sharing passive optical networks," IEEE photonics technology letters, vol. 19, no. 15, pp.1139-1141, 2007.

[28] S. Deng, C. Gan, and Q. Shao, "Novel WDM-PON scheme enabling reliable protection and dynamic bandwidth allocation," in 2nd International conference on consumer electronics, communications and networks (CECNet), 2012.

[29] "Ericsson mobility report," http://www.ericsson.com/res/docs/2014/ericsson-mobility-report-november-2014.pdf, retrieved on 20 December 2014.

[30] FP7 European project, convergence of fixed and Mobile broadband access/aggregation networks (COMBO), http://www.ict-combo.eu/.3GPP TS36.300, "Evolved universal terrestrial radio access (EUTRA) and evolved universal terrestrial radio access network (EUTRAN), Overall description".

[31] H. Shahzad, "Tactile Internet - The Future 5G Internet," Pakistan Android blog, retrieved 20 November 2014.

[32] "Heterogeneous networks, TIA 2012|@Ericsson AB 2012," http://tia2012.org/sites/default/files/pages/Coyne%20Michael.pdf, retrieved 20 December 2014.

[33] "How to meet your backhaul capacity needs while maximizing revenue," http://www.skyfiber.com/assets/docs/pdf/technologyandresouces/WP_SkyFiber_Mobile_Backhaul.pdf, 2013, retrieved 20 December 2014.

[34] M. Paolini, "An analysis of the total cost of ownership of point-to-point, point-to-multipoint, and fibre options," White paper on crucial economics for mobile data backhaul, 2011.

[35] C. Khirallah, J. S. Thompson, and H. Rashvand, "Energy and cost impacts of relay and femtocell deployments in long-term-evolution advanced," Institution of engineering and technology communications, vol. 5, no. 18, pp. 2617-2628, 2011.

[36] J. Hoydis, S. ten Brink, and M. Debbah, "Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?," IEEE journal on selected areas in communications, vol. 31, no. 2, pp. 160-171, 2013.

[37] 3GPP TR 36.819, "Coordinated multi-point operation for LTE physical layer aspects," V.11.1.0, 2011.

[38] K.Chen, "C-RAN: The road toward green RAN," China mobile research institute, 2001.

[39] T. Pfeiffer, and F. Schaich, "Optical architectures for mobile back- and fronthauling," in proceeding of IEEE optical fiber communications conference (OFC), 2012

[40] Free space optic forum, http://www.freespaceoptics.org/.

[41] S. Hur, T. Kim, D. J. Lova, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," IEEE transactions on communications, vol. 61, no. 10, pp. 4391-4403, 2013.

[42] "Ericsson microwave towards 2020 report," 2014, http://archive.ericsson.net/service/internet/picov/get?DocNo=19/28701-FGB101004&Lang=EN&HighestFree=Y, retrieved 21 December 2014.

[43] "FTTH council – definition of terms," 2011, http://www.ftthcouncil.eu/documents/Publications/FTTH_Definition_of_Terms-Revision_2011-Final.pdf, retrieved 21 December, 2014

[44] C. P. Larsen, "Access network technologies: deployments in Sweden," in proceeding of European conference on optical communications (ECOC), 2007.

[45] "Gigabit-capable passive optical networks (GPON): General characteristics," G.984.1, http://www.itu.int/rec/T-REC-G.984.1-200803-I/en, retrieved 27 December 2014.

[46] IEEE Standard 802.3, EPON, http://standards.ieee.org/getieee802/802.3.html, retrieved 27 December 2014.

[47] FP7 European project, OASE deliverable 3.1, "Overview and assessment of existing optical access network architectures".

[48] "Practical steps in techno-economic evaluation of network deployment planning," UGent/IBBT – department of information technology (INTEC) white paper, 2009.

[49] C. Evans, "Cost justifying the carriers migration to strategy to Ethernet in DWM and Metro optical networking," Metro Ethernet forum, 2004.

[50] C. Mas Machuca, Ø. Moe, and M. Jäger , “Modelling of OpEx in network and service life-cycles,” in proceeding European conference on optical communications (ECOC), 2007.

[51] FP7 European project, OASE deliverable 5.2, “Process modeling and first version of TCO evaluation tool”.

[52] W. S. Soh, Z. Antoniou, and H. S. Kim, “Improving restorability in radio access networks,” in Proceeding IEEE global telecommunications conference (GLOBECOM), 2003.

[53] S. Verbrugge, D. Colle, P. Demeester, R. Huelsermann, and M. Jaeger, “General availability model for multilayer transport networks,” in proceeding IEEE conference design of reliable communication networks (DRCN), 2005.

[54] D. Gardan, A. Zaganiaris, A. Madani, R. Madigou, and D. Machon, “Techno-economics of advanced optical subscriber networks,” in proceeding IEEE global telecommunications conference (GLOBECOM), 1989.

[55] Koen Casier, “Techno-economic evaluation of a next generation access network deployment in a competitive setting”, PhD thesis, faculty of engineering of the Ghent university, 2009.

[56] Exiample district in Barcelona, http://en.wikipedia.org/wiki/Eixample, retrieved 21 December 2014

[57] OpenStreetMaps, http://openstreetmap.org .

[58] A. Mitcsenkov, G. Paksy, and T. Cinkler, “Geography- and infrastructure-aware topology design methodology for broadband access networks (FTTx),” Journal of photonic network communications, vol. 21, no. 3, pp. 253-266, 2011.

[59] A. Autenrieth, O. Kipouridis, K. Grobe, and C. Mas Machuca, “Application of WDM-based PON architectures for next-generation optical access using street-aware infrastructure planning,” in proceeding IEEE Asia communications and photonics conference (ACP), 2011.

[60] O. Kipouridis, “Power, resilience and cost study of next generation optical access networks,” master's thesis, technical university of Munich (TUM), 2011.

[61] K. Fall, “NS2 manual,” VINT Project, 2000, http://www.isi.edu/nsnam/ns/ns-documentation.html, retrieved 21 December 2014.

[62] J. Chung, and M. Claypool, “NS by Example,” http://nile.wpi.edu/NS/, retrieved 18 November 2014.

[63] H. Xie, A. Krishnamurthy, A. Silberschatz, and Y. R. Yang, “P4P work group white paper,” http://www.dcia.info/documents/P4P_Overview.pdf, 2007, retrieved 27 December 2014.

[64] M. Hogan, “Mobile backhaul and synchronization for heterogeneous networks”, IEEE international telecom sync forum (ITSF), 2012.

[65] FP7 European project, EARTH deliverable D2.3, “Energy efficiency analysis of the reference systems, areas of improvements and target breakdown”.

[66] A. W. Ahmed, J. Markendahl, C. Cavdar, and A. Ghanbari, “Study on the effects of backhual solutions on indoor mobile deployment macrocell vs. femtocell,” IEEE symposium on personal, indoor and mobile radio communication (PIMRC), 2013.

[67] Z. Frias, and J. Perez, “Techno-economic analysis of femtocell deployment in long-term evolution networks,” EURASIP journal on wireless communications and networking, vol. 2012, no. 1, pp. 1-15, 2012.

[68] M. Mahloo, J. Chen, and L. Wosinska, “COMP backhauling solutions via PON,” Filed at 9 September 2014 with number PCT/SE2014/051029.

[69] Full service access network (FSAN), http://www.fsan.org/.

[70] LTE 3GPP standard, http://www.3gpp.org/technologies/keywords-acronyms/98-lte.

[71] FP7 European project, OASE, deliverable D5.1, “Overview of methods and tools”.

[72] F. Aurzada, M. Scheutzow, M. Herzog, and M. Maier, and M. Reisslein, “Delay analysis of Ethernet passive optical networks with gated service,” Journal of optical networking, vol. 7, no. 1, pp. 25-41, 2008.

[73] C. Choi, Q. Wei, T. Biermann, and L. Scalia, “Mobile WDM backhaul access networks with physical inter-base-station links for coordinated multipoint transmission/reception Systems,” in proceeding IEEE global telecommunications conference (GLOBECOM), 2011.

Summary of original work

Paper I: **M. Mahloo**, A. Gavler, J. Chen, S. Junique, V. Nordell, and L. Wosinska, "Off-Loading the Aggregation Networks by Locality-Aware Peer-to-Peer Based Content Distribution", IEEE/OSA/SPIE Asia Communications and Photonics Conference and Exhibition (ACP), 2011.

The benefits of applying a locality-awareness scheme for video on demand applications using peer-to-peer (P2P) techniques are assessed. The results show that a considerable saving is possible in the amount of P2P traffic passing the core and aggregation network by keeping the traffic locally.

Contribution of the author of the thesis: Implementation of the simulator, running all the simulations, analysis of results, writing the first draft of the manuscript.

Paper II: **M. Mahloo**, J. Chen, and L. Wosinska, "PON versus AON: Which is the Best Solution to Offload Core Network by Peer-to-Peer Traffic Localization", Elsevier Journal of Optical Switching and Networking (OSN), Volume 15, Number 1, Pages 1–9, 2015.

This paper analyzes the efficiency of supporting locality-aware P2P video distribution algorithm in three main types of optical access network architectures, i.e., active optical networks (AON), wavelength division multiplexing passive optical networks (WDM PON) and hybrid time/wavelength division multiplexing PON (TWDM PON or HPON). These architectures are compared with respect to traffic distribution in different aggregation levels, power consumption taking into account sleep mode functionality at the user premises, and required switching capacity in the network nodes. A home-made simulator is developed which allowed us to measure the amount of traffic in each network's link for various architectures and translate the results to model network power consumptions and nodes switching capabilities.

Contribution of the author of the thesis: Implementation of the simulator, modeling the network and scenario definitions, running all the simulations, analysis of the results, writing the first draft of the manuscript.

Paper III: C. M. Machuca, **M. Mahloo**, J. Chen, and L. Wosinska, "Protection Cost Evaluation of Two WDM-based Next Generation Optical Access Networks", IEEE/OSA/SPIE Asia Communications and Photonics Conference (ACP), 2011.

In this paper, the cost of protection up to the first remote node is assessed for two WDM-based next generation access networks referred to as the UDWDM PON and HPON in dense urban area. The proposed fiber layout and remote node replacement can minimize the trenching cost needed for the protection. Both technologies show considerable improvement on reliability performance in the proposed scenario compared to the unprotected one. The cost study shows that with a suitable fiber layout, small extra investment on protection can decrease the failure related cost such as service interruption penalties.

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

Paper IV: **M. Mahloo,** C. M. Machuca, J. Chen, and L. Wosinska, “Protection Cost Evaluation of WDM-based Next Generation Optical Access Networks", Elsevier Journal of Optical Switching and Networking (OSN), Volume 10, Number 1, Pages 89-99, 2013.

In this paper, we extend the work in Paper III and investigate the influence of different client counts and splitting ratios on the CAPEX and OPEX considering protection of feeder section for two WDM-based NGOAs, namely UDWDM PON and HPON. Fiber and trenching layouts are designed according to the remote node splitting ratio to reduce the extra investment cost needed for the protection. According to the results, higher client count or higher splitting ratio of the second remote node will lead to less cost per-user since more number of users is sharing the same resource.

Contribution of the author of the thesis: The proposed fiber layout and remote node replacement, all the CAPEX related calculations and analysis, OPEX (including the power consumption and floor space) related calculations and analysis, writing the first draft of the manuscript.

Paper V: A. Dixit, J. Chen, **M. Mahloo**, B. Lannoo, D. Colle and M. Pickavet, “Efficient Protection Schemes for Hybrid WDM/TDM Passive Optical Networks”, IEEE International Conference on Communications (ICC), New Trends in Optical Networks Survivability, 2012.

In this paper, we analyze the availability and failure impact 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 the author of the thesis: The protection of CAN, the results and some text related to the wavelength selected HPON, contributing to the protected architecture design.

Paper VI: **M. Mahloo**, A. Dixit, J. Chen, C. Mas Machuca, B. Lannoo, D. Colle, and Lena Wosinska, “Towards End-to-End Reliable Hybrid TDM/WDM Passive Optical Networks”, IEEE Communications Magazine (ComMag), Volume 52, Number 2, Pages s14-s23, 2014.

In this paper, we extend the work in Paper V and propose a cost-efficient end-to-end protection mechanism for three HPON variants. 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 the author of the thesis: The proposed unprotected and protected schemes, all the calculations and analysis related to the reliability performance and cost, writing the first draft of the manuscript.

Paper VII: M. Mahloo, P. Monti, J. Chen and L. Wosinska, "Cost Modeling of Backhaul for Mobile Networks", IEEE International Conference on Communications (ICC), Fiber-Wireless Integrated Technologies, Systems and Networks, 2014.

A comprehensive cost model is proposed to calculate the total cost of ownership for various backhaul technologies. This helps operators to find a cost-efficient backhaul architecture while designing their network aiming to reduce the total required investment for deploying and running their services. We apply the proposed model in several case studies in a dense urban scenario considering backhauling radio access network via microwave or fiber technology.

Contribution of the author of the thesis: The proposed techno-economic model, scenario definition, all the cost calculations and analysis related to the case studies, writing the first draft of the manuscript.

Paper VIII: M. Mahloo, P.Monti, F. Farias, J. C. Weyl, L. Wosinska, and J. Chen, "Techno-Economic and Business-Feasibility Modeling of Mobile Backhaul", submitted to IEEE Communications Surveys and Tutorials, March 2015.

This paper extends the work in Paper VII and introduces a complete techno-economic evaluation method along with a comprehensive business viability assessment for future mobile networks considering both radio access network and backhaul segments. This paper also includes a sensitivity analysis on several important cost factors of the backhaul network in order to assess the impact of the assumptions and input values used in the business study for various scenarios.

Contribution of the author of the thesis: The proposed techno-economic framework and business analysis tool, scenario definition, all the cost calculations and analysis related to the case studies, writing the first draft of manuscript.

Paper IX; Mozhgan Mahloo, L. Wosinska, and J. Chen, "Efficient Mobile Backhaul Architecture Supporting Coordinated Multipoint Transmission", submitted to IEEE Communications Letters, March 2015.

This paper proposes a novel low-latency and cost-efficient backhaul architecture based on PON supporting the coordinated multipoint (CoMP) transmission. The proposed architecture leads to a reduction in the power consumption, operational complexity of the backhaul network compared to the conventional ones. It also offer an end-to-end protection for each cell site.

Contribution of the author of the thesis: The backhaul architecture design, results calculation and analysis, writing the first draft of the manuscript