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Departamento de Electrónica, Telecomunicações e Informática

SOMAYEH ZIAIE

Análise tecno-económica em Redes de Acesso Óptico

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia de Computadores e Telemática, realizada sob a orientação científica do Prof. Dr. Armando Nolasco Pinto, do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

To whom I love and respect

o júri

presidente

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palavras-chave FTTH, PON, GPON, TDM-PON, WDM-PON, OFDM-PON, CapEx

resumo

Esta dissertação tem como objectivo analisar os principais problemas que os fornecedores de serviços têm que considerar ao implementar e ao migrar as redes de acesso ópticas existentes e futuras. Iremos considerar a migração da rede GPON, como rede de acesso actual, para as Redes Óticas de Acesso de Próxima Geração (NG-OANs), como a WDM-PON e a OFDM-PON.

O trabalho foca-se nos Custos de Capital (CapEx) por utilizador, e em três factores que condicionam este custo: densidade populacional, topologia da rede e custo dos componentes. Uma visão geral e avaliação das redes óticas passivas existentes e futuras é apresentada. Um modelo tecno-económico para o cálculo do custo das redes de acesso é proposto, tendo em conta o efeito da taxa de subscrição.

O custo total de cada tecnologia de rede é calculado. O CapEx por utilizador para esquemas divisores simples e em cascata é também calculado, para diferentes taxas de subscrição. O custo dos componentes é considerado quando o preço é extrapolado em função do tempo e do volume.

key words FTTH, PON, GPON, TDM-PON, WDM-PON, OFDM-PON, CapEx

abstract This dissertation aims to analyse the main issues to be faced by the service providers in implementation and migration of existing and future optical access networks. We are going to consider the migration of the networks from GPON, as the current access network technology, to Next Generation Optical Access Networks (NG-OANs), such as WDM-PON and OFDM-PON.

The work focuses on the Capital Expenditures (CapEx) per user and three factors that drive this cost: population density, network topology and components cost. An overview and assessment of existing and future passive optical networks is provided. A techno-economic model for calculating of deployment cost of access networks is presented, accounting for the effect of take rate.

The total cost of each network technology is calculated. The CapEx per user for both single and cascaded splitter schemes for different take rates is also calculated. Furthermore the components cost is considered, when the price is extrapolated considering time and volume.

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ADSL	Asymmetric digital subscriber line
ANACOM	National Communications Authority
AON	Active Optical Network
APON	Asynchronous Transfer Mode PON
APD	Avalanche photodiode
ASE	Amplified Spontaneous Emission
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BPON	Broadband PON
CAGR	Compound Annual Growth Rate
CapEx	Capital Expenditures
CATV	Cable Television
CO	Central Office
DML	Directly Modulated DFB Lasers
DSL	Digital subscriber line
DSLAM	DSL Access Multiplexer
DSP	Digital Signal Processing
EDFA	Erbium Doped Fibre Amplifier
EML	Electro-absorption Modulated Laser
EPON	Ethernet PON
FIVER	Fully-Converged Quintuple-Play Integrated Optical-Wireless Access Architectures
FSAN	Full Service Access Network
FTTB	Fibre to the Building
FTTC	Fibre To The Cabinet
FTTCell	Fibre To The Cell
FTTH	Fibre-To-The-Home
GPON	Gigabit PON
HD-TV	High Definition Television
HFC	Hybrid fibre-coaxial
IEEE	Institute of Electricaland Electronics Engineers
IM-DD	Intensity Modulation – Direct Detection
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
IPTV	Internet Protocol TV
LR-GPON	Longe reach GPON
MDF	Main Distribution Frames
NG-OAN	Next Generation Optical Access Network

NGPON	Next Generation Passive Optical Network
ODF	Optical Distribution Frame
ODN	Optical Distribution Network
OEO	Optical-Electrical-Optical
OFDM-PON	Orthogonal Frequency Division Multiplexing PON
OLT	Optical LineTerminal
ONT	Optical NetworkTermination
ONU	Optical Node Unit
OpEx	Operational Expenditures
P2P	Point to Point
PD	Photo Detector
PDF	Population Distribution Function
PIN	Positive Intrinsic Negative
PON	Passive Optical Network
RF	Radio Frequency
RSOA	Reflective-SOA
RN	Remote Node
SOA	Semiconductor Optical Amplifier
TC	Transmission Convergence
TCO	Total Cost of Ownership
TDM-PON	Time Division Multiplexing PON
TEC	Temperature Controllers
TL	Tunable laser
TRx	Tunable Receivers
TWDM-PON	Time & Wavelength-Division Multiplexing PON
UDWDMPN	Ultra Dense WDM PON
UPS	Uninterruptible power supply
VNI	Visual Networking Index
VOD	Video On Demand
VOIP	Voice Over IP
WDM	Wavelength-Division Multiplexing
WDM-PON	Wavelength-Division Multiplexing PON
WiMAX	Worldwide Interoperability for Microwave Access

CHAPTER 1 INTRODUCTION

Summary

Next Generation Optical Access Networks (NG-OANs) are the fastest growing parts of the telecommunication area and the availability requirements for today's and tomorrow's access networks are very demanding. Therefore, network planning and design decisions should take into account cost estimations as accurately as possible. There are many factors that have to be taken into account when implementing and managing access networks. How can operators make the current and future FTTH economical, is one of the questions that this M.Sc. work tries to answer. This chapter gives details of motivation, objectives and original contributions. The dissertation organization is presented at the end of this chapter.

1.1 Background and Motivation

Data rate hungry applications, whether domestic (for residential user) or professional (for business user, mobile backhaul and data centre), are permanently pushing operators to upgrade and develop their access network to Fibre-To-The-Home (FTTH) technology. A FTTH access network is a residential communications infrastructure where fibre cables run all the way to the user homes and allow service providers serve their current customer and adapt to future market changes. Also this network enables operators to deliver triple services (Voice, Video and Data) in the same infrastructure as an open access network and can support the increasing demands for high speed services with good quality.

In the other side, the digital divide is a social issue that refers to the discrepancy between those who have access to information and communication tools, such as the Internet (especially broadband access) and those who do not have access. The digital divide can exist between people who live in rural areas and people who live in urban areas or between economic classes and on a global scale. As digital divide is a challenge faced by today's virtual world and International Telecommunication Union – Telecommunication (ITU-T), it can be reduced by making access network economical in everywhere for everyone [1].

Besides, according to statistical information published by the Cisco Visual Networking Index (VNI) forecast [2], global IP traffic will increase threefold over the next 5 years and will grow at a Compound Annual Growth Rate (CAGR) of 23 percent from 2012 to 2017. 80 to 90 percent of this traffic belongs to all forms of video such as TV, video on demand (VoD), Internet and P2P. Also mobile data traffic and business IP traffic will grow at a CAGR of 66 and 21 percent from 2012 to 2017, respectively. The network requirements such as availability, data security, support and bandwidth provision are outlined for different customer classes and not per single services. Types of services, total traffic and data rate scales can be the metrics for classification of system adaptability to the user profiles. Definition of end-user category helps us projecting traffic and aiming at predicting the time limit for a certain technology. As an assumption, the end-user categories can be divided as follow:

- Light user - voice, VOIP, gaming, data and IPTV.

- Heavy user - voice, video conference, gaming, data, cloud computing, VOD dedicated, live VOD, pear to pear, IPTV.
- Business: fixed IP WAN or Internet traffic generated by businesses and governments.
- Mobile back hauling: includes mobile data and internet traffic generated by handsets, notebook cards and mobile broadband gateways.
- Fixed backhaul and Data centres: services with highest requirements define backhaul link parameter

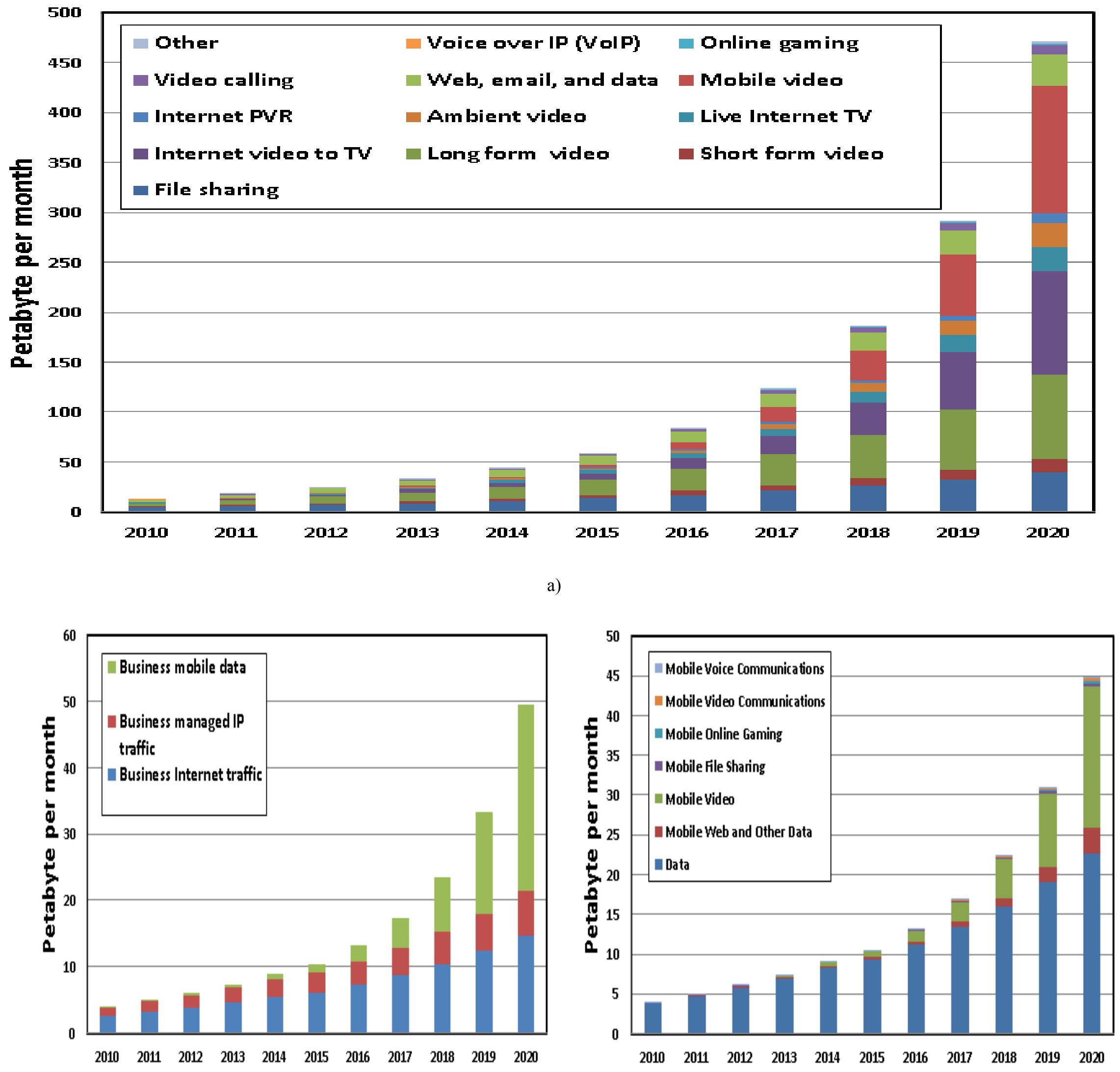


Figure 1-1. Forecast of Internet traffic consumption per service. a) Residential users b) Business users c) Mobile backhaul users [2]

Figure 1.1 shows the service bandwidth evolution forecasts of each user category by 2020 based on the traffic model described in CiscoVNI [2].

Under these circumstances, service providers are trying to identify a technology choice that allows them to profitably serve their subscribers today and also adapt to future market changes. NG-OAN architectures will offer not only higher bandwidths enabling more products and services, but also better quality of service, that enable more efficient and reliable networks, thereby increasing subscriber satisfaction and penetration rates.

One of the cost effective FTTH concept that has appeared in recent years is Passive Optical Network (PON). PON enables point-to-multipoint fibre access networks based on passive optical nodes and provides high bit rate for number of users with sharing optical line terminal (OLT) port and feeder fibre. Furthermore availability of network for all users with using optimum amount of resources can make these access networks economical. Figure 1.2 presents an example of PON for supporting all services and users in same feeder fibre.

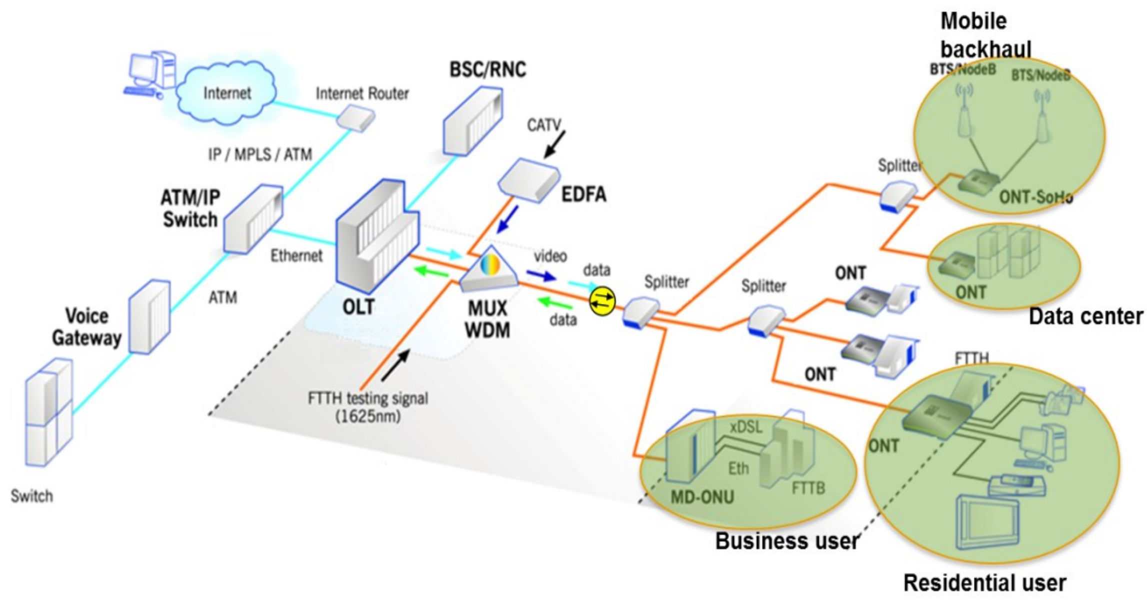


Figure 1-2. FTTH structure with supporting residential, business, mobile backhaul and data center users.

According to bottom-up business model [3], services are key requirements for each system and architecture design. In Fig. 1.3 the downstream and upstream bandwidth data requirements for each user type are demonstrated, together with the bandwidth of some of today's access solutions. For forecasting of the service bandwidth evolution and types of user, traffic study in [2, 3] has been used in the user profile. According to bottom part of

Fig. 1.3, operator can carry out what is the best technology for future application. As shown, WDM and P2P solutions are optimum technologies that can support all the users. Several network technologies can be implemented to deliver broadband services to the customer.

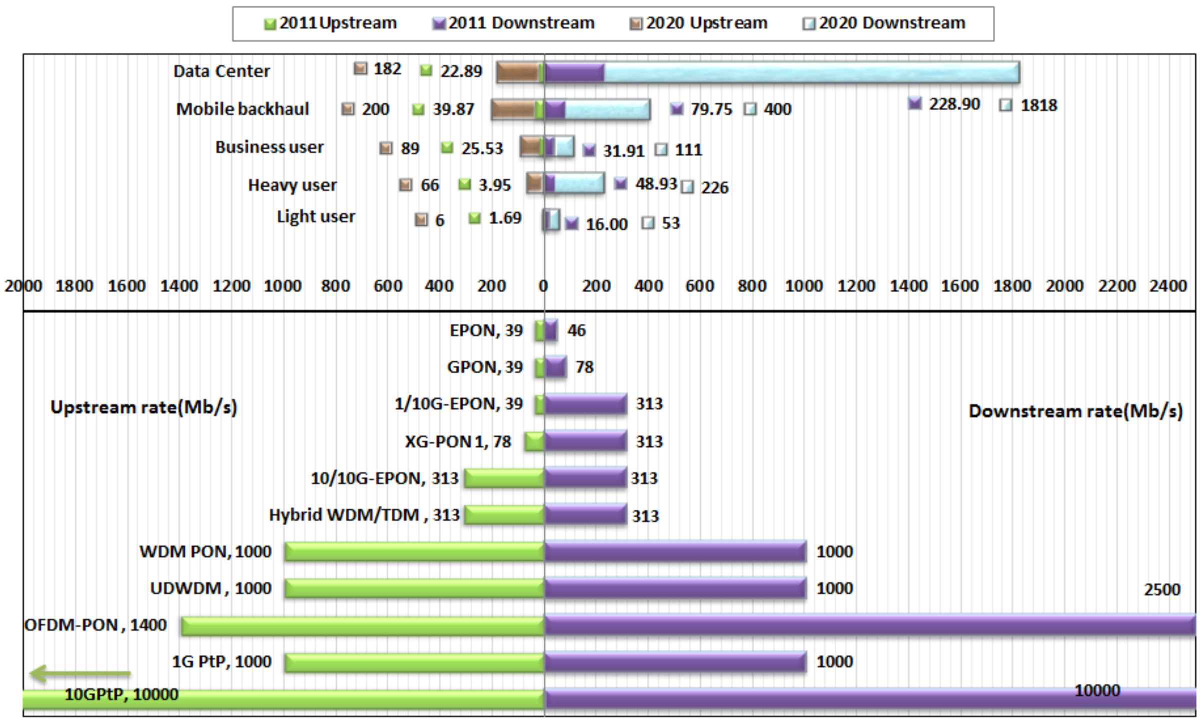


Figure 1-3. Today and future bandwidth requirements and solutions [1-3].

Nowadays, several types of Time-Division PON (TDM-PON) architectures [4-7] such as Gigabit-capable Passive Optical Networks (GPON) and 10-Gigabit-capable Passive Optical Network (XG-PON), Ethernet PON (1G/1G-EPON, 1G/10G-EPON) , 10Gbps Ethernet PON (10G-EPON) are options which can sustain data rate for 32 to 128 end users. Wavelength-Division Multiplexing PON (WDM-PON), Ultra-Dense WDM-PON, hybrid WDM/TDM-PON are considered as the potential solutions for future network, that can combine the best of P2P and PON by creating a logical point-to-point with end all types of users without any limitation in bandwidth and reach and number of user [8-12]. They will emerge in next two years and are new solution with high bandwidth for business and heavy users and are growing quickly for extended data rate.

Time and Wavelength-Division Multiplexing PON (TWDM-PON) with stacking 4 or 8 XG-PONs and a typical split ratio of 1:64, can achieve an aggregate rate of 40Gbps in the downstream and 10Gbps in the upstream. All transmitters and receivers in OLT and customer side are able to tune to any of the 4 or 8 upstream/ downstream wavelengths [13]. Using Orthogonal Frequency-Division Multiplexing-PON (OFDM-PON) [14-15], orthogonal subcarriers can be dedicated to different services to form a protocol transparent digital data pipe and is a pronounced reliance on electronic Digital Signal Processing (DSP) to compensate physical-layer impairments and achieve bandwidth flexibility.

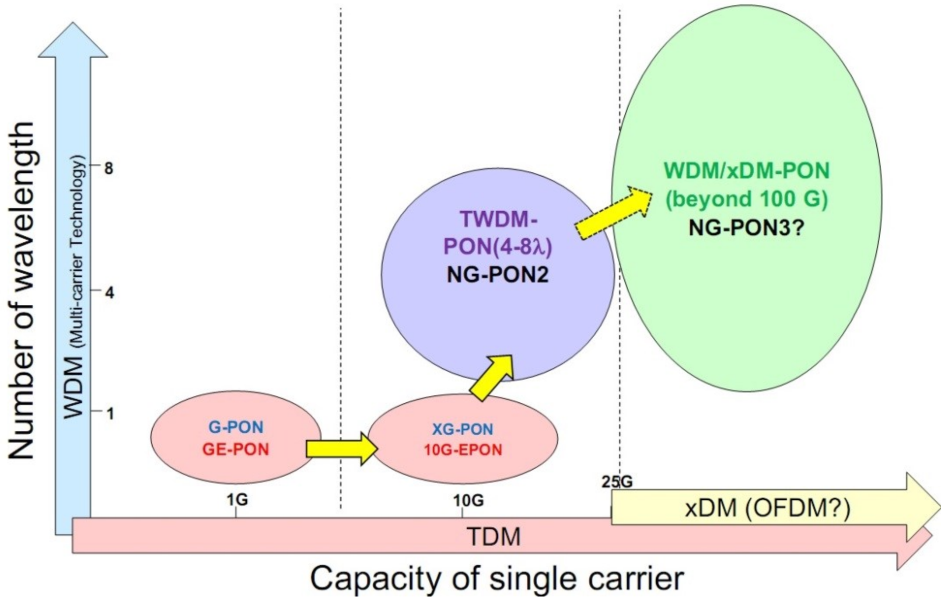


Figure 1-4. Technologies beyond NG-PON2 for increasing capacity [15].

The main goals of each of these networks is flexibility, reliability and easy to upgrade architectures for reducing the cost and complexity of delivering high bandwidth services. Operators are trying to identify a technology that can guaranty them with high benefit from current subscribers and adoption for future market changes. Although with this types of contributing issues and the rapid developing of new technology, it is very difficult to answer what the best economical technology is for today and tomorrow, but with optimization of development in current access network and have a glance for total cost and type of new technologies, the operator almost can get their answer.

Above all, the development of these networks has an important rule to characterize both the long-term cost implications and the long-term benefits of investing in the chosen technology [16]. Although, fibre as a base resource of PON is considered to be a cheap part in the total Capital Expenditures (CapEx), but it is not free and fibre with its installation take high cost per user. In the other side, OLT ports are expensive and consume most of the power in PON, so with sharing of OLT port for more users, costs of the OLT and its power consumption are decreased. Thus, under this circumstance, it is important to optimize outside of the network with implementing of several kind of distribution points and placement of them due to their effects on efficient use of OLT ports, fibre installation and power saving.

The CapEx per household greatly depends on demographics [17-21]. Therefore co-operation in rural areas with cascades splitter configuration in conjunction with reach extension technologies offers an improvement in resource sharing and decrement of deployment costs.

Also, flexibility is the key that prepares easy migration for FTTH network to unknown transmission technologies. For instant a splitter based PON using tuneable filter in customer side equipment can relatively easily be upgraded to any kind of new networks.

Furthermore, since the new components in optic or electrical parts of network are so expensive, especially in advanced optical devices and DSP, due to integrated optics devices and competition in market the estimation of future cost of new technology is needed [22]. The price learning curve for all components and demand forecast is presented over the study period for the residential users.

1.2 Objectives and Structure

When service providers start to develop a network, several questions should be considered before selecting a technology and designing a topology:

1. What are the services, networks and operation requirements for today and future access network for a seamless evolution toward NG-OANs?
2. How do the take rate (subscription rate), population density and data demand demographics influence selected technology and architecture?
3. How to calculate the CapEx considering realistic scenarios?

This work is trying to answer these questions with proposing a techno-economic model based on combining two bottom-up and top-down models with operators and scientific perspectives [20-23].

In order to fulfill the aforementioned objectives, this dissertation is divided in four chapters, in the first chapter the context of this work with summarizing the motivation, the objectives and the structure of the study are presented.

The second chapter presents an overview of PON standards based on TDM and WDM technologies and describes the requirements and needs for future PONs. In Chapter 3 we focus on techno-economic models of NG-OAN and propose physical architectures for PON networks and then estimate the entire devices price for future technologies. Finally in the last chapter, the conclusions drawn from the work presented in this dissertation and suggestions for future work will be made.

1.3 Main Contributions

The main contributions of this work are as follows:

- Overview and assessment of existing and future PONs.
- Implementation of geometric model for calculation of CapEx [18].
- Optimizing CapEx with splitter configurations [21].
- Development a techno-economic model for calculating total CapEx of optical access networks and calculating deployment and migration cost from GPON to WDM-PON.
- Applying techno-economic model for a realistic network and estimating the material cost when the price of new components is extrapolated in time and volume [14].
- Analysing the impact of different types of splitter structures on resource sharing and power consumption in long reach PON [31].
- Considering multi system Next-Generation PONs impact on Video Overlay [32].

1.4 Concluding Remarks

This chapter presented an overall view of the dissertation. The motivation and background for PONs were discussed. The services and different types of users as drivers of PON technologies were analysed and the required technology for each service versus time was presented. The main motivation of PONs was to maintain connectivity at high data rate with reliability and availability but cost-effective and without substantial changes in network infrastructures. The original contribution of the dissertation and also the dissertation organization were presented.

CHAPTER 2 DEPLOYMENT OF PASSIVE OPTICAL NETWORKS TECHNOLOGIES

Summary

PON technologies are becoming more and more attractive to service providers by offering efficient network resource sharing and high bandwidth demand. There is great attention given to exploiting different PON technologies and topologies in optical access networks. The purpose of this chapter is to provide an overview and assessment of existing passive optical access network architectures, along with a review of the architecture domains for NGOA networking. Also topological as well as numerical data in terms of the key requirements for bandwidth, reach and scalability are provided regarding current and future PON deployments in networks.

2.1 Introduction

Currently with progressing in the communication systems, larger bandwidth for sending more data at higher speed is required. Subscribers are interested the latest high bandwidth demanding internet applications and services such as Internet Protocol Television (IPTV), Voice Over IP (VOIP) and Video-On-Demand (VOD) applications. So internet providers must develop their network in order to present such technologies.

In this regard fibre based access networks can support the increasing demands for high speed connections. A FTTH network is a fibre-based access network that connects a large number of subscribers to a central office. In fact in the FTTH technology, the entire existing copper infrastructure such as telephone wires and coaxial cable are replaced by optical fibres. Each central office involves the required electronic transmission equipment to prepare applications and services over optical fibre to the subscriber.

Basically, there are three kinds of architectures for delivering FTTH: point-to-point, switched (active Ethernet network) and Passive Optical Network (PON) [16]. PON enable point-to-multipoint fibre access networks based on passive optical nodes. Nowadays, several types of PON architectures have been or are being developed. The main objective of this chapter is to present PON technologies and topologies and give an overview of TDM-PON, WDM-PON, hybrid PON and OFDM-PON. A short introduction on the existing and operating PON networks is made while also commenting on possible future solutions.

2.2 Passive Optical Network Standardization and Overview

Recently, several research groups and the telecom industry are putting a lot of effort towards the development of new access technologies. The main goal has been focused to the deployments and development of cost-effective, flexible, reliable and easy to upgrade architectures for access networks based on PON [4-15]. PON have been recognized for future access networks, because of providing high bit rate for number of users with sharing OLT port and feeder fibre. Furthermore availability of network for all users with using optimum amount of resources can make these access networks economical.

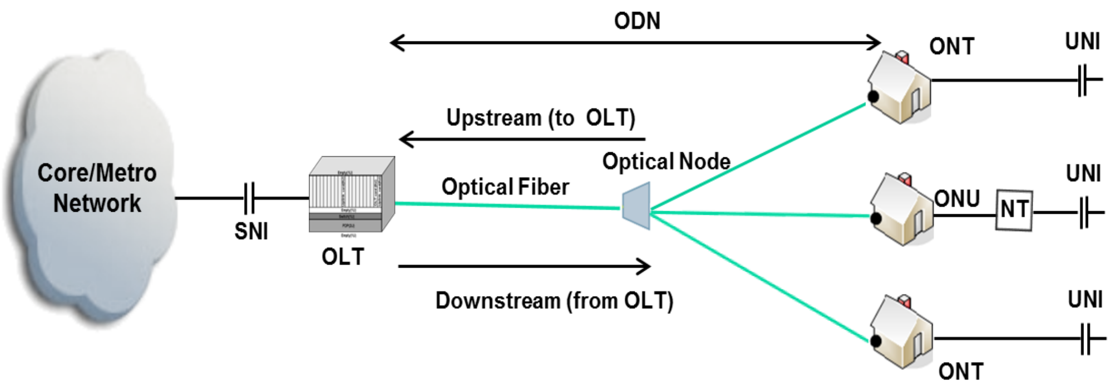


Figure 2-1. Basic concept of PON systems.

Figure 2.1 presents the basic concept of PON systems. A PON consist of one OLT that located at the service provider's Central Office (CO), optical fibres, Optical Network Terminal (ONT: user side equipment of PON for FTTH) or Optical Network Unit (ONU: user side equipment of PON for FTTC) at the end subscriber sites that is located to serve as the interface between PON and subscriber equipment. The Optical Distribution Network (ODN) is used for transmission network between OLT and ONTs/ONUs that includes all outside parts of PON such as fibres, distribution points. With Service Node Interface (SNI), OLT has a connection with metro or core networks. In the customer side User Network Interface (UNI) enables communication between ONU and customers. As ONU can have different protocols and connection, UNI may be used to convert the specific device protocol to the common one.

Recently, several PON technologies such as GPON and EPON have been standardized by the ITU-T and the Institute of Electrical and Electronics Engineers (IEEE), respectively. GPON delivers asymmetric 1.25 Gbps for upstream and 2.5Gbps for downstream directions whereas EPON provides symmetric 1Gbps for upstream and downstream [4, 5]. As shown in Fig. 2.2, upgraded versions of these technologies, one referred as XG-PON [6], has been deployed in recent years in order to extend reach and capacity. 10G-EPON has already been deployed since 2009 [7]. GPON is being marketed in several countries in the world. In some, the penetration is already quite high, e.g. In South Korea, India, Sweden, Japan, United Arab Emirates, etc. [16]. In Europe, several countries have been investing mostly on GPON deployments to enhance their broadband capabilities [16]. Also in Portugal, the State together with the various operators are promising to cover a very significant percentage of the population by allocating a very significant amount of resources in pursuing this objective (Annex I).

Beyond of GPON and XG-PON, several brilliant proposals for NG-PON2 such as TWDM-PON, WDM-PON, hybrid WDM/TDM-PON, UDWDM-PON, OFDM-PON under the umbrella of the FSAN group have been considered [8-15].

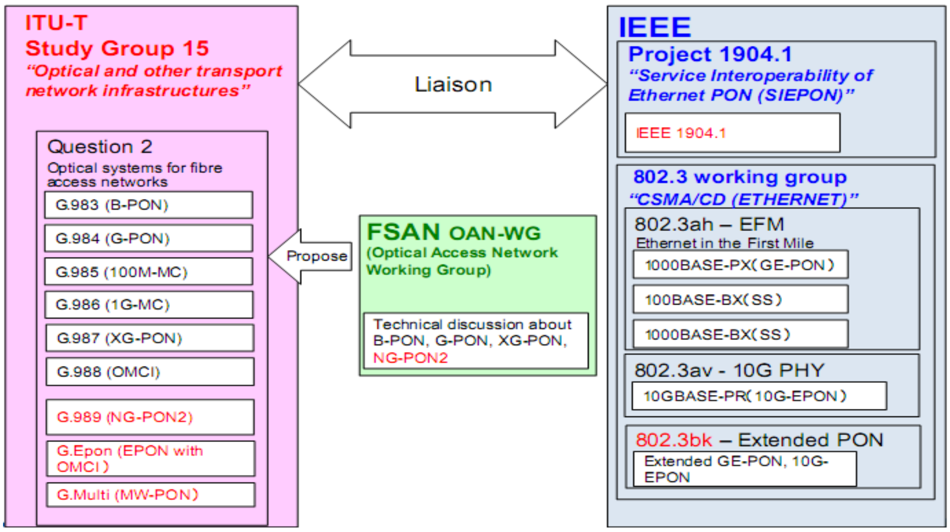


Figure 2-2. ITU-T & IEEE [15].

It follows that, all PONs deployed to date are all considered by three topologies: the majority of them is TDM based PONs (mostly GPON) then WDM-PON with hybrid of WDM/TDM and finally OFDM-PON. In continue an overview of these deployed optical access network architectures with focus on technical issues and solutions is given.

2.3 Time Division Multiplexed Passive Optical Network (TDM-PON)

TDM-PON applies the time division multiplexing technique that share a common wavelength between a set of ONUs. TDM-PONs use one wavelength for downstream transmission and another wavelength for upstream transmission. In this technology, the CO dedicates time slots to the ONUs and each ONU can see its own data through the address labels that was inserted in the signal. Beside downstream, TDM also used upstream direction in order to prevent collisions on the PON. During the assigned time slot, each ONU can use the full upstream bandwidth of the optical link. Main concepts of TDM-PON are shown in Fig. 2.3. Three versions of the TDM-PON already exist: EPON, Broadband PON (BPON) and GPON.

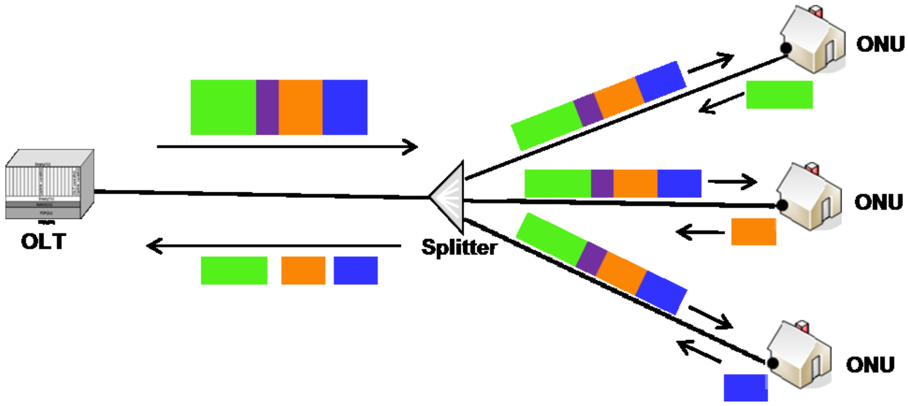


Figure 2-3. TDM PON basics concept.

2.3.1 GPON

GPON is a technology for passive optical access networks. It is specified by ITU-T G.984 series. GPON has improved capabilities compared to BPON and is backwards compatible. Depending on the class of equipment, the physical reach of GPON, i.e., the maximum physical distance between the ONU and the OLT, can be 10 km or 20 km. However, the

Figure 2-4. Optical passive materials [25]

standard defines that besides the physical reach limitation, the maximum distance between the ONU and the OLT (the logical reach) can go up to 60 km. Regarding the splitting ratio, it is obvious that for service providers, the largest split ratio and the best recommended splitting ratio is 64 users per PON.

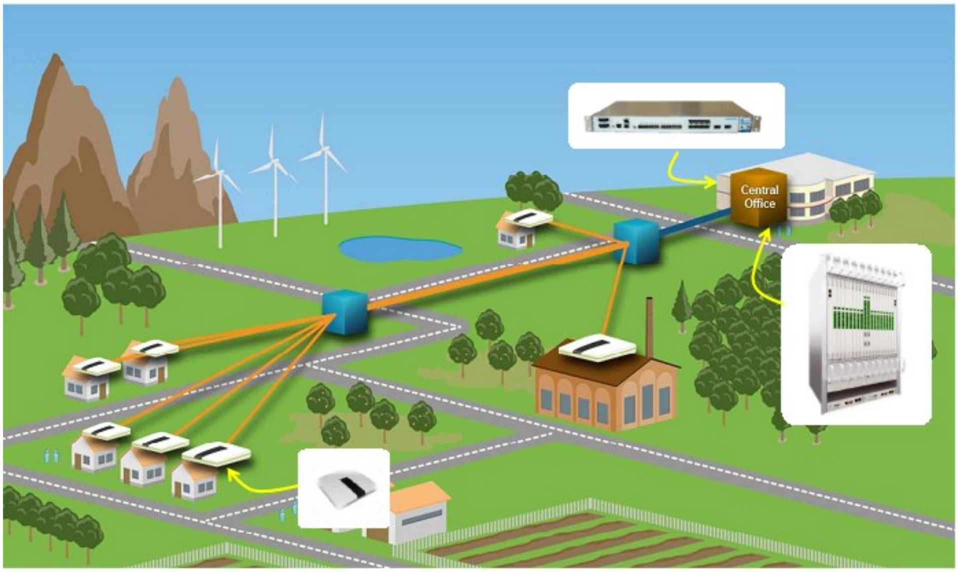


Figure 2-5. Active equipment Central Office and terminal equipment [25]

Still, the TC (Transmission Convergence) layer considers splitting ratios up to 1:128, which is a factor favouring. The reference configuration of a GPON network is depicted in Fig. 2.4 and Fig. 2.5. The network is constituted of an OLT, splitters, ONUs and optical fibre cables. The bidirectional transmission is accomplished by using WDM on a single fibre using 1490 nm (S band) in downstream and 1310 nm (O band) in upstream direction, the upstream access is made in TDMA (Time Division Multiple Access). It is also reserved the 1550 nm (C band) for the Video Overlay.

Even though the standard defines different approaches in the implementation of the GPON technology, the market choice has fell on 2.488Gbps and 1.244Gbps on downstream and upstream rates, respectively, over a single fibre. The main channel characteristics are shown in Table 2.1.

Table 2-1. Channel characteristics for GPON.

Description	Downstream	Upstream	Units
Nominal transmit wavelength	1490	1310	nm
Maximum range	Up to 60		km
Available power budget	28		dB
Minimum channel insertion loss	13		dB

The maximum and minimum optical power values for the transmitters and receivers of OLT and ONU are shown in Table 2.2. The parameters are specified relatively to an optical section design objective of a BER not worse than 10^{-10} and the optical fibre utilized to be a single mode defined in G.652.

Table 2-2. GPON receiver and transmitter characteristics

Transmitter Description	**Downstream**	**Upstream**	**Units**
Wavelength range	1480 to 1500	1260 to 1360	nm
Maximum optical launch power	+5	+5	dBm
Minimum optical launch power	+1.5	+0.5	dBm
Receiver Description	**Downstream**	**Upstream**	**Units**
Wavelength range	1260 to 1360	1480 to 1500	nm
Maximum bit error ratio	Less than 10^{-10}		-
Maximum receive power	-8	-8	dBm
Damage threshold	-	-	dBm
Receive sensitivity	-28	-27	dBm

Moreover, basically there are two common configurations for designing outside plant of a GPON, single splitter and cascaded splitter approaches. Figure 2.6 presents both configurations.

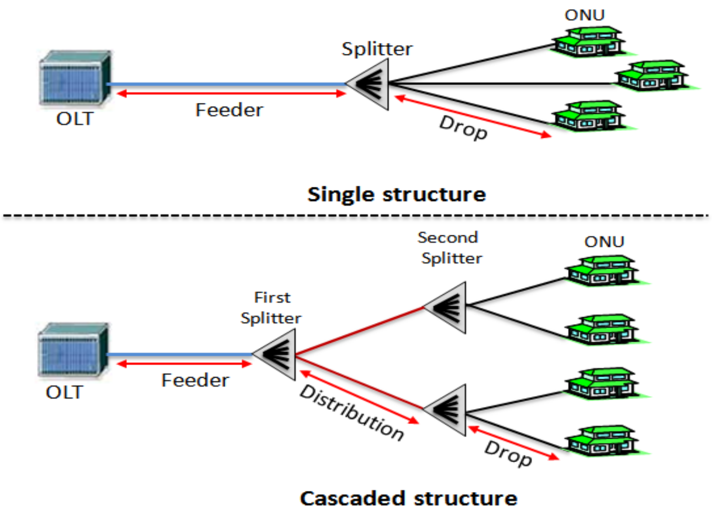


Figure 2-6. Single and Cascaded configurations

Advantages of GPON:

- GPON consists of a cheap solution in terms of CapEx. The TDM technology allows for sharing of the feeder fibre, among 16, 32, 64, 128 users according to the splitting ratio (1:16, 1:32, 1:64 and 1:128 respectively). The number of the ducts, sub-ducts and trenching, therefore the overall cost of the outside plant are diminished when compared to a point to point architecture.

- GPON consist of a low cost solution in terms of Operational Expenditures (OpEx). Un-powered or passive optical splitters are used, so that a single optical fibre serves multiple premises.
- Lower floor space usage at CO. Save CapEx in terms of cooling, UPS.
- It is well suited for legacy networks; it allows incumbents to reduce the number of main distribution frames (MDFs) in the short term, lowering considerably OpEx.
- Providers share the cost of the feeder fibre between 32, 64 or 128 users. Cost effectiveness regarding fibre optic cable installation and central office equipment.
- Reduction of the OLTs needed.
- No active electronics in the access network ("Green" solution).
- The GPON standard provides native carrier class transport of both Ethernet and legacy TDM.
- Upgrades or new services with equipment changes at the network ends and on a customer basis.
- Analog video overlay for existing broadcast services.

Disadvantages of GPON

- More customers affected by link failure.
- Shared bandwidth limits bandwidth to each subscriber.
- Maximum recommended distance between OLT and ONU restricted to 20km.
- Capacity planning difficult for business applications.
- If less than 32, 64 or 128 subscribers in the cases of 1:32, 1:64, 1:128 splitting ratio respectively are located within the ONU serving radius, the OLT cost per subscriber served is very high.
- Considering 1:64 splitting ratio, if more than 64 subscribers are located within an ONU serving radius a second OLT port must be deployed to support the 65rd subscriber and results in a steep spike in the OLT cost per subscriber served.
- If one customer requires service outside of an existing ONU serving radius, a new OLT port must be deployed to support the customer and results in the OLT cost per subscriber served being very high.

- If customers outside the 20km OLT serving area require service, a complete OLT chassis must be deployed in a new physical location that can reach the customer and results in the OLT cost per subscriber served being very high.

2.3.1.1 Long Reach GPON

In most urban settings, the GPON standard can satisfy the majority of the customers without big adaptations. However, to more rural and scattered scenarios (interior and south of the country or large countries) the standard equipment cannot operate. The power margins that the standard defines are not suitable for this type of scenario, where distances are greater than 20 km and division ratio is small.

One way to solve this problem is by installing top class equipment. This solution entails a higher cost and in many cases will not be enough, as the extra margin is small, resulting in the lack of coverage in some areas. The other solution is to install a device to increase the physical reach of the signal, both in amplitude and in quality. The second option is the subject of this work.

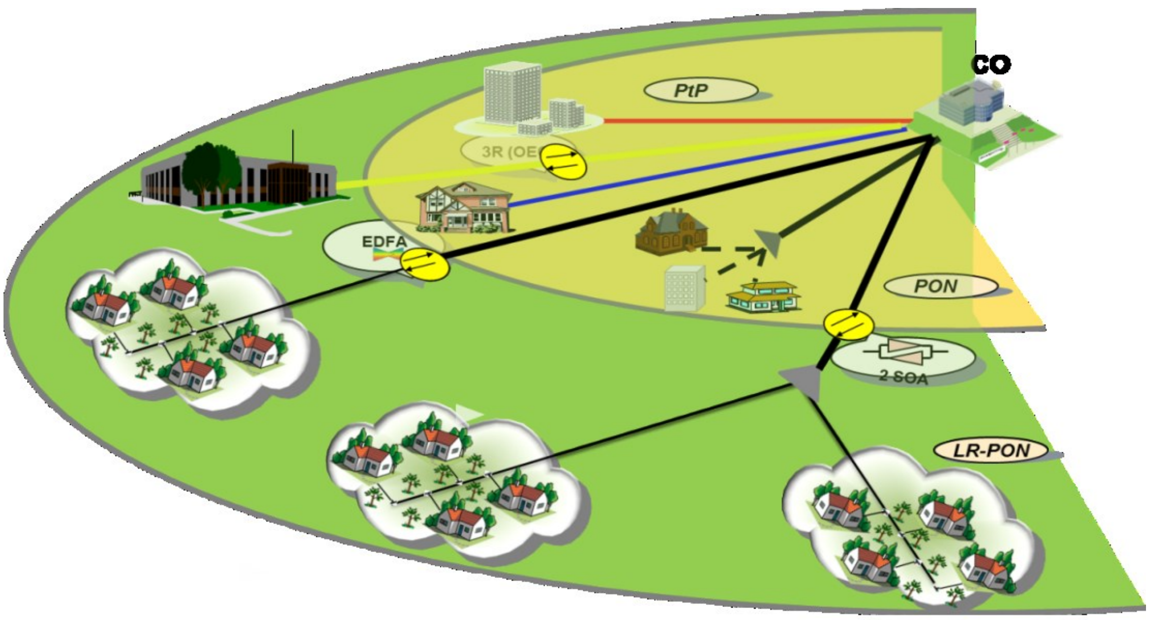


Figure 2-7. Mid-span extension.

The need to extend the physical reach or the number of clients in a GPON led the ITU to outline the architecture and interface parameters to achieve that goal. The standard defines two general classes of extender devices. The first class is based on the use of Optical-

Electrical-Optical (OEO) regeneration, which can be 2R or 3R. The 2R receives an optical signal, reshapes and re-amplifies the signal. The 3R reshapes, retimes and re-amplifies the signal. These processes are done in the electrical domain and then the signal is again converted to the optical domain and is retransmitted.

The second is using an optical amplifier, which provides gain in optical domain such as Semiconductor Optical Amplifier (SOA) and Erbium Doped Fibre Amplifier (EDFA). Hybrid schemes are also possible, using regeneration in upstream and optical amplification in downstream or vice-versa. The insertion of the extender device is recommended to be between the ODN and an OLT as depicted in the Fig. 2.7.

The standard defines the essential parameters for the design of a mid-span extender for both optoelectronic regeneration and optical amplification. But as the choice fell on using optical amplification in the design the extender box in this project, the parameters that here presented, are focused just in the recommendations for optical amplification.

The system with the insertion of the extender box must remain compatible with the existing terminal equipment and thus, new power budgets are defined. With the introduction of the extender box, in the OLT, the power budget is now 23 dB in downstream and 28 dB in upstream, and in the ODN, between 13 and 28 dB for both downstream and upstream.

Table 2.3 summarizes the recommended characteristics for an extender box based on optical amplifiers.

Table 2-3. Relevant parameters of an extender box based on optical amplifiers

Transmitter Description	**Downstream**	**Upstream**	**Units**
Maximum power output	+1.5 – minimum gain – OLT loss	+5 – minimum ODN attenuation + maximum gain	dBm
Minimum power output	+0.5 – maximum gain – OLT loss	+0.5 – maximum ODN attenuation + minimum gain	dBm
Maximum ASE output @ -28 dBm input	+5	+7	dB
Receiver Description	**Downstream**	**Upstream**	**Units**
Maximum receive power	-5	-8	dBm
Minimum sensitivity	-23	-28	dBm

2.3.2 XG-PON

XG-PON is an improvement to GPON with enhancement framing and management in Mac layer. It can provide full-service operations via higher rate (upstream rate: 2.5Gbps and the

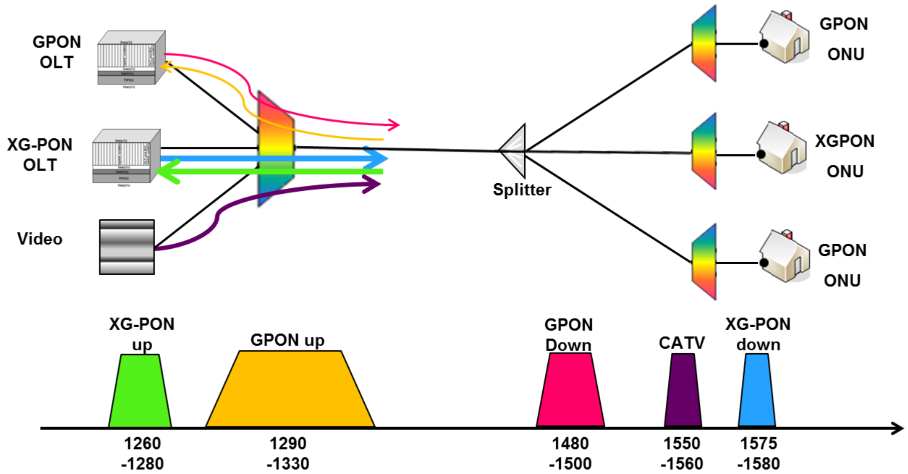


Figure 2-8. Coexistence of GPON, XG-PON and CATV

downstream rate: 10Gbps) and larger split to support diverse access scenarios such as FTTH , Fibre To The Cell (FTTCell), Fibre To The Building (FTTB) and Fibre To The Cabinet (FTTCabinet).

Table 2-4. XG-PON and 10G-EPON comparison [15].

Item			**10G-EPON(10G symmetric)**	**XG-PON**
Services			Ethernet data	Full services (Ether, TDM,POST)
Mac layer	Frame		10G Ethernet frame	XGTC/XGEM frame
	Max number of ONU		32,768(Max of LLID)	1,024 (Max of ONU-ID)
	FEC		Up: RS(255, 223) Mandatory Down: RS(255, 223) Mandatory	Up: RS(255,239) Option Down: RS(255,223) Mandatory
Physical layer	Line rate		Up: 10.3125Gbps Down: 10.3125Gbps	Up: 2.488Gbps Down: 9.953Gbps
	Transmission bandwidth		10Gbps for upstream and downstream (64B66B coding)	Same as the line rate (Scrambled NRZ coding)
	Maximum loss		20 / 24 / 29dB	29 / 31dB
	Optical level	ONU	TX: +2～+5dBm RX(min): -25dBm	TX: +2～+6dBm、RX: -28～-8dBm
		ONT	TX: +4～+9dBm、RX(min): -27dBm	TX: +2～+7dBm、RX: -27.5～-7dBm

This technology is able to coexist with legacy GPON and CATV as shown in Fig. 2-8. With adding 10G interface board to the OLT, the service providers can achieve smooth evolution from GPON to XG-PON, which completely leverages the ODN of GPON.

In the same way 10G-EPON is an improvement to EPON. Both XG-PON and 10G-EPON are based on the existing PON technologies and are upgraded for 10Gbps but they have some differences that are considered in Table 2.4.

2.4 Wavelength Division Multiplexed PON (WDM-PON)

EPON and GPON systems are based on TDM-PON architecture because they both rely on TDM technology. This is in contrast to WDM-PON systems, which use frequency to separate users' signals.
Clients and industries have been demanding bandwidth that only passive optical networks can achieve and a crucial feature for the evolution of GPONs towards higher capacity WDM-PONs is the reuse of existing infrastructure. The research and development of optoelectronic technologies enables the optical fibre capacity to be exploited and this is the main reason for the current data traffic growth and nowadays the dominant carrier of information is the optoelectronic technology, being central for the realization of future networks, that will have virtually unlimited capacity to carry communication services. To this aim, full transparency is required to allow terminal upgrades in capacity and flexible routing.

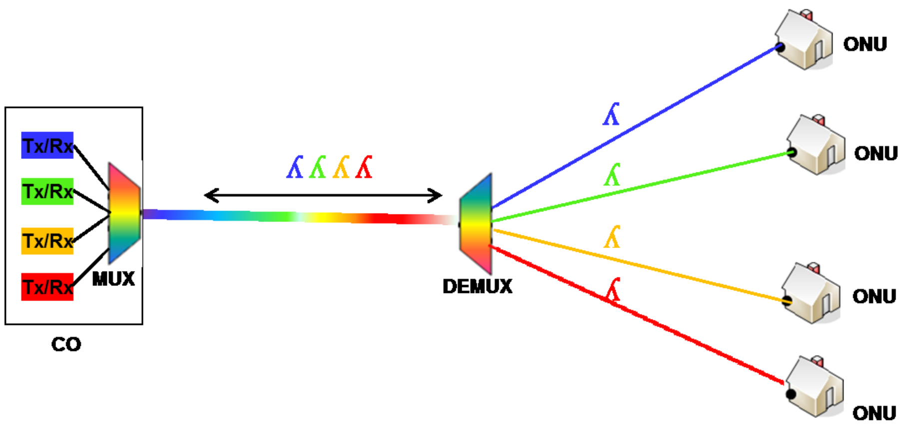


Figure 2-9. WDM-PON basic concept

WDM-PON applies separate wavelength channels from the OLT to the ONUs in the downstream direction and from the ONUs to the OLT in upstream direction. In this technology the wavelength division MUX/DEMUX is employed in the ODN part. Figure 2.9 shows Array Waveguide Gratings (AWGs) are used to MUX and DEMUX wavelengths to or from ONUs.

A WDM-PON:

- Consists of dedicating a λ and associated bandwidth to every user connected to a PON, providing dedicated bandwidth over a shared infrastructure.
- The WDM PON standardization body is the FSAN Group but the technology has not been standardized yet, although some operators have already deployed proprietary solutions from leading vendors.
- The OLT puts all the λ onto the shared feeder fibre, broadcasts to all receivers and the splitters replicate the wavelengths.
- To select the appropriate channel to each home static and tunable filters are used. ONUs operate on different λ and hence higher transmission rates can be achieved.
- WDM-PON requires the replacement of the optical power splitter by an AWG at the Remote Node (RN).

Table 2.5 shows the main differences between GPON and WDM-PON technologies and next an approach on the main evolution and scenarios is made.

Table 2-5. Differences between GPON and WDM-PON technologies.

	GPON	**WDM-PON**
Standard	ITU G.984	ITU G.983
Data Packet Cell Size	53 to 1518 bytes	Independent
Maximum Downst. Line Rate	2.5 Gbps	1-10 Gbps per channel
Maximum Upst. Line Rate	1.25 Gbps	1-10 Gbps per channel
Downstream Wavelength	1490 and 1550 nm	Individual λ/ channel
Upstream Wavelength	1310 nm	Individual λ/ channel
Traffic Models	ATM Ethernet or TDM	Protocol Independent
Voice	TDM	Independent
Video	1550 nm overlay/ IP	1550 nm overlay/ IP
Max PON Splits	64	16/100’s
Max Distance	**60 km**	**٤0- ٨٠km**
Average Bandwidth per User	40 Mbps	Up to 1-10 Gbps

Several WDM-PON architectures have been proposed for providing scalability that is lacking in traditional PONs. In this section, we review two representative WDM-PON architectures which have been proposed in the literature [3, 8, 15].

2.4.1 Broadcast-and-select WDM-PON

Figure 2.10 shows a broadcast-and-select WDM-PON architecture based on passive optical power splitters in ODN field. All wavelengths are transmitted to each ONU. Therefore, each ONU has tunable lasers (TL) and tunable receivers (TRx) modules that can select the wavelength to be received as well as the wavelength for upstream signal. The tenability in the laser and filter at ONU side are required for effective deployment. Also for tunable filter maximum number of ONUs is limited by the number of available wavelengths in filtering. Splitter base WDM-PON coexists with GPON over the same ODN; thereby operators have easy migration and can protect their investments on GPON. This coexistence is shown in Fig. 2.10.

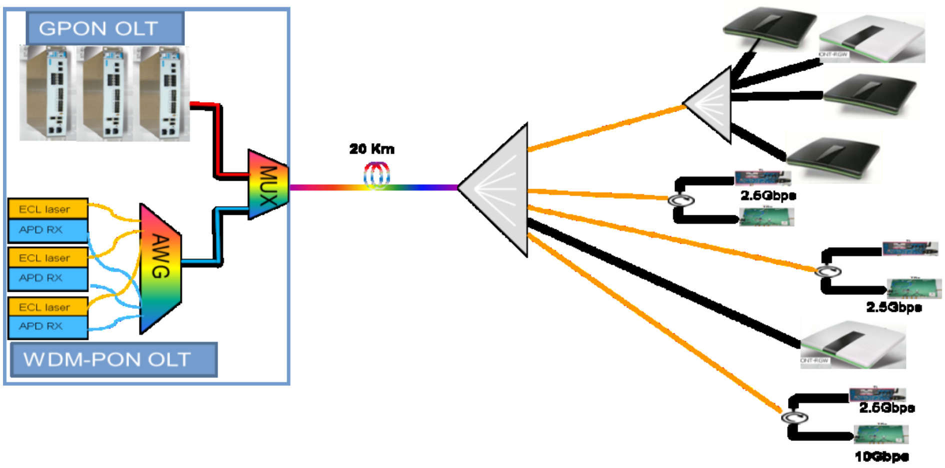


Figure 2-10. Wavelength-selected WDM-PON [25].

This is a solution that provides scalability because it can support multiple wavelengths over the same fibre infrastructure, taking advantage of sending information packets on different wavelengths, determined by the destination of the information. The tunable lasers were used due to their simplicity, reliability, performance, and because they offer the possibility to control dynamically and remotely the wavelength in the network. The operational parameters of the tunable transmitter such as optical line width, tuning range, tuning speed will determine the network design. Using high split ratio with single and cascaded splitter is depended to power budget of systems. However, high split ratio leads to limitations on reach. Also all ONUs can be tuned to all wavelengths and security issues should be solved in upper.

2.4.2 Wavelength-filtered WDM-PON

The wavelength filtered WDM-PON is based on multiplex/demultiplex wavelengths namely AWG in ODN part as shown in Fig. 2.11. The transmitted signal from OLT is routed by AWG (40 to 90 channels) to each ONU and so in customer side each ONU is not colourless. A Rx module in ONU consists of a Photo-Detector (PD), and its accompanying electronics for signal recovery and can be designed with Positive-Intrinsic-Negative (PIN) or Avalanche photodiode (APD) with 10 dB higher sensitivity. The TX in ONU could be designed either with tuneable lasers or Reflective-SOA (RSOA).

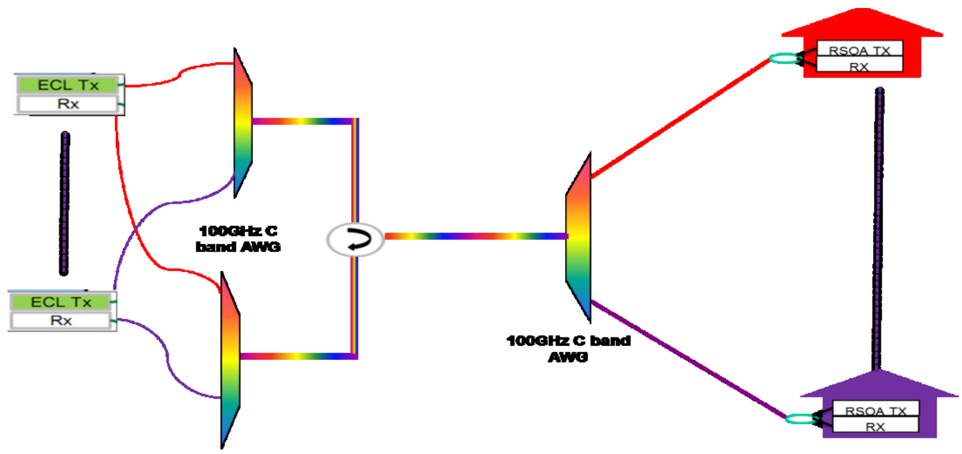


Figure 2-11. Wavelength-routed WDM-PON [3,8]

Advantages:

- Low loss
- Allows for spatial reuse of the wavelengths channels
- The same AWG output port can be assigned for both up and down transmission

Disadvantages:

- Needs Temperature Controllers (TEC); AWG's centre wavelength shift of 0.01nm/°C.
- Operators have to change its fibre plant.

2.4.3 Ultra Dense WDM-PON (UDWDM-PON)

Ultra Dense WDM PON (UDWDM-PON) is based on optical coherent detection in receiver and splitter in ODN part. Combinations of power splitters and AWGs can be used in the distribution network depend to the reach and number of users. Figure 2.12 presents the architecture of UDWDM-PON.

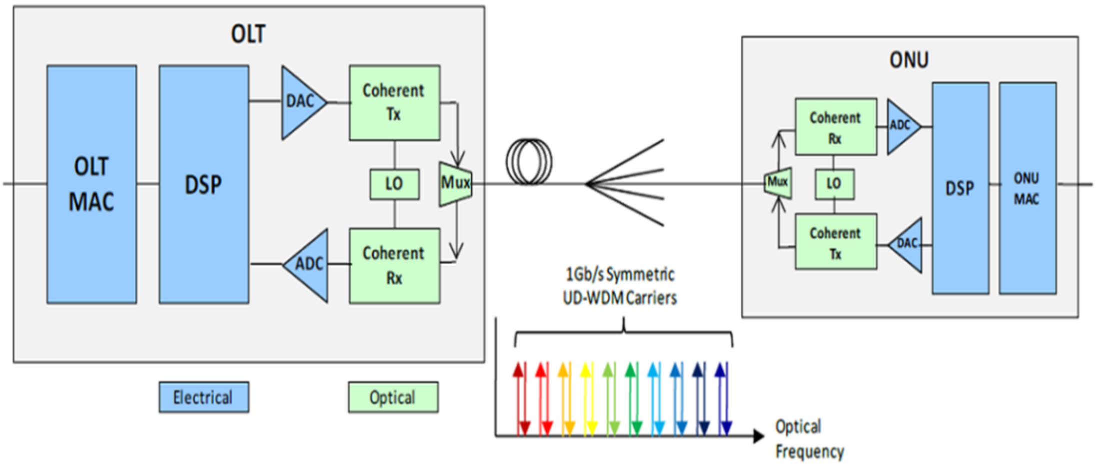


Figure 2-12. Architecture of UDWDM-PON [3].

The high wavelength selectivity of coherent detection enables ultra-dense wavelength spacing as narrow as 3 GHz without the use of optical filters. The inbuilt intrinsic signal amplification by the local oscillator laser enables a very high sensitivity and therefore both high split factors and long reach. Thanks to coherent-PON in both side of transmitter and receiver, the capabilities can be extended to:

- High transmission speed, FTTH residential peak data rates ≥1 Gbps and business, backhaul peak date rate: ≥10 Gbps.
- Enabling the connection of up to 1000 customers per feeder fibre.
- Support of splitter- based and totally passive ODN with desirable compatibility.
- ONU with bandwidth efficiency and lowest electronic requirements.
- Low power consumption in ONUs and OLT.
- Minimum channel spacing and good spectral efficiency.

With all these benefit this technology is so expensive and it is too soon to come in access networks (maybe in mobile backhaul users should be economical).

2.5 Hybrid PON

Since TDM-PON limit each user to a certain time slot, the security of the transmission is low because each user receives all the information sent to the other users on the network. This issue can be solved by assigning a specified wavelength to each user. Combining TDM and WDM in a hybrid PON network can be the most cost effective way for introducing TDM/WDM PON in access network. In this work we explain two types of hybrid PON.

2.5.1 Time and Wavelength Division Multiplexed PON (TWDM-PON)

The baseline architecture of TWDM-PON is shown in Fig 2.13. Four XG-PONs are stacked with a typical split ratio of 1:64, achieving an aggregate rate of 40Gbps in the downstream and 10Gbps in the upstream. So, upstream and downstream rate can be 2.5G - 10Gbit/s/ch.

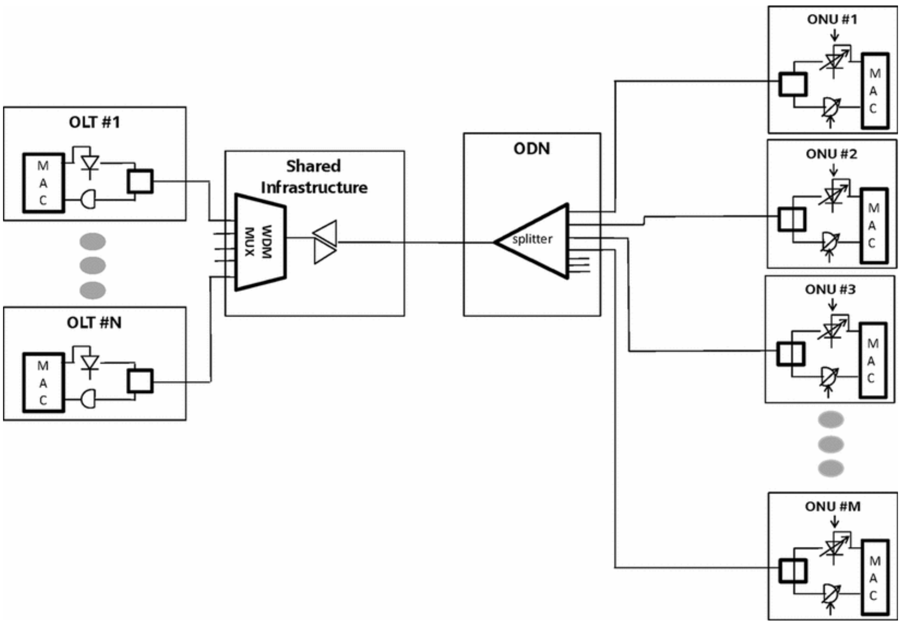


Figure 2-13. Architecture of TWDM-PON [12].

ONU transmitters are able to tune to any of the four upstream wavelengths. ONU receivers are able to tune to any of the four downstream wavelengths. Depending on the service demand, available spectrum and optics capability, the number of stacked XG-PONs can be increased as an extension of the basic architecture. The key technology of TWDM-PON includes the commercially viable tunable transmitter and tunable filter for ONU development. TWDM-PON system is primary system for NG-PON2. In order to adapt to different NG-PON2 implementations, TWDM-PON's ONUs can be simplified as ONUs with tunable transmitter and fixed receiver, ONUs with fixed transmitter and tunable receiver, as well as ONUs with fixed transmitter and receiver.

2.5.2 Wavelength-Switched hybrid WDM/TDM-PON

The hybrid WDM/TDM-PON concept aims to improve the fan-out of the WDM-PON architecture using combination of wavelength and time-division multiplexing.

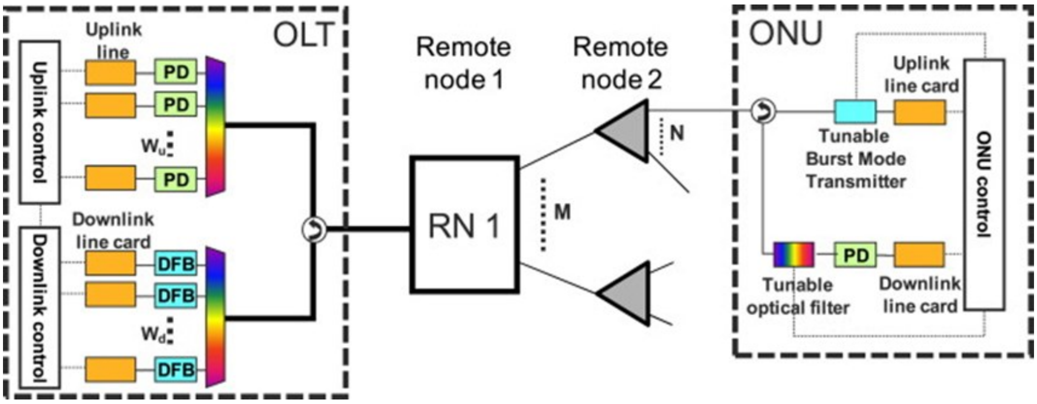


Figure 2-14. Architecture of WDM/TDM-PON [3, 10].

The ODN can be based on only splitter or different combinations of AWGs and splitters as shown in Fig. 2.14. Although in the case of a purely power splitter-based ODN the architecture has high flexibility concerning resource allocation, but insertion loss is high and also filtering is needed at the ONUs to select downstream wavelengths. The feeder fibre in WDM/TDN may be made as a ring (e.g. SARDAN [11]) or tree topologies. The comparison indicates that WDM/TDM due to its access-metro convergence provides the potential of serving a high number of customers with a small number of fibres especially in the feeder part of the network, which translates to great savings in terms of material and labour.

2.6 Orthogonal Frequency Division Multiplexing PON (OFDM-PON)

While entirely amenable to use hybrid WDM/TDM-PON, the distinguishing feature of OFDM-PON is a pronounced reliance on electronic DSP to compensate physical-layer impairments and achieve bandwidth flexibility [13-15]. OFDM-PON employs orthogonal frequency division multiplexing method to increase the supplying data rate. OFDM is the data modulation scheme that encodes digital data on multiple carrier frequencies; it splits the available spectrum into many carriers, each one being modulated by a low rate data stream.

OFDM-PON applies one wavelength for downstream and another one for upstream. It divides the total OFDM bandwidth into N sub-bands in both downstream and upstream traffics. Each sub-band contains a quantity of subcarriers required by each user [13-15]. The OFDM-PON architectures based on Intensity Modulation – Direct Detection (IM-DD) is expected to generate high-speed signals by low-bandwidth cost-effective transceivers, such as commercially matured 10GHz Directly Modulated DFB Lasers (DMLs) or Electro-absorption Modulated Lasers (EMLs), and 10GHz photo-detectors. An example of OFDM-WDM-PON is FIVER as shown in Fig. 2.15. The FIVER project proposes and develops a novel integrated access network architecture, which employs only OFDM signals for the provision of quintuple play services, i.e. Internet, Intranet, phone/voice, HDTV, and home security/control.

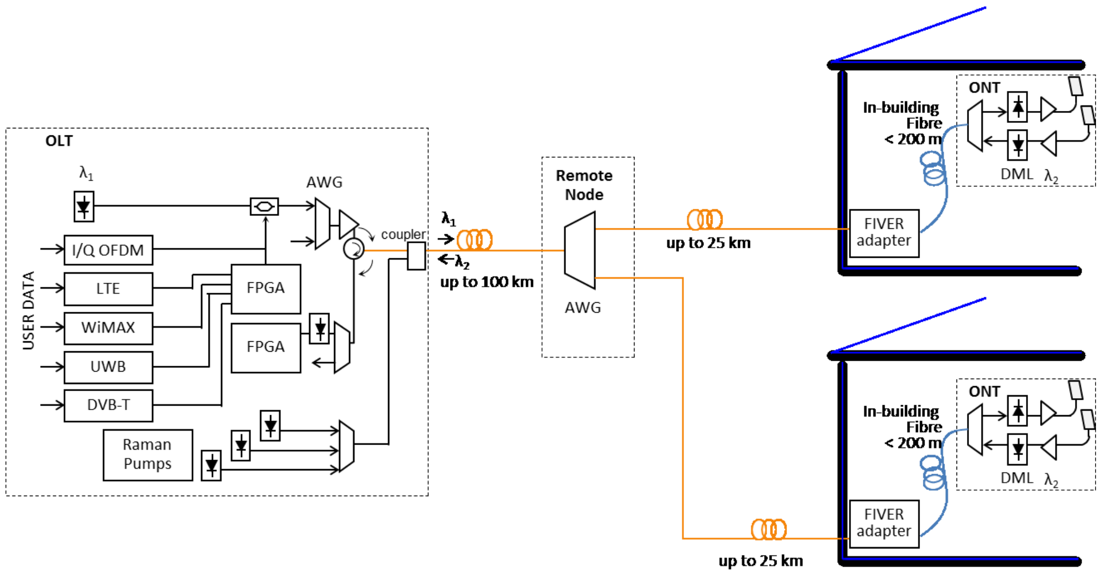


Figure 2-15. Architecture of OFDM-PON [14].

The FIVER architecture is completely FTTH integrated as shown in Fig. 2.15. The FIVER solution is a fully OFDM based network that allows cost effective, fully centralised network architecture:

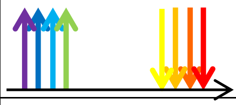
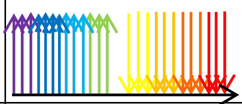
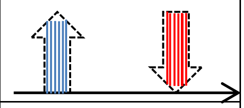
- The optical and radio transmission impairments compensation and network management are done only at the CO.
- No further compensation, regeneration or format conversion is required along the network giving the streamlined network architecture the capability of handling future services of interest.

All the transmission compensation algorithms, electro optical and network management subsystems are developed by the FIVER consortium [14]. The FIVER transport technologies are fully converged, i.e. both baseband (Gigabit-Ethernet provision) and standard wireless (WiMAX, UWB and LTE) signals are transmitted in radio-over-fibre through the FTTH. The in-building optical infrastructure and also the final user radio link.

2.7 Concluding Remarks and Comparison

In this chapter, PON architectures were investigated from the viewpoints of standardization, ODN topology, capacity and reach. PONs aim to reach bandwidth demand of operators at a lower cost using resources sharing.

Table 2-6. PONs comparison [10]

	TDM	TWDM	WDM	OFDM
				
Rate(Down/Up)	40/10G	4*(10/2.5G)	N*(1/1)G	40/10G
Optical budget	31 dB	37 dB	29-43 dB	30-36.5 dB
Split ratio	32-64-128	32-64-128	40-80	32-64
Reach	<40 km	<40 km	<20-60 km	<100 km
Cost	Medium	Low	High	High

The existing and future PONs in the access network were presented and it was discussed how different types of ODN can improve the performance of these systems. As an outcome of this chapter it was seen that the main candidates for NG-PON2 based on the posed requirements are different types of WDM-PON, hybrid WDM/TDM-PON and OFDM-PON with IM-DD.

CHAPTER 3 TECHNO-ECONOMIC STUDY

Summary

This chapter is focused on the estimation of all costs for the deployment of GPON, WDM-PON and OFDM-PON comparing them also with other optical network topologies. A model for cost estimation of the multiple needed components is presented. The CapEx per user for both single and cascaded splitter schemes for different take rates is calculated. The comparison indicates that in cascaded configuration length of drop fibre and consequently duct and trenching are reduced which translates to great savings in terms of material and labour. The calculated cost for key individual elements of WDM-PON and FIVER is extrapolated in time and then incorporated in the model for calculation of deployment costs and migration cost from GPON to WDM-PON.

3.1 Introduction

When looking ahead, there are a large variety of optical access network technologies and architectures for operator that provide wide service portfolio to the subscriber. The complexity, flexibility, network functionality, services, bandwidth supported and overall network costs for each of the potential optical access network technologies are different. It is crucial for operators to know a detailed assessment of the economic viability of different type of access network scenarios per their control areas.

The literatures and tools [16-23] show that the carriers use two classes of approaches for network and cost modelling in optical access networks: top-down versus bottom-up. As shown in Fig. 3.1, the bottom-up needs as a starting point, the demand for the services then incorporates this service demand with population information on all potential users and requires minimizing network costs with difficult optimization problems. But the top-down starts from the existing network infrastructure, uses engineering experience and guiding principle over time in the telecom industry to dimension specific or general population.

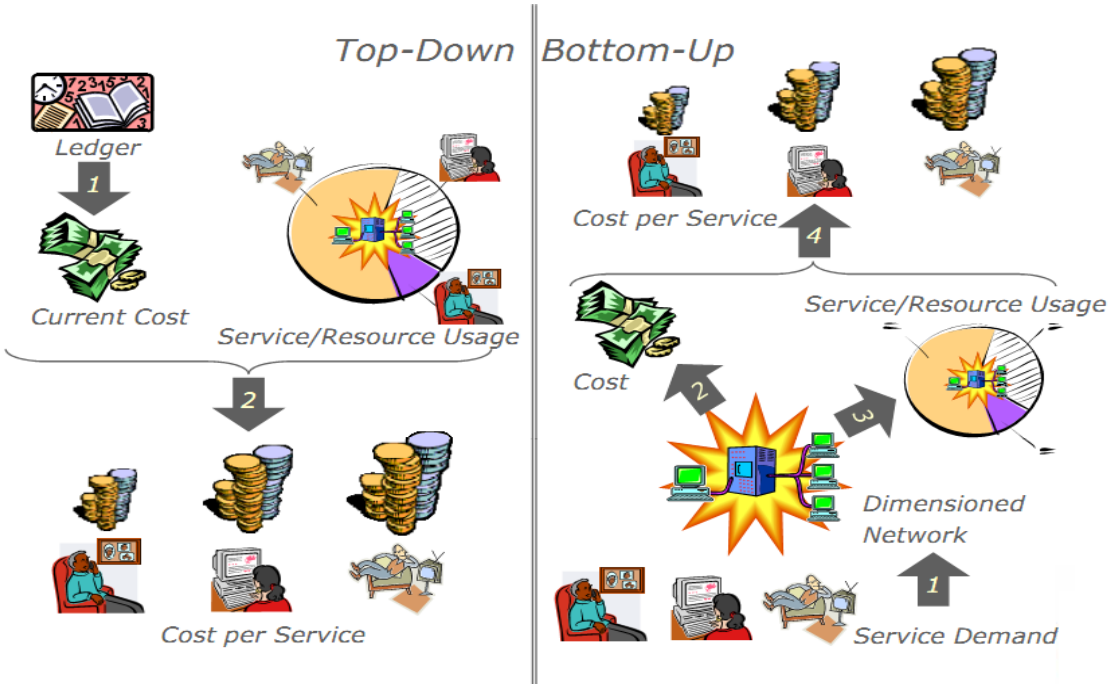


Figure 3-1. Top-down and bottom-up cost and network modelling approaches [20].

Also, bottom-up assigns costs to products and services of existing or optimized future networks, while top-down relies on identification cost information for a deployed network.

However, a model by incorporating the bottom-up approach as an optimization-focus with the top-down approach as an engineering-rules based would enable to remove the cost calculation limits and describe how population and technology choice drive network topology. Moreover, during the last decade many studies have focused on network CapEx, but the recent studies have begun to classify the important cost drivers in OpEx and few literatures have integrated CapEx with OpEx network or comparison of lifetime network costs beyond access technologies and population. A variety of research-based and commercial driven techno-economic studies for comparison of different optical access architectures can be found in [3]. However, in order to be able to estimate the CapEx, it is important to start from a life-cycle of the project and get firstly complete cost breakdown for the costs of the different phases in the FTTH deployment and define the table to classify all cost components based on their cause, calculation, and size.

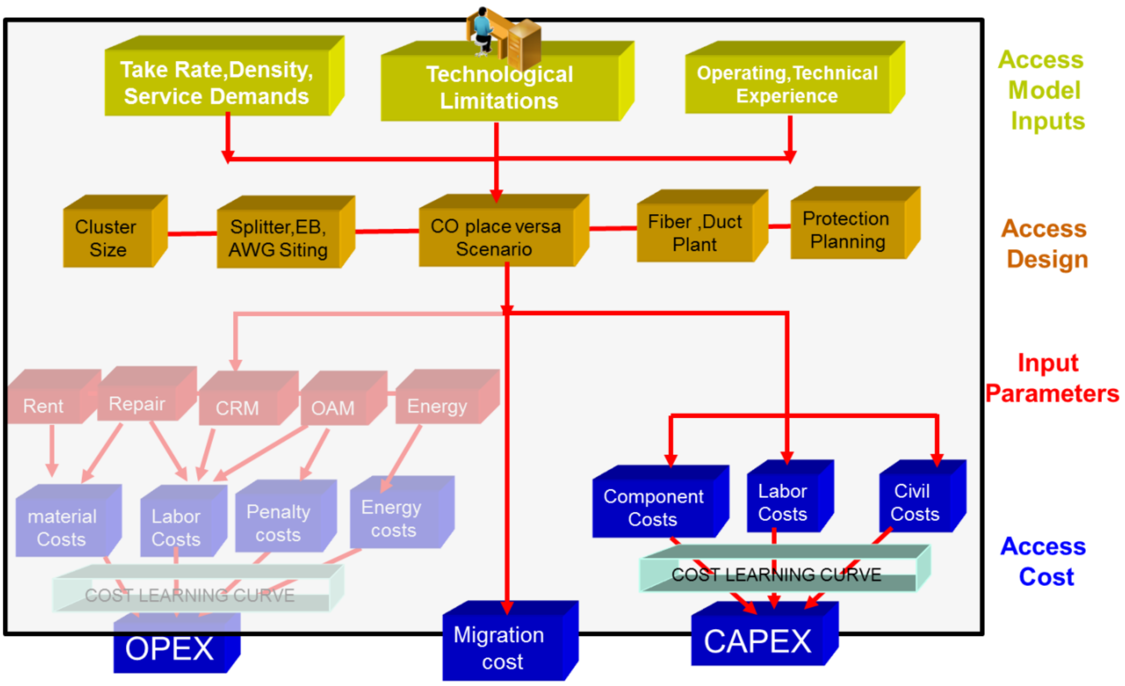


Figure 3-2. Full cost breakdown for an FTTH deployment project.

The result for final cost breakdown is shown in Fig.3.2. With combining this cost breakdown and the parameter classification coming from selected access network, Total Cost of Ownership (TCO) tool can obtain and the outcome of TCO tool can help in calculation of the full cost of deployment, operation and migration. This cost modelling can be supported with the following assumptions:

- Applying bottom-up approach with focus on network, population and related cost-drivers.
- Utilizing top-down approach with the computational tractability where bottom-up is not feasible or necessary.

3.2 GPON Cost Model

Although, fibre as a base resource of GPON is considered to be a cheap part in the total CapEx, but fibre with its installation take high cost per user. In the other side, OLT ports are expensive and consume most of the power in GPON, so with sharing of OLT port for more users, costs of the OLT and its power consumption are decreased. Thus it is important to optimize outside plant with implementing several kind of splitters and placement of them due to their effects on efficient use of OLT ports, fibre installation and power saving.

In general, lower CapEx per user is not obtained only with reducing the fibre installation and changing type of splitter, but efficient sharing of resource can also make the access network economical [16,18]. The authors in [17] present the cost drivers of outside plant with a techno-economic investigation between the standard FTTH deployments for future high-splitting ratio PONs. With geometric models all the important parameters for development of outside plant like population density, take rate, distance between splitters, users and central office (CO) are employed. Herein several geometric models have been developed to calculate the deployment cost of PON networks [19-23, 27, 28]. In [23] splitters are located near the centre of the serving areas.

We introduce one strategy for designing outside plant of a GPON network then consider different scenarios with single and cascaded configurations and then compare the results obtained by them in order to find more cost effective scenario with power saving. Also we analyse all the related cost factors and values in inside plant of GPON.

For designing a GPON, we put central office in the middle of the city and use a type of triangle model, this model is a polygon based model for the access network [26]. In this regard because the population density is different in various parts of the city, the coverage region is divided by k circles. Beside it, depend on selected angle for triangles we have p triangles in each region.

Also we can assume that the radius of each region is twice bigger than previous region, it means that half of each triangle was covered by previous regions. In practice, except first region we have *p* trapezoid in each region.

3.2.1 Single splitter

In this configuration, for first region we can divide triangles to 4 smaller triangles and for other regions we break up each trapezoid to 3 triangles then put splitters on central point of each small triangle. According to the industry several splitters can located in one site, so we can put specific number of splitters in each central point as a site. Subscriber in each small triangle can connect to related splitters. Figure 3.3 illustrates this configuration.
The total fibre length in single configuration is given by

$$T_F = \sum_{i=1}^{k} (F_e(i) + D_r(i)), \tag{1}$$

where $F_e(i)$ is the total feeder fibre and $D_r(i)$ is the total drop in each fibre in each region *i*. Also feeder fibre and drop fibre in each region is obtained by summing feeder fibres and drop fibres $F_e(t)$, $D_r(t)$ in each triangle *t*.

$$F_e(i) = \sum_{t=1}^{p} (F_e(t)), \tag{2}$$

$$D_r(i) = \sum_{t=1}^{p} (D_r(t)), \tag{3}$$

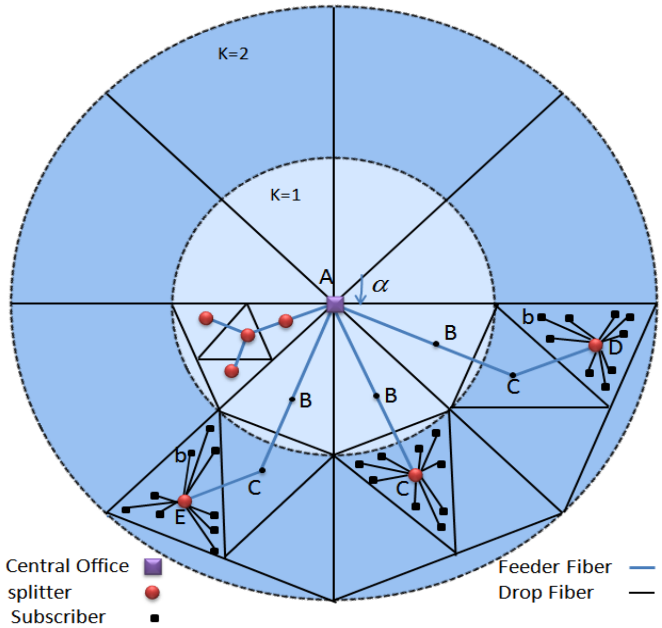


Figure 3-3. Single splitter for GPON architecture

For calculating total fibre in each triangle t, we need to know the distance between central points and centre point. They can obtain by following formulas [26].

$$|AB|=|BC|=(R/3).Cos(\alpha/2), \tag{4}$$

$$|CD|=|CE|=(R/6).\sqrt{1+8.Sin^2(\alpha/2)}, \tag{5}$$

$$|DF|=|CF|=|EF|=|BF|=R.(0.123+0.336/y), \tag{6}$$

where R is the radius of each region, $\propto$ is the angle of triangle and y is the number of fibre cables that leave from the D and E points. Beside it, for reducing the length of installation, we can use Y-branch for every 3 houses and put them on F point, and then we can calculate the average distance between F points and subscriber, with knowing the number of potential user per km^2, d and the number of potential user per F points, n.

$$b = 2/3(\sqrt{n/\pi d}), \tag{7}$$

so feeder fibre for each triangle t in first region will be

$$F_e(t)=|AC|+|CD|, \tag{8}$$

if we use y-branch for every 3 houses total drop fibre is given by

$$D_r(t)=\sum_{S=1}^{H}(R_i(0.132+0.336/y)+2/3(\sqrt{S/\pi d})), \tag{9}$$

in this case y is the number of Y-branch. The number of splitters per site N_{SPS}, is given by dividing the number of households per each small triangle H by the maximum number of client that splitter can support in model N_{Max}.

$$N_{SPS}=\left\lceil H/N_{\max} \right\rceil, \tag{10}$$

for calculating total ducts in this configuration, as regards that several fibres can be put into the one duct, we can calculate total required duct length L_D, that is much shorter than total fibre length. Total duct length is given by summing total duct of feeder L_{DF} and total duct of drop fibre L_{DDr}. Furthermore depending on the average distance between subscribers, we can define the duct factor F_D. For an average distance between houses of around 20 m in urban area the ducts factor F_D is between 7% and 10% [5], so we have

$$L_D = L_{DF} + L_{DDr}, \tag{11}$$

$$L_{DF} = F_e, \tag{12}$$

$$L_{DDr} = D_r.F_D, \tag{13}$$

According to the number of splitters in one site, we can achieve type of feeder fibre N_{FeF} in each duct (2, 8, 24, 32, 72, 96 fibres).

$$N_{FeF} = (N_{SPS}) + N_{Extra}. \tag{14}$$

where N_{SPS} is the number of splitters per site and N_{Extra} is the number of additional fibres that can be added for future development planning.

3.2.2 Cascaded splitter

For developing cascaded splitter configuration, we need to characterize how the first and second splitters are connected together. Firstly, like single splitter approach we divide each triangle in first region to 4 small triangles and in other regions each trapezoidal break up to 3 triangles. We can put first splitter sites at the central point of big triangle. For putting second splitter sites, as seen in Fig.3.4, we can break each small triangle to 4 smaller cells and then put second splitter sites in each central point of them. The total fibre length in cascaded strategy will be

$$T_F = \sum_{i=1}^{k} (F_e(i) + D_i(i) + D_r(i)), \tag{15}$$

where F_e is the feeder fibre, D_i is the distribution fibre and D_r is the drop fibre. Also feeder fibre, distribution fibre and drop fibre in each region is obtained by summing length of

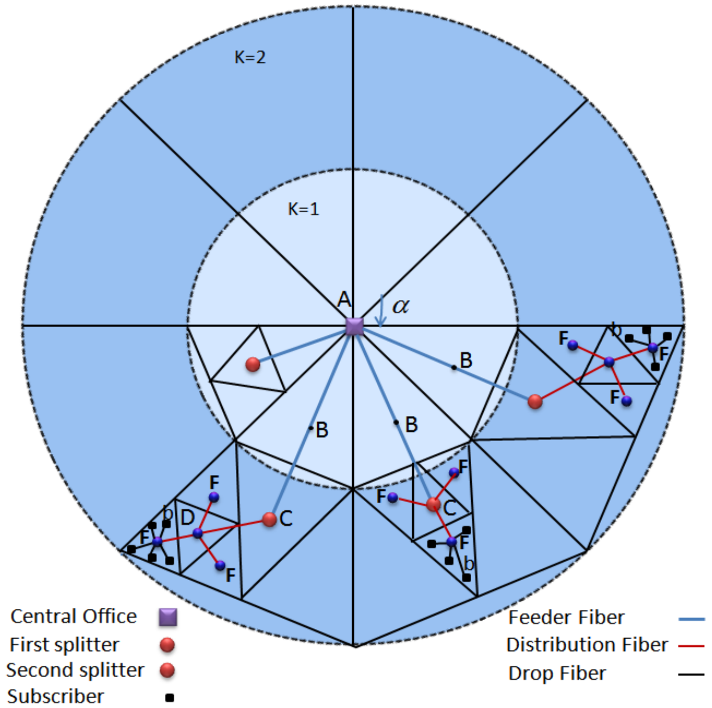


Figure 3-4. Cascaded splitter scenario for PON architecture

feeder, distribution and drop fibres $F_e(t)$, $D_i(t)$, $D_r(t)$ in each triangle *t*.

$$F_e(i) = \sum_{t=1}^{p} (F_e(t)), \tag{16}$$

$$D_i(i) = \sum_{t=1}^{p} (D_i(t)), \tag{17}$$

$$D_r(i) = \sum_{t=1}^{p} (D_r(t)), \tag{18}$$

Total feeder for each triangle *t* is given by

$$F_e(t) = |AC|, \tag{19}$$

Distribution fibre and drop fibre for n users in each triangle *t* in first region is calculated by

$$D_i(t) = |CD| + |DF|, \tag{20}$$

$$D_r(t) = \sum_{S=1}^{H} \frac{2}{3} \left(\sqrt{\frac{S}{\pi d}}\right), \tag{21}$$

where *H* is the average number of user in each Cell. The number of second splitters in each site $N_{SecondSPS}$ is obtained by dividing total user in each cell *H* by maximum number of user that second splitters can support N_{MaxS}. Also the number of first splitters in each site $N_{FirstSPS}$ is given by dividing all of second splitters in triangle *t* by maximum number of user that first splitters can support.

$$N_{SecondSPS} = H / N_{MaxS}, \tag{22}$$

$$N_{FirstSPS} = \sum \left(\frac{N_{SecondSPS}}{N_{MaxF}}\right), \tag{23}$$

In cascaded strategy the total duct length L_D is given by summing total duct of feeder L_{DF}, total duct of distribution L_{DDi} and total duct of drop fibre L_{DDr}.

$$L_D = L_{DF} + L_{DDi} + L_{DDr}, \tag{24}$$

$$L_{DF} = F_e, \tag{25}$$

$$L_{DDi} = D_i, \tag{26}$$

$$L_{DDr} = D_r . F_D. \tag{27}$$

The number of terminal equipment in both two strategies depends on the number of clients and the type of deployment. In our model, we address a PON deployment; this means that each client has its own ONU, so the numbers of ONUs depend only on the take rate.

3.2.3 Inside plant

In this part we need to know the number of COs that coverage a city, the number of required optical distribution frames N_{ODF}, the number of line-cards N_{LC}, the number of chassis N_{Ch}, and the number of ports that are needed to support all subscriber N_P.

$$N_P = \left\lceil \sum N_{Clients} / N_{Max} \right\rceil, \tag{28}$$

$$N_{ODF} = N_{ODFperCO}, \tag{29}$$

$$N_{LC} = N_P / N_{PperLC}, \tag{30}$$

$$N_{Ch} = N_{LC} / N_{LCperCh}. \tag{31}$$

where N_{Max} is the maximum number of clients supported by an OLT port. Since the OLT ports are bundled in cards with several ports per card, typically 2, 4 or 8, we assume that the manufacturer provides OLT cards with 8 ports; each port supports up to 64 clients and uses 11 watt power [25].

3.2.4 Equipment Cost

The cost of equipment is calculated very easy and is dependent on the number of subscribers and the place of them. Herein the cost model that we use will reflect cost of the equipment and cost of fibre simultaneously, total cost C_c is given by the sum of the cost of the fibre C_F, the cost of installation C_I and cost of the equipment C_E.

$$C_C = C_F + C_I + C_E, \tag{32}$$

It is clear that the cost of fibre depends to the total fibre length T_F and price of the fibre C_f.

$$C_F = T_F . C_f, \tag{33}$$

Beside it installation cost is obtained by summing the costs of CO installation C_{CoI}, developing a manhole C_M, total duct C_D and total trenching C_T.

$$C_I = N_{CO}.C_{CoI} + N_{FS}.C_M + N_{SS}.C_M + L_D.C_D + L_D.C_T, \tag{34}$$

where N_{CO} is the number of CO that cover the city, N_{FS} is total number of first splitter sites, N_{SS} is total number of second splitter sites and L_D is the total duct length. We can also split the cost of equipment to cost of CO C_{CO}, cost of splitter C_S and cost of ONU C_{ONU}, so we have

$$C_E = \sum (C_{CO} + C_S) + \sum (C_{ONU}), \tag{35}$$

In the other hand, its need to know the cost of equipment in the CO, that depends on optical port number, so

$$C_{CO} = C_{ODF} + C_{Ch} + C_{LC}. \tag{36}$$

3.2.5 Case study

We apply our model to Aveiro district as a realistic scenario. The population characteristics, area and distance from Aveiro with potential customers for each region are presented in Table 3.1. In our work, we are going to calculate cost of GPON and LR-GPON with different take rates for rural, suburban and urban scenarios.

Table 3-1. Population densities in Aveiro municipalities.

Name	Area (km²)	Population	Customer	Pop/Area (1/km²)	Distance to Aveiro (km)	Sigma	Customer
Aveiro	200	73626	30678	368	·	20	35678
Ílhavo	74	12000	5000	163	6		
Vagos	170	24000	10000	141	11	16	10000
Oliveira do Bairro	64	24000	10000	375	24	9	10000
Albergaria-a-Velha	155	25497	10624	164	24	16	10624
Estarreja	108	28279	11783	261	26	9	11783
Murtosa	73	9657	4024	132	28	9	4024
Anadia	217	31671	13196	146	31	16	13196
Águeda	335	49691	20705	148	34	16	20705
Sever do Vouga	130	12940	5392	100	36	9	5392
Mealhada	111	21500	8958	194	40	9	8958
Oliveira de Azeméis	164	71243	29685	436	40	16	29685
Ovar	147	56715	23631	385	42	16	23631
São João da Madeira	8	21538	8974	2726	47	4	8974
Santa Maria da Feira	215	142295	59290	662	48	16	59290
Vale de Cambra	147	24761	10317	169	49	16	10317

First we apply our model to a realistic scenario and consider the single and cascade splitter schema for the sample city with an area of around 199.9 km^2 and 73626 inhabitants, the radius about 20 km and subscribers living in 35000 houses. We assume the normal distribution function for its subscriber density, and divide city to 5 regions. According to the number of user in the sample city, we need only one CO that is located in the centre of city. Also we assume that each chassis supports 16 OLT cards with 2 uplink cards. The cost of all used equipment for GPON in our scenario is demonstrated in Table 3.2. These prices have been suggested by [6, 14].

Table 3-2. Components costs

Device	Component	Unit	Price(€)
Inside	ODF+ patch cable	m	34
	Line card(8 ports)	each	8000
	Uplink card	each	6000
	Chassis for OLT	each	3000
Outside	1-fibre cable	m	0.2
	8-fibre cable	m	0.7
	12.fibre cable	m	0.8
	72.fibre cable	m	1.47
	96-fibre cable	m	1.96
	Y-branch	each	24.7
	Splitter 1:4	each	40
	Splitter 1:8	each	50
	Splitter 1:64	each	514
	Duct Feeder	m	0.9
	Duct and Distribution)	m	0.4
	Duct(Drop)	m	0.2
	Manhole	each	350
	Hand hole	each	280
	Trenching	m	18-25
	Extender Box(SOA)	each	1400-2500
	Extender Box(OEO)	each	500-600
	Chassis for 16 Extender Box	each	2000-2500
Customer side	ONU	each	120

For sensitivity analysis of model we compare the total feeder, distribution and drop fibre of numeric model by Matlab and with analytic triangle model. As seen in Fig. 3.5 the length of fibre for feeder and distribution are the same and for drop fibre because of using average for TM model we have difference slightly. In simulation with Matlab the place of user are different and so the results present better accuracy.

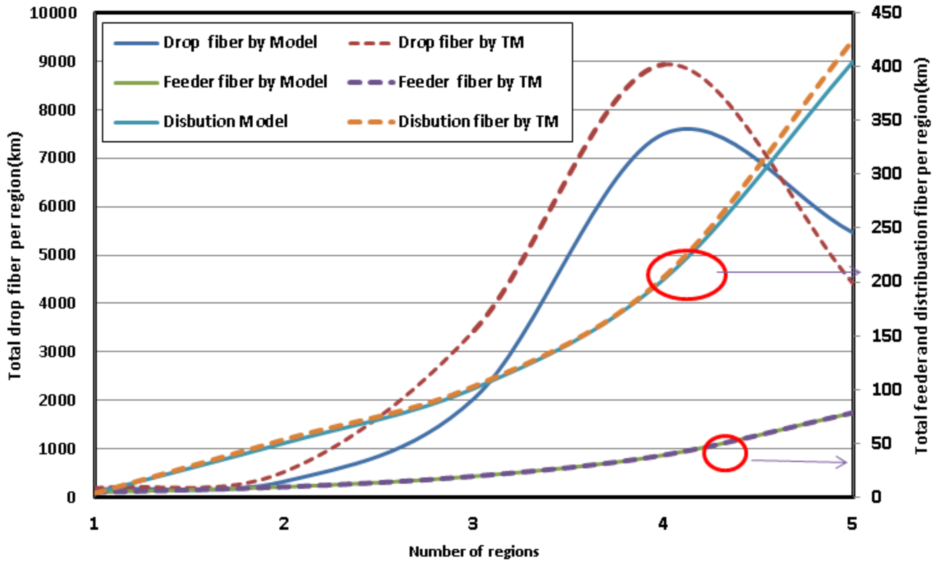


Figure 3-5. Comparison between simulated model and triangle model

In order to find optimum OLT port in these two strategies, we can consider effect of triangle's size on the number of ports and total fibre that we need. Figure 3.6 compares these results for different angles, we consider 60°, 45°, 30°, 20° and 10°. These results are shown for 3 different take rate 70%, 50%, 20%.

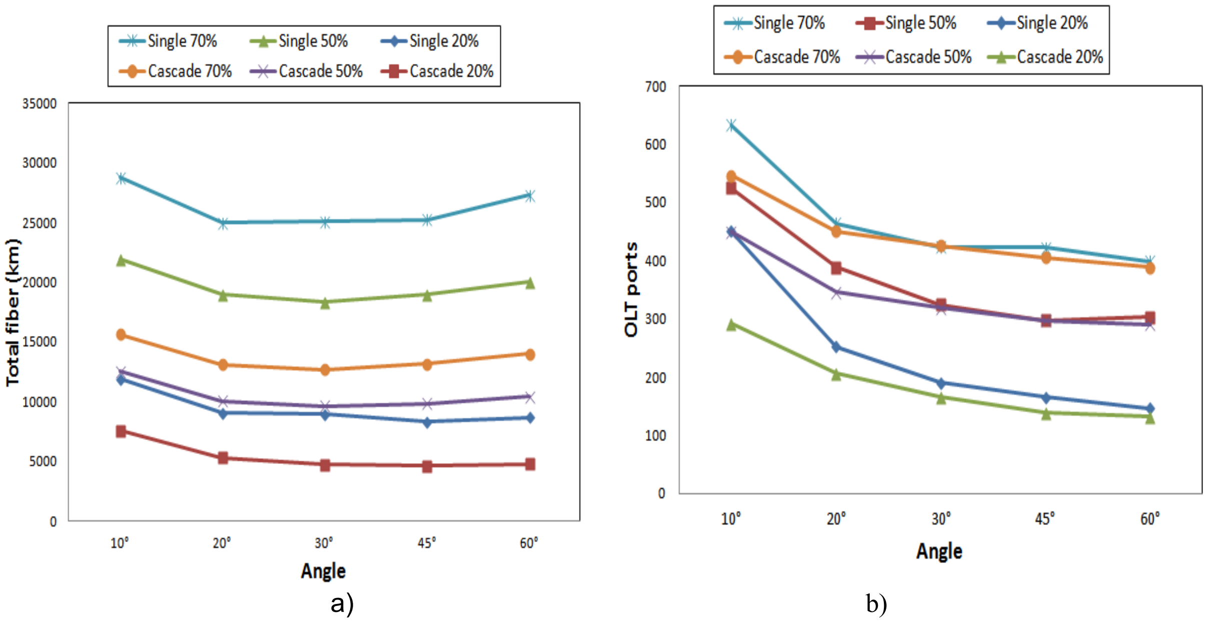


Figure 3-6. a) Comparison of Total fibre for different angles and different take rates b) Average OLT port loading versus each angle and for different take rates.

In designing triangles, reducing the size of the angle in each triangle leads to increase the number of supplying triangle and eventually splitter sites and total length of the feeder fibre. Beside it increasing the size of angles aggrandizes the total drop fibre in each triangle. As seen in Fig 3.6. a), with reducing the size of angle between 60^o to 20^o, total fibre will decrease; it is because of the effect of total drop fibre on total fibre. But for angle of 10^o total fibre will increase for both strategies, because feeder fibre has increased. In this regard we can find angles of 45^o and 30^o have the minimum total fibre. Also Fig. 3.6 b) presents that large size of angles usually gives better port loading. In fact although reduce the size of cells help to have smaller drop fibre but it leads to increase the number of OLT ports. According to these two figures we can find out with choosing angle of 45^o, we can obtain optimum OLT port and almost minimum total fibre.

For better clarifying the impact of triangle's size on OLT efficiency in both configurations, we can investigate average number of OLT ports of triangles in different regions. Figure 3.7 illustrates average number of OLT ports for different take rate in 5 regions. As shown in this figure, for take rates 70% and 50% we almost have the same OLT port for both configurations. Due to share one OLT port for smaller triangle by cascaded splitter, in low take rates cascaded configuration needs lower OLT ports than single configurations.

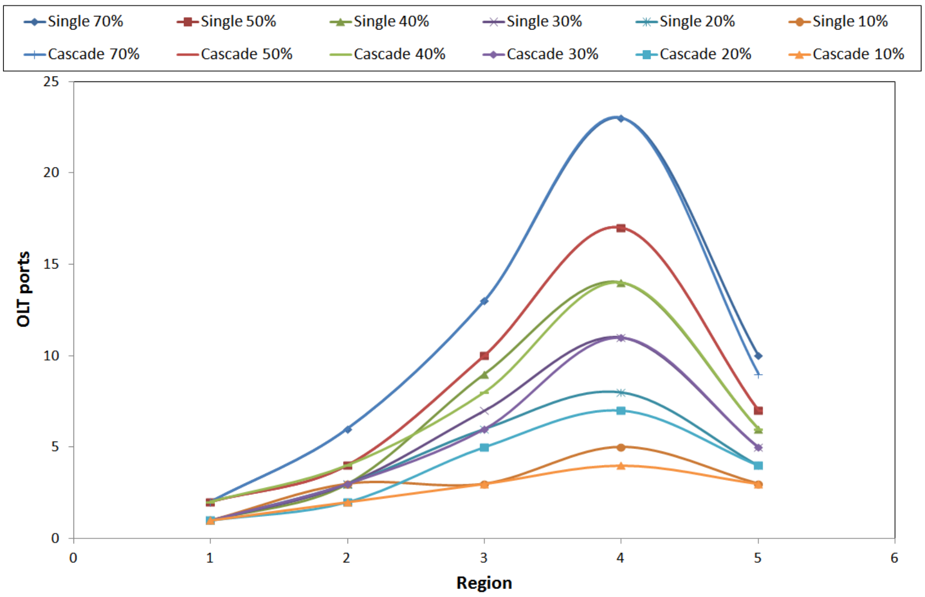


Figure 3-7. Average OLT port loading versus each area for different take rates

With finding out the average number of OLT port of triangles in each region and also knowing required energy for each one and then dividing them to average number of user connected over the port in the same region, we can calculate energy consumption per user. Figure 3.8 presents power consumption per user in low take rates.

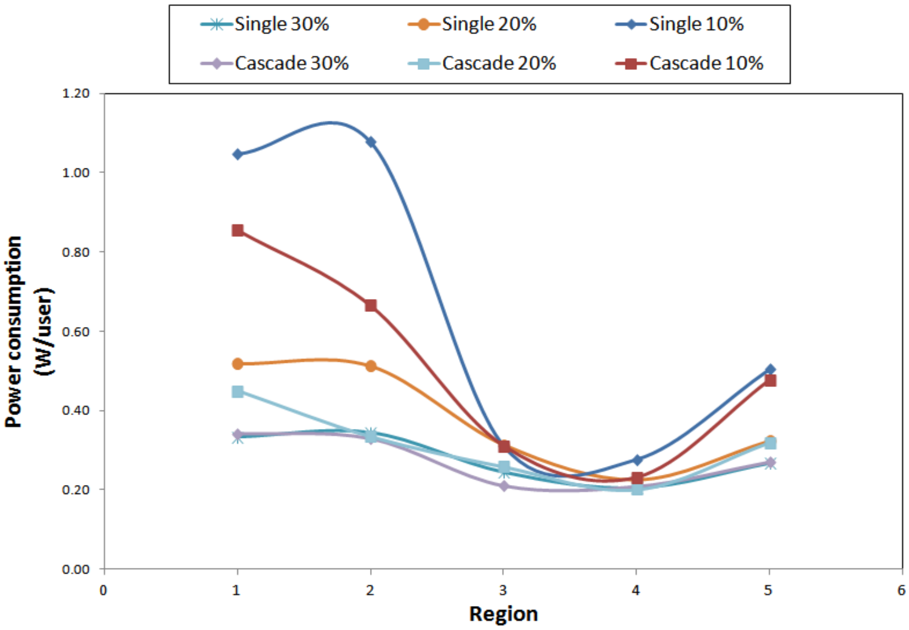
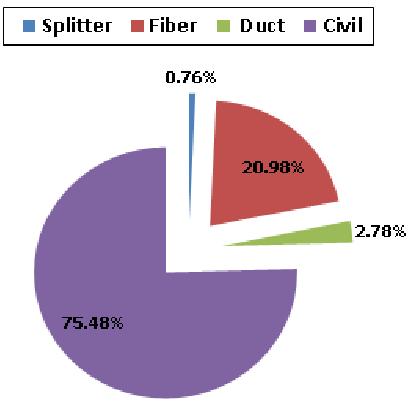


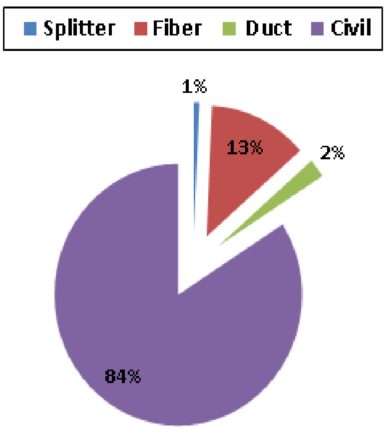
Figure 3-8. Power consumption per user for low take rates in each area

Depend on take rate, density of population and type of splitter, power per user is different. In this study we are using normal distribution for subscriber density and this figure indicates that power consumption in regions 3, 4 for all take rates is around 0.30 W/user. At low take rates, cascaded splitter strategy prepares better power consumption than single strategy. It is more obvious in take rates 10%, while energy consumption should be divided between less numbers of users connected over the one port.

The details of CapEx values for outside plant of take rate 50% are demonstrated in Fig.3.9. The most expensive part is civil work in both structures. The reason of civil work in cascaded strategy being more expensive than single strategy in proportion with another part is the additional cost for constructing manhole for second splitters.



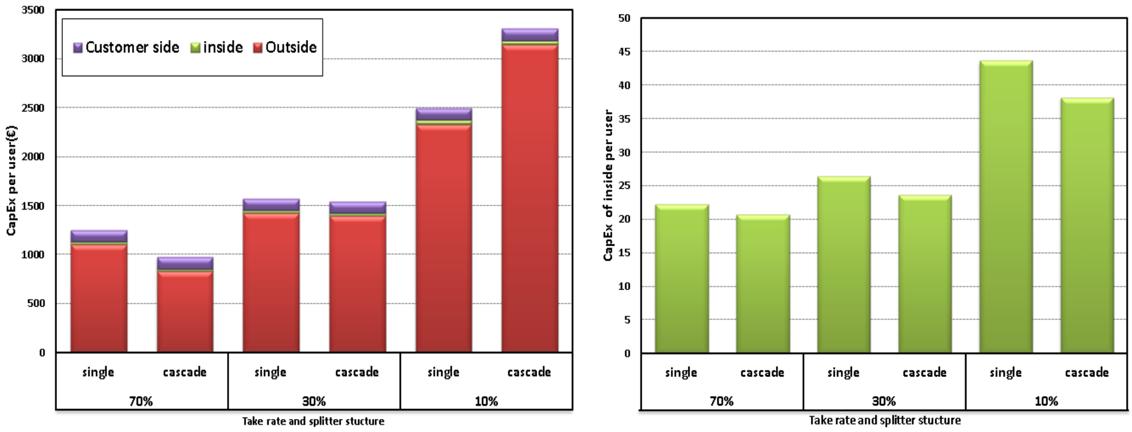
a)



b)

Figure 3-9. Outside cost breakdown for a) single and b) cascaded structures

If we want to consider the effect of choosing single and cascaded configuration on outside and inside plant of the network, we find out in high take rate, total per user cost of single strategy is more than cascaded strategy. But with decreasing take rate the cost of cascaded is more. But inside plant cost and source sharing in OLT are more efficient for cascaded. Fig.3.10 presents this case per user in 3 different take rates.



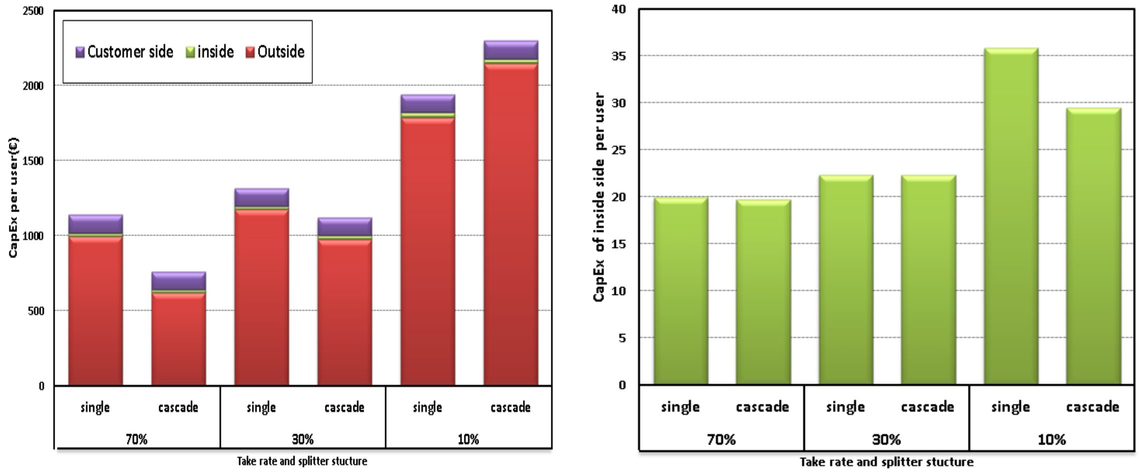
a) b)

Figure 3-10. Deployment cost comparison between single and cascaded strategy for different take rates for the case study 1) total CapEx b) Inside plant cost.

We developed model for the same area with standard deviation of 4 but for 50000 potential user and different take rate. As seen in Fig. 3.12. a), for high take rate because of putting more users near to splitter, total drop fibre and also relative costs of trenching and type of duct decrease.

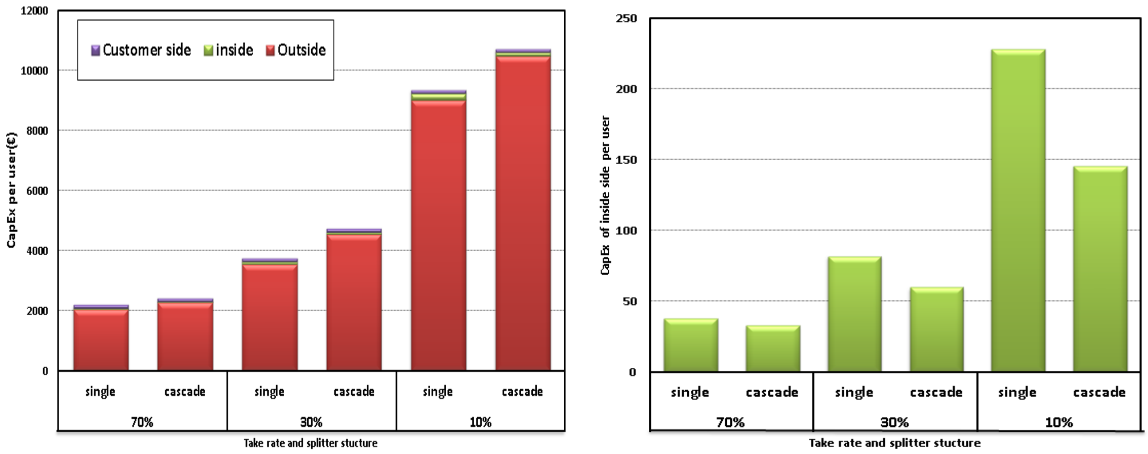
We assume one rural scenario with 5000 users and standard deviation of 3 km. As low numbers of users are located in ~100km^2 and population density is little especially for 10% take rate the resource sharing in outside are not suitable and for one rural area this cost is between 2000 to 1000 €.

In inside plant (Fig. 3.12. b)), total cost of OLT port, shelves and ODF are decreased by using cascaded structure. In next sections we will develop the model for 3 stage cascaded structure (1:4, 1:4, 1:4) and will see that resources sharing in OLT side will be optimizes remarkably.



a) b)

Figure 3-11. Deployment cost comparison between single and cascaded for different take rates 50000 users with variance of 16 km 1) total CapEx b) inside plant cost.



b)

Figure 3-12. Deployment cost comparison between single and cascaded for different take rates 5000 users with variance of 9 km a) total CapEx b) inside plant cost.

3.3 Long Reach GPON with using Extender Box

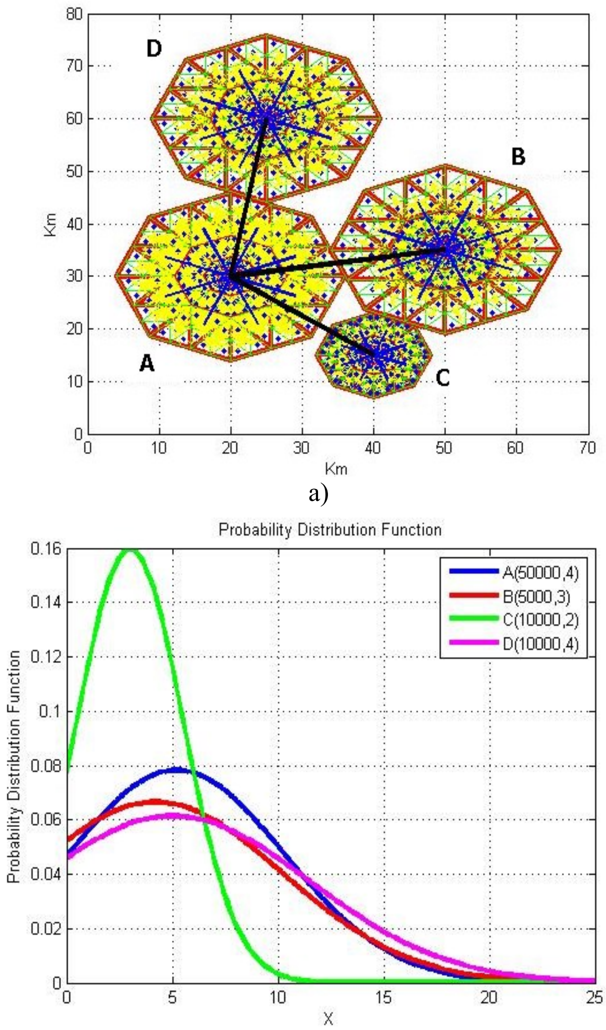
As shown in Fig 3.13, several scenarios are targeted for LR-GPON, depending on the coverage, number of served homes, distance reach (feeder-distribution-drop), bandwidth, etc, among the infinite possible combinations. They stress the LR-GPON system in different ways and can cover different new connectivity requirements.

We have defined one urban scenarios, three rural, collector (of different old access systems, like DSLAM, radio, HFC, APON, etc). Everyone uses different combination of elements, affecting the total cost and may also affect the unitary cost. Especially in

Portugal because of high number of rural and suburban areas, to put these kinds of area in order to calculate the cost is necessary.

This scenario is the same for some municipals of Aveiro. All areas that are in Fig. 3.13 are describing in Table 3.3.

We implemented our geometric model for these areas and the Fig. 3.14 shows the resulting total outside and inside plant for the different splitter structure solutions with respect to the different take rate and with respect to the different density. It is obvious that in most of the cases, for high take rate user cost for installation, fibre, civil and splitters is decreasing due to high resource sharing. Also we see for urban a cascaded splitter is cost efficient for high take rate but for low take rate is high slickly.



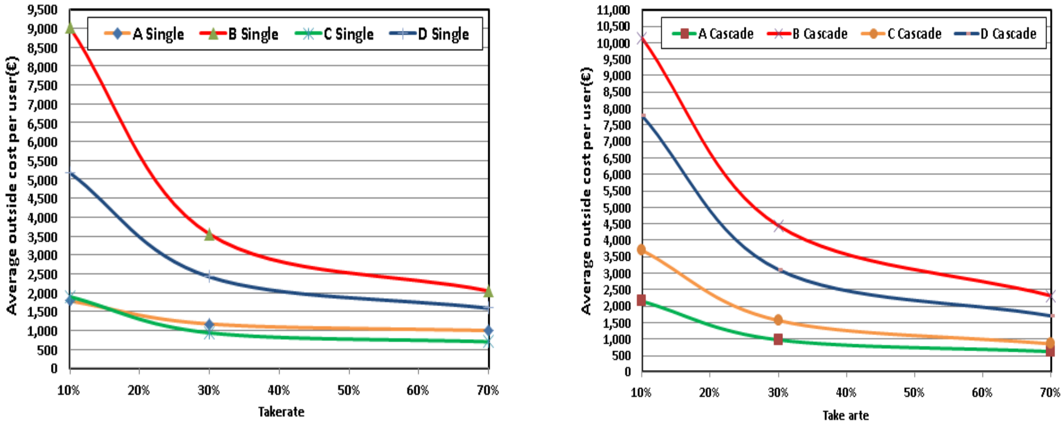
a)

b)

Figure 3-13. a) schematic of all scenarios b) population distribution function (PDF) all areas

Table 3-3. Targeted LR-GPON scenarios

Scenario	Area (km²)	Population	Customer	Pop/Area (1/km²)	Distance to Co(km)	Standard deviation
Urban A	200	120000	50000	600	0	4
Rural B	74	12000	5000	163	24	3
Suburban C	170	24000	10000	141	40	2
Rural D	64	24000	10000	375	30	4



a) b)

Figure 3-14. Average outside plant cost per users: a) single and b) cascade structures

But for all rural and suburban scenarios because of sparseness the single splitter is economical in case of outside plant. Because we are putting splitter of second stage in near to customer place and the cost of hand hole and the duct for distribution cable are high. When we look for future customer and focus on Fig. 3.15 in case of OLT side, the situation is different.

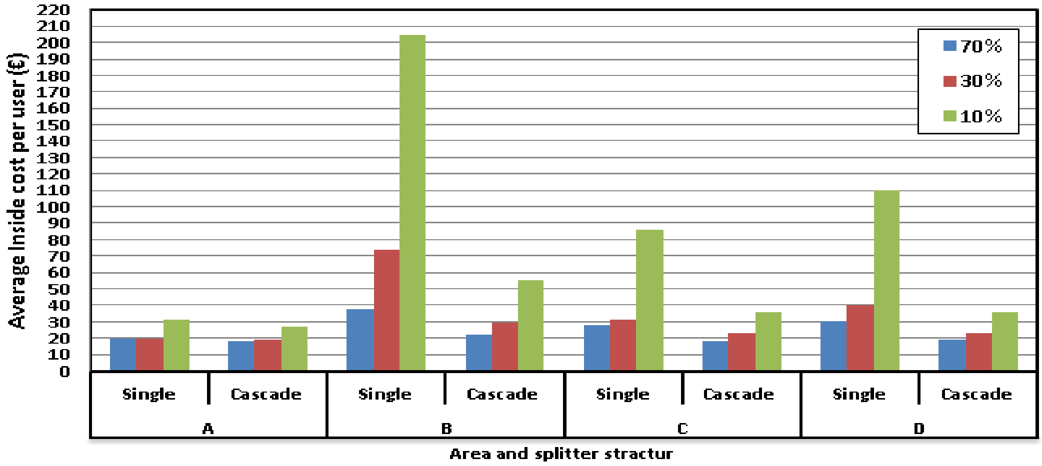


Figure 3-15. Average OLT side cost per users

For all scenarios resource sharing such as OLT card, chassis and uplink cards sharing are better. If the operators already installed the fibre for CATV and other applications and the prices of OLT equipment are important for them, this structure is recommended. Although with increasing the number of users the deficiency of installation cost is obviated.

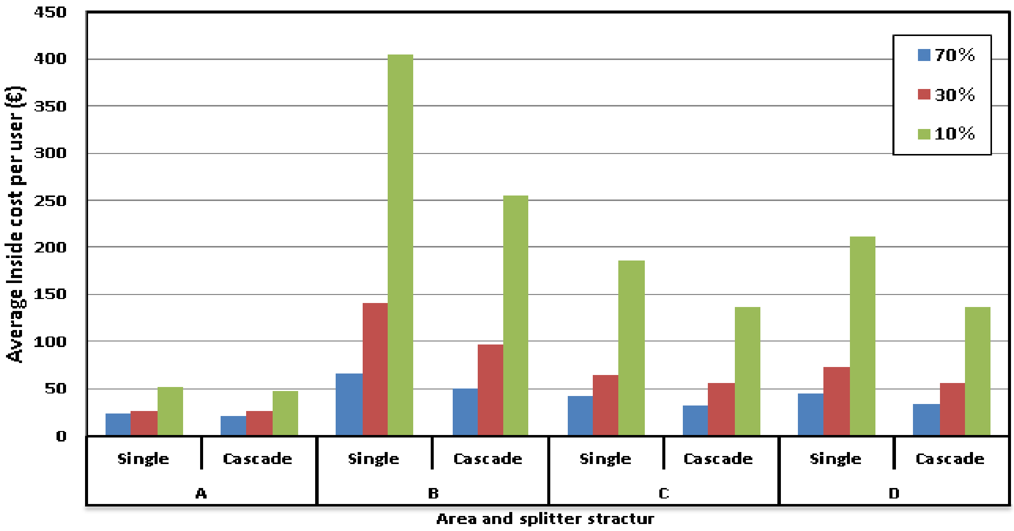


Figure 3-16. Average OLT side cost per users with 100000 € miscellaneous costs with GPON structure per each area.

From this analysis we can get the price of inside plant using extender box. We didn't consider the cost of the switch, router, building, air condition and power supply. But for all of them we assume the cost is around 100000 €. The Fig. 3.17 and Fig. 3.18 show the inside cost for this assumption.

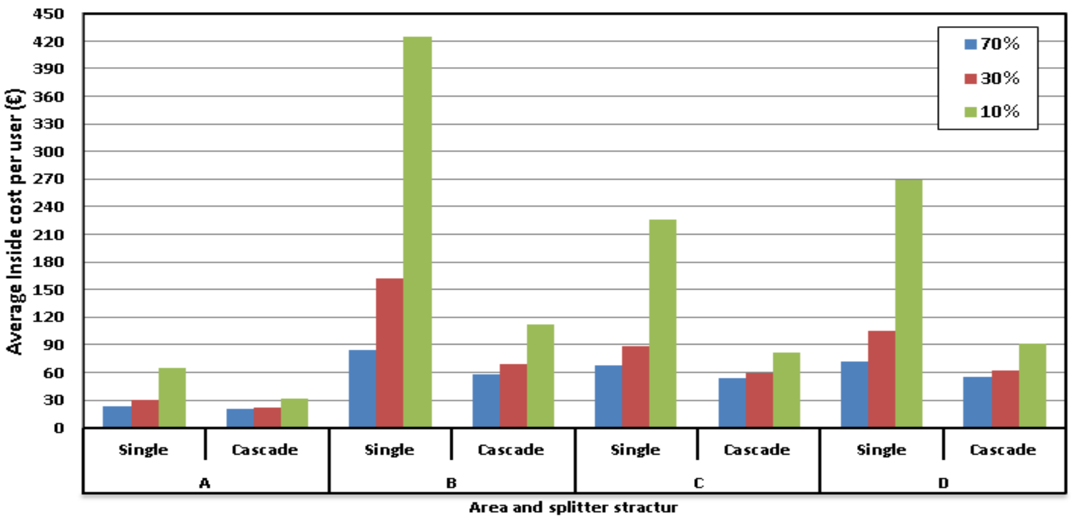


Figure 3-17. Average OLT side cost per users without miscellaneous costs with LR-GPON structure and extender box.

Now we can compare the result with using extender box for both assumptions. The more important thing that we need to focus is cascaded structure for using in deployment. For both assumption central office resources sharing is notable in cascaded structure.

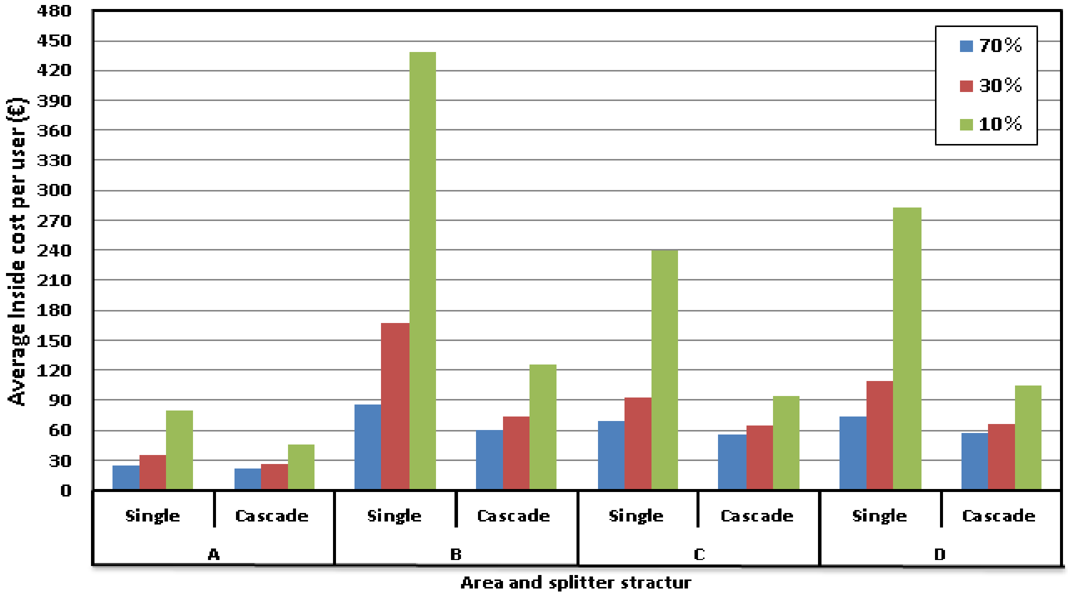


Figure 3-18. Average OLT side cost per users with 100000 € miscellaneous costs with LR-GPON structure and extender box.

The calculation of CapEx for the other solutions/architecture proves that LR-GPON extended reach and enhanced number of end users served are translated into cost savings as far as the material of the infrastructure and the construction labour is concerned, when compared to the other using separate central office for other networks.

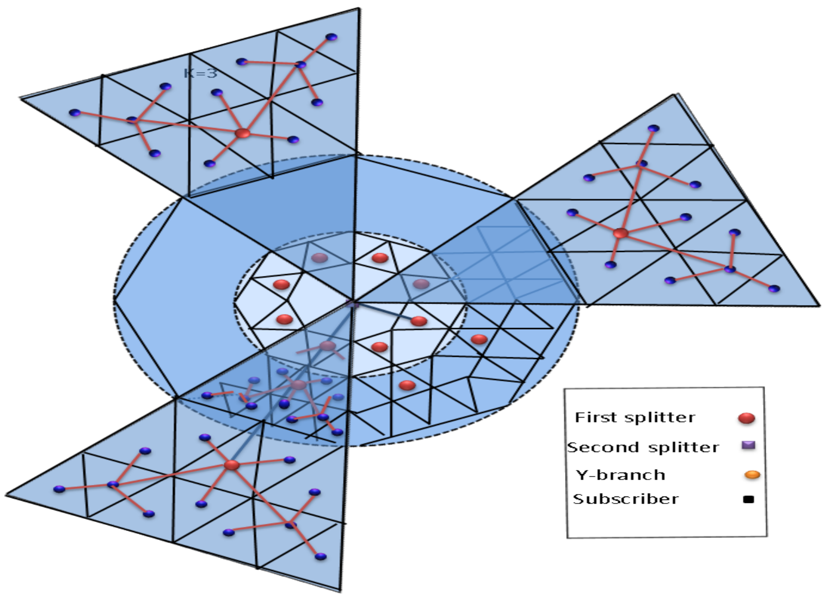
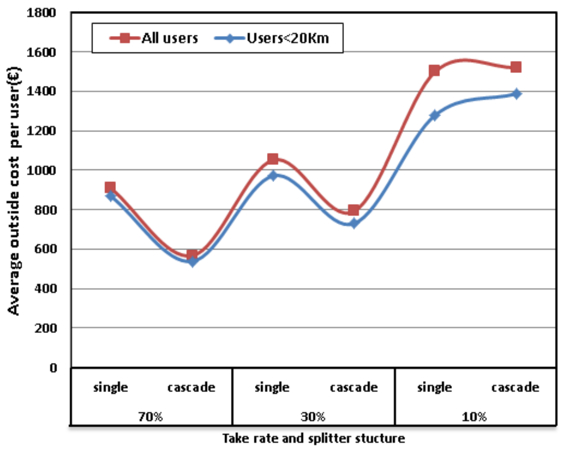
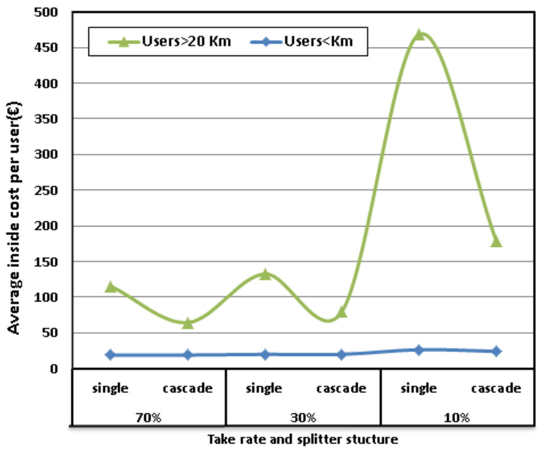


Figure 3-19. Schematic for urban scenario.

We consider a scarcely populated area, the same considered in sub pervious section and in here we deploy a GPON, considering at the same time the deployment of a extender box serving the access network's needs. The city same Porto with 100000 potential subscribers and population density with variance of 25 km is taken in to account. We observe with selecting good splitter and the number of the fibres, the number of ducts / sub ducts and the overall installation cost is significantly decreased. Using cascaded splitter as well as placement of first and second splitter we can decrease the number of manhole and hand hole. The results of the calculations are shown in Fig. 3.20



a)



b)

Figure 3-20. CapEx for all coverage area a) Average outside plant cost per user b) Average inside plant cost per user.

3.4 Migration from GPON to WDM-PON

After designing and deploying our access network, now GPON is becoming a reality in our cities, streets and homes. As we mentioned in pervious sections, GPON supports 2.5/1.25 Gbps in down/up-stream, to 32 or 64 or 128 users; as a consequence, once the fibre is arriving to our home, it can be somehow disappointing, we can only enjoy about 40 MBps guarantied, when we know that fibre with small change can support 1 or 2 or 10Gbps or more. Therefore, time is now suitable for us with GPON in a Box in a hand support at least 2 or 10Gbps per each user.

However, future is for coming WDM-PON from backhaul, metro core and backbone transport, to access, with or without advanced modulation techniques. But the question is which type of WDM-PON is cost-efficient? Is there any solution available to have GPON with WDM-PON in same fibre? How much is the cost of this technology? And so on. However, the requirement for colourless or wavelength-agnostic ONUs leads to the necessity to use tunable lasers in the ONUs. The use of tunable receivers enables phased rollout of multi-wavelength services, thus reducing expenses and making targeted bandwidth upgrades is possible. Also if the easy migration from GPON to WDM-PON is considered, tunable filter and receiver must be used in side of ONU. In this section, cost of user with GPON and WDM-PON is considered. If we assume in each city 1-2 percentage of customers are business customer and they need to 1-2.5Gbps sustained data rate with our WDM-PON solution only we need to change customer side and OLT side. As seen in Fig. 3.21 due to use WDM-PON based splitter with tunable filter and tunable receiver, migration from GPON customer to WDM-PON user is very easy.

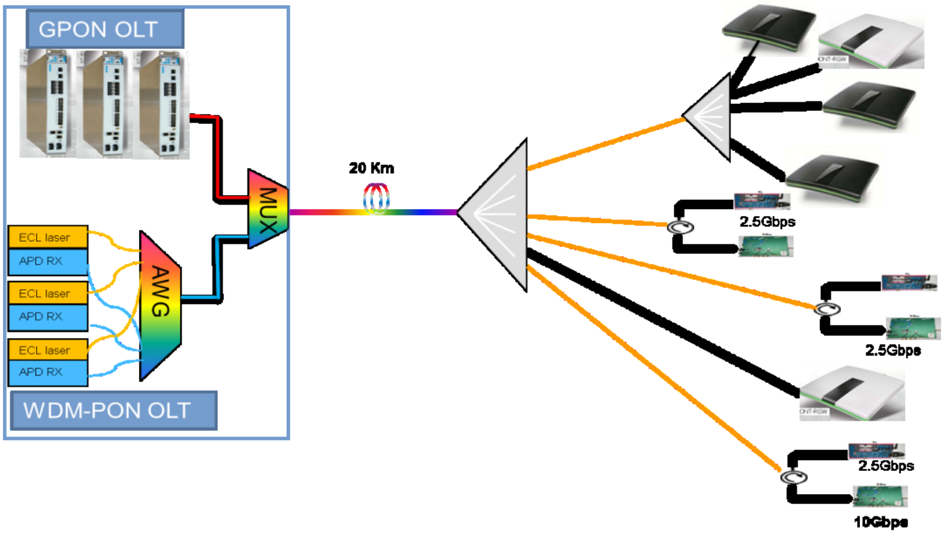


Figure 3-21. Migration schematic from GPON to WDM-PON [25]

Considering this schematic, we need to add one AWG and 1x2 triplexes WDM coupler. The prices of each component are presented in following Table 3.4.

Table 3-4. Detail price of SFP base WDM-PON OLT with our electronic devices

Type	WDM-PON OLTdevices	Current unitary cost per user (€)	Price of 512 volumes (€)	Price of 1k volumes (€)	Price of 10k volumes (€)	Price of 50k volumes (€)
Advanced Optical component	F-ECL SFP (non-BM Rx operation)	197.54	128.04	119.63	105.27	93.00
	λ connector	101.76	65.70	56.30	47.30	39.86

Electrical Component	TRX board for 8 λ	500.00	450.00	425.53	343.82	306.58
	Uplink card	6000.00	5400.00	5106.31	4125.80	3679.01
	OLT Mac for 8 λ	1000.00	900.00	851.05	687.63	613.17
Optical component	AWG	800.00	624.67	584.84	490.53	354.55
	Triplexer	60.00	46.85	43.86	36.79	26.59
Mechanic	chassis	3000.00	2370.00			
	Total	5659.30	9985.26			

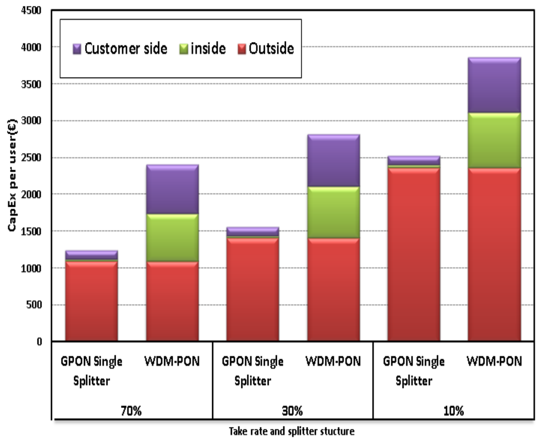
We assume that one chassis support two shelves and each shelf support 16 WDM-PON cards. Duo to comparison with GPON OLT we assume each card support 8 WDM ports. So each chassis can support 512 business users. The OLT cost per user for 512 and 1000 users is calculated with considering of last Table 3.5.

Table 3-5. Detail price of SFP base WDM-PON OLT per user.

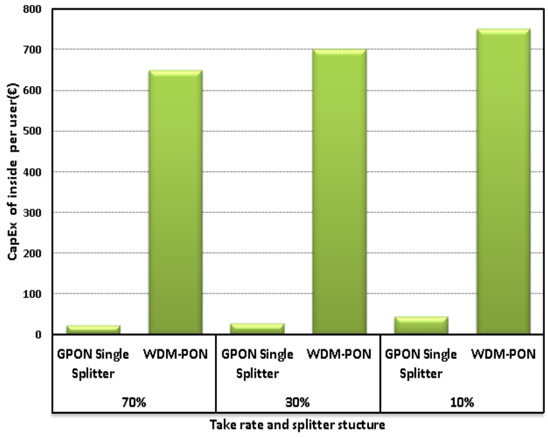
Type	**WDM-PON OLT devices**	**OLT cost per user for 1Volume(€)**	**OLT cost per user for 512 Volumes(€)**	**OLT cost per user for 1k Volumes(€)**
Advanced Optical component	F-ECL SFP (non-BM Rx operation)	197.54	128.04	119.63
	λ connector	101.76	65.70	56.30
Electrical Component	TRX board for 8 λ	500.00	56.25	53.19
	Uplink card	6000.00	84.38	79.79
	OLT Mac for 8 λ	1000.00	112.50	106.38
Optical component	AWG	800.00	15.62	14.62
	Triplexer	60.00	46.85	43.86
Mechanic	chassis for 4 shelves	6000.00	9.26	9.26
Total			518.59	483.03

For CapEx cost per user we consider one city with 30000 users that business user are 10 % of each take rate. As we mentioned on Annex I, the total potential customer base in Portugal amounts to 4.9 million customers. 4.45 million are residential customers (households including second homes) and 0.45 million are business customers.

GPON scenario uses the schematic in Fig. 3.21 and the operator doesn't need to change outside plant. We can change the OLT side and customer side with ONU and OLT devices according to Tables 3.4 and 3.5. In Fig. 3.22 total CapEx per user for GPON with single structure and WDM-PON is presented.



a)



b)

Figure 3-22. a) Cost break down of WDM-PON and GPON customers in same outside plant b) inside plant costs for GPON and WDM-PON

As seen in Fig. 3.22 with only 1400 € for each business user we can support 2.5Gbps uplink and downlink. For 70 % take rate means there are 20000 GPON users and 2000 business users that can be supported with 4 chassis. In this scenario we assumed the price of each chassis for 512 users is two times more than the chassis for two shelves. However, if we wanted to consider for all the 30000 users, the price for customer side and OLT side was decreased, but this scenario is not feasible.

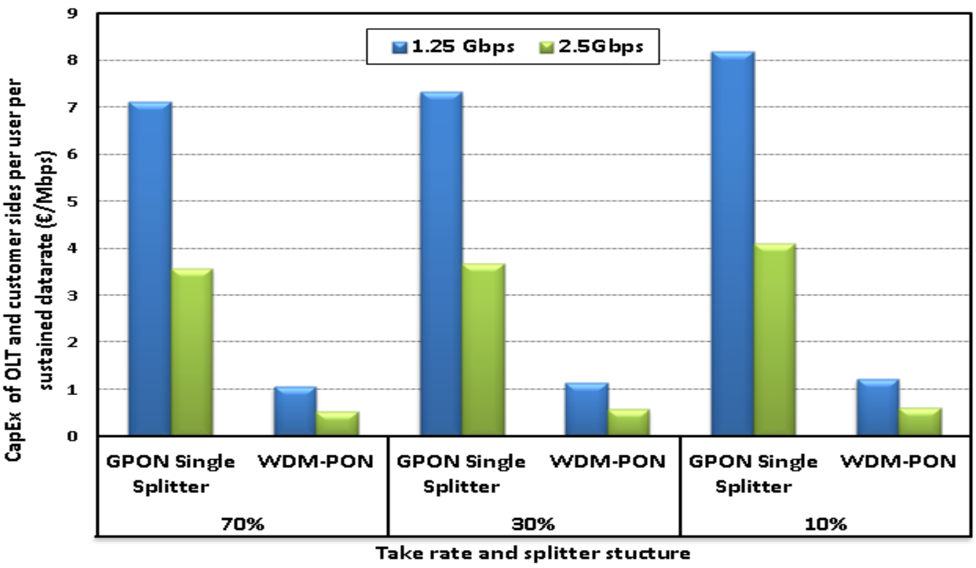


Figure 3-23. Costs of OLT and customer sides per sustained data rate for each user

In WDM-PON 1.25Gbps and 2.5Gbps sustained data rate for each user is guaranteed. In GPON sustained data rate from 20 Mbps up to 40Mbps is delivered to each user. Figure 3.23 presents OLT and customer side of each user vs. their data rate. As the price of high data rate service for business user is more than common user, and operators get more money from business users, with this migration scenario the benefit for operator is increased.

3.5 Impact of Equipment Cost

The GPON with or without extender box and WDM-PON network include a huge diversity of different elements, from optics, electronic and also mechanic. The cost of each main node (CO, RN, ONU and fibre infrastructure) can be analysed by dividing to different part of equipment and calculated for the different possible scenarios and architectures. As we implemented extender box and ONU for WDM-PON and they are new technologies, so the cost of them is decreased during the time and also vs. the volume of purchase. Thus we can use the model that is presented in [24] by Olsen. A learning curve is defined as the percentage decline in the price of a product as the (cumulative) product volume doubles [20, 24]. To account for this we classify the types of element according to its maturity, and predict the unitary cost to the future, as the production processes are improved when the volumes increase. It has been validated for the cases of the introduction of different new products.

The main parameter of mathematical model is the *k* coefficient of the learning curve. Specifically, it stands for the relative unitary cost reduction every time that the production volume doubles. For example, for electronics it is about 80%, while for labor civil works it is 100%, meaning that this cost does not reduces with the time since it is a very mature task. Table 3.6 presents different categories of elements in terms of the learning curve classes.

Table 3-6. Different categories of elements

	Type of different component	***K***
0	constant (raw mat., civil works,..)	1.00
1	optical component	0.80
2	advanced optical comp.	0.70
3	optical cable	0.90
4	electronics	0.80
5	installations	0.85
6	software	0.60
7	mechanics	0.90

The main equation that defines the model is the following [11, 24]:

$$Cost = C_{\inf} + (C_{cur} - C_{\inf})\left(1 + \frac{V}{V_{ref}}\right)^{\log_2^k}, \tag{37}$$

where C_{cur} is the current cost, *k* is the learning curve coefficient, V_{ref} is the reference production volume at which the cost is reduced in a factor of *k*, and the C_{inf} that stands for the cost at infinite production (remaining raw material cost…). The Table 3.7 defines different categories of elements in terms of these parameters.

Table 3-7. Learning curve parameters for different categories of elements

TYPE OF COMPONENT	current cost +1unit	% cost at infinite volume productions	delta	K%(delta cost reduction)	Cost at $+V_{ref}$	V_{ref}		targeted volume example	rel. unitary cost
Constant (raw mat., civil works,..)	1.00	1.00	0.00	1.00	1.00	1	units	1000	1.00
Optical component	1.00	0.50	0.50	0.80	0.90	100	units	1000	0.73
Advanced optical components	1.00	0.30	0.70	0.70	0.79	100	units	1000	0.50
Optical cable	1.00	0.50	0.50	0.90	0.95	100	km	1000	0.85
Electronics	1.00	0.50	0.50	0.80	0.90	500	units	1000	0.85
Installations	1.00	1.00	0.00	0.85	1.00	1000	units	1000	1.00
Software	1.00	0.00	1.00	0.60	0.60	1000	units	1000	0.60
Mechanics	1.00	0.10	0.90	0.90	0.91	10	units	1000	0.55

Of course the number of *k* and V_{ref} must be defined carefully. With this trend of technology these values will change definitely.

For developing of the model for extender box, we can use all the prices in following Table 3.8 .

Table 3-8. Total and detail cost for extender box.

Type		Component	Quantity	Application	Price/unit in (€)	Total in (€)
Optical part	**Advanced Optical**	CIP SOA-S-OEC-1550	1	Downstream	595	595
		Alphion SAO29p	1	Upstream	1538	1538
					Total Advanced Optical	2133
	Optical component	1x3 Triplexer WDM Couplers	2	OADM	113	226
		VOA	1		141	141
		Isolator	1	Upstream	19	19
		Isolator	1	Downstream	21	21
		PIN	2		15	30
		optical Connector for panel	14		2	34
		WDM Coupler	2		20	40
		patch cord	0		3	0
		Pigteail	0		4	0
					Total optical	510
Electrical Part	**Electronic**	Current source	2		40	80
		Temperature controllers	2		50	100
		Card control + interface	1	Micro conroller	40	40
		LCD	1		15	15
		Power supply	1		80	80
		Board for SOA	2		5	10
		Connector for SOA	0		15	0
		Electrical connector	30		1	30
		interfaces power	1		1	1
		Switch	1		1	1
					Total Electrical	357
Mechanical Part	**mechanic**	BOX	1		80	80
		Pannel	0		50	0
		Electrical adaptor DB9	1		1	1
		Cover	0		20	0
		Cable tie	10		1	5
		wiring	10		1	5
	Assembly	Assembling				
					Total mechanical	81
Total cost						3081

This price is for one lab buddy device and of course for RN implementation some mechanic and wiring part and also electronic part need to be removed. However next Fig. 3.24 shows the different evolution of their relative cost as a function of the production volume.

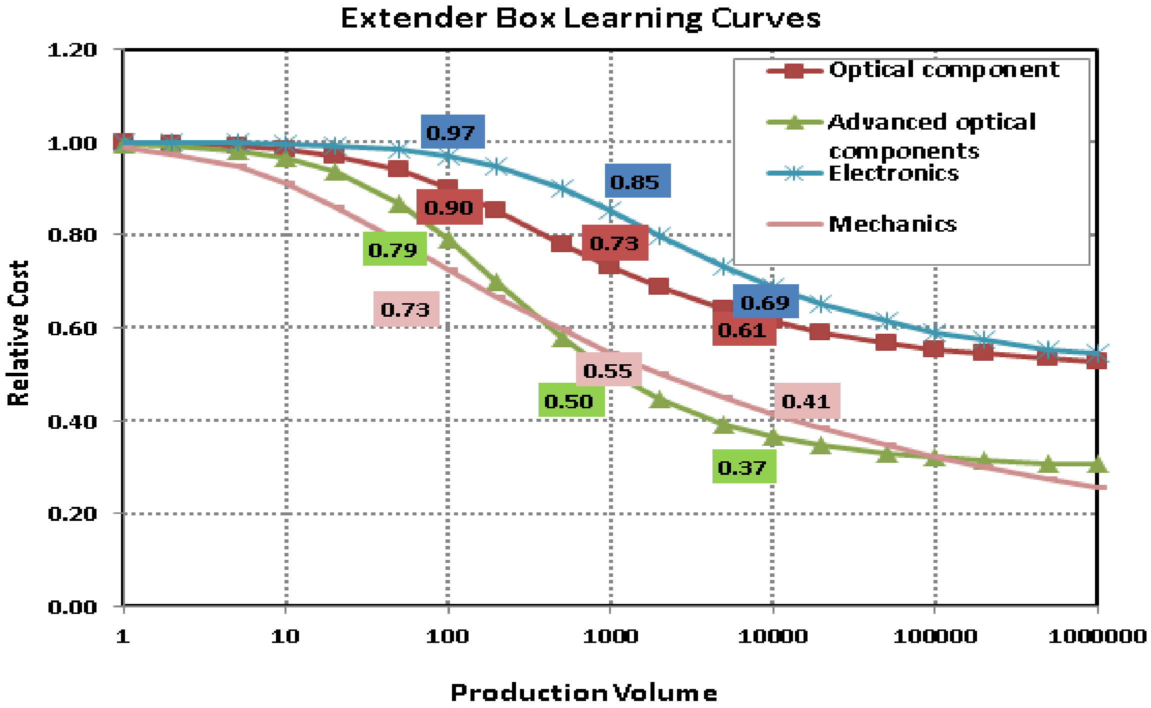


Figure 3-24. Extender box learning curves

So we can see the cost of extender box for 100 volumes is 2378 € and for 10000 volumes is 1379 €.

In case of ONU for WDM-PON, total price for one tunable TX and RX is 2541 €. We remind that the prices of electronic parts are for one lab buddy case. If we make this part by our self the total cost of electronic roughly will be decreased to 50-70% as seen in Tables 3.9, 3.10.

Estimation of price for high volume of ONUs is achieved by cost learning curve of Table 3.9.

Table 3-9. Detail price of tunable WDM-PON ONU

Type	ONU devices	Detailed Price (€)	Price (€)	Price of 100 Volume (€)	Price of 1000 Volume (€)	Price of 10000 Volume (€)
Advanced Optical	Tunable Filter and APD photodetector	364.00	948.00	748.92	477.61	346.14

component	Tunable laser	584.00				
Electrical Component	TX electronic	800.00	1193.00	1159.00	1015.30	820.35
	RX Electronic	293.00				
	Mac ONU	100.00				
Optical component	Circulator	100.00	200.00	180.00	146.21	122.63
	Connector and splice	100.00				
Mechanic	Box and connectors	200.00	200.00	145.02	109.25	82.98
	Total	2541.00	2541.00	2232.94	1748.38	1372.10

Table 3-10. Detailed price of tunable WDM-PON ONU, with electronic devices in [25].

Type	**ONU devices**	**Detailed Price (€)**	**Price (€)**	**Price of 100 Volume (€)**	**Price of 1000 Volume (€)**	**Price of 10000 Volume (€)**
Advanced Optical component	Tunable Filter and APD photodetector	364.00	948.00	748.92	477.61	346.14
	Tunable laser	584.00				
Electrical Component	TX electronic	150.00	350.00	340.02	297.87	240.67
	RX Electronic	100.00				
	Mac ONU	100.00				
Optical component	Circulator	100.00	200.00	180.00	146.21	122.63
	Connector and splice	100.00				
Mechanic	Box and connectors	100.00	100.00	72.51	54.63	41.49
	Total	1598.00	1598.00	1341.45	976.32	750.93

The WDM-PON FIVER network includes a huge diversity of different elements, from optics, electronic and also mechanic. The cost of each main node (CO, RN, ONU and fibre infrastructure) can be analysed by dividing to different part of equipment and calculated for the different possible scenarios and architectures. As we implemented OLT and ONU for FIVER WDM-PON and they are new technologies, the cost of them is decreased during the time and also vs. the volume of purchase. Thus we can use the model that is presented in [11, 24] by Olsen. To account for this we classify the types of element according to its maturity, and predict the unitary cost to the future, as the production processes are improved when the volumes increase. It has been validated for the cases of the introduction of different new products.

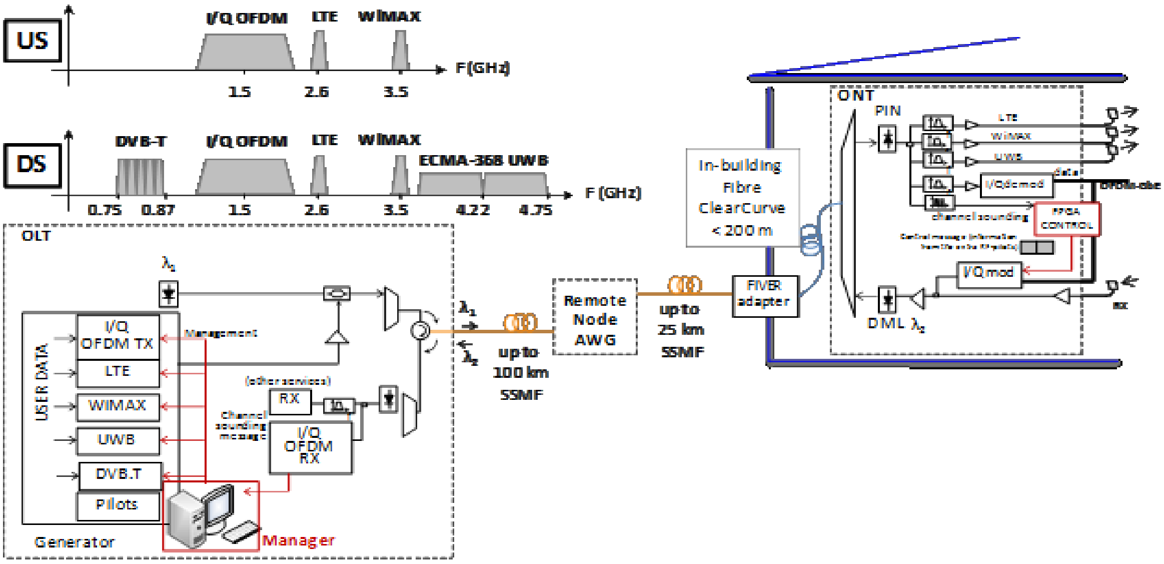


Figure 3-25. Network architecture block diagram for Downstream and Upstream directions [14].

Figure. 3.25 shows the architecture block diagram for performance evaluation of FIVER in FTTH networks.

In our techno-economic analysis, we are considering two main architecture variants, based on the location of the optical amplifiers to achieve long-reach operation: i) EDFAs located at the RN; ii) Raman amplifiers, with the Raman pumps located at the OLT in the central office. The associated architectural schematic configurations are indicated in the following two figures, which also show the different device requirements at the RN for two architectural configurations. The configuration of the ONT and FIVER adapter is essentially the same for the two architectural variants, so that only a single ONT techno-economic analysis is necessary.

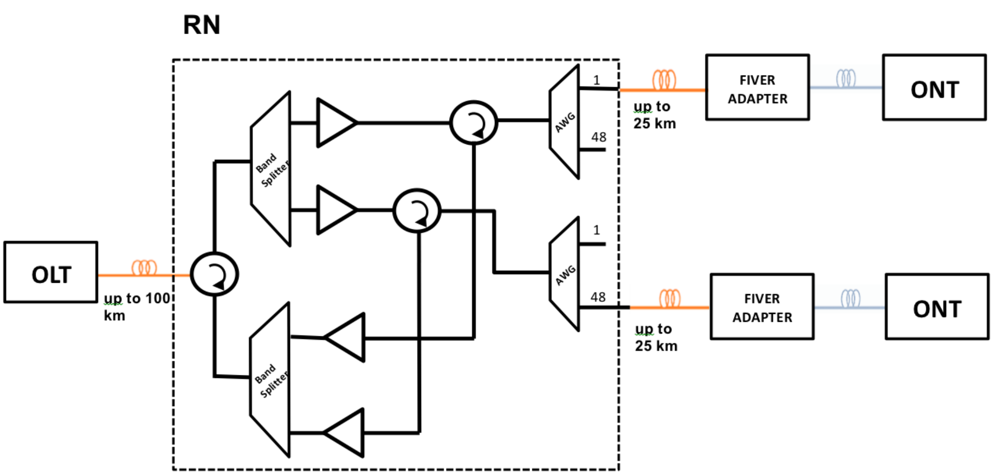


Figure 3-26. Architecture (i) with optical amplifiers located at RN [14].

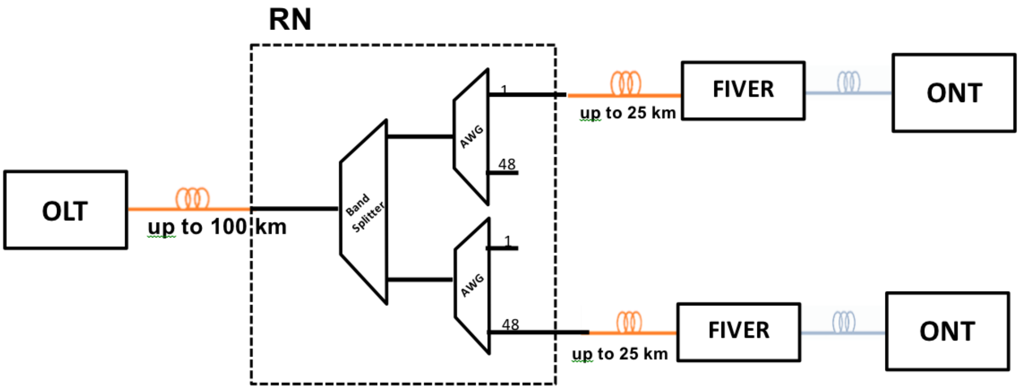


Figure 3-27. Architecture (ii) with Raman pumps located at OLT in central office [14].

3.5.1 OLT – Amplifiers at the Remote Node

In this part we calculate total price of OLT when amplifiers located at RN. For developing this model we can use all the prices in following Table 3.11.

Table 3-11 baseline cost estimation for Amp@RN

OLT [Amp@RN]			
Component	**Unit Cost (€)**	**Quantity**	**Total Cost (€)**
Optical Devices			
1550nm DFB Laser Diode	950.00	96	91200
MZ EO Modulator	1900	96	182400
Photodiode	124.3	96	11932.8
1x96 AWG	2850	2	5700
Optical Circulator	154.41	1	154.41
RF/Electrical Devices			
RF 1:5 power splitter	87	96	8352
OFDM modem			
FPGA board	1300	96	124800
2DAC/2ADC board	4000	96	384000
IQ-Mixer	800	384	307200
LO	50	384	19200
LPF	25	384	9600
BPF	45	288	12960
Tx Amp	50	96	4800
Rx Amp	50	96	4800
LTE			
BPF	25	96	2400
Low-noise Amp	232	96	22272

WiMAX			
DX250 fr	200	96	19200
BPF	25	96	2400
Low-noise Amp	232	96	22272
UWB			
BPF	32	96	3072
UWB Amp	850	96	81600
– inc. ADC/DAC	4000	96	384000
–Centralised Management Subsystem	1300	1	1300
– inc. channel sounding	4000	96	384000
Prototype Components Total			2089615.21

This price is for one lab buddy device and of course for implementation some mechanic and wiring part and also electronic part need to be removed. However next Table 3.13 shows the different evolution of their relative cost as a function of the production volume.

3.5.2 OLT- Raman amplifier at OLT

Here we calculate total price of OLT when Raman amplifiers located at OLT. For developing this model we can use all prices in following Table 3.12.

Table 3-12. Baseline cost estimation for Amp@OLT

OLT [Amp@OLT]			
Component	**Unit Cost (€)**	**Quantity**	**Total Cost(€)**
Optical Devices			
1550nm DFB Laser Diode	950.00	96	91200
MZ EO Modulator	1900	96	182400
Photodiode	124.3	96	11932.8
1x96 AWG	2850	2	5700
Optical Circulator	154.41	1	154.41
Raman Amplifier	6300	4	25200
RF/Electrical Devices			
RF 1:5 power splitter	87	96	8352
OFDM modem			
FPGA board	1300	96	124800
2DAC/2ADC board	4000	96	384000
IQ-Mixer	800	384	307200
LO	50	384	19200
LPF	25	384	9600
BPF	45	288	12960
Tx Amp	50	96	4800
Rx Amp	50	96	4800

LTE			
BPF	25	96	2400
Low-noise Amp	232	96	22272
WiMAX			
DX250 fr	200	96	19200
BPF	25	96	2400
Low-noise Amp	232	96	22272
UWB			
BPF	32	96	3072
UWB Amp	850	96	81600
– inc. ADC/DAC	4000	96	384000
– Centralised Management Subsystem	1300	1	1300
– inc. channel sounding	4000	96	384000
Prototype Components Total			2114815.21

This price is for one lab buddy device and of course for implementation some mechanic and wiring part and also electronic part need to be removed. However next Table 3.13 shows the different evolution of their relative cost as a function of the production volume.

Table 3-13. Unitary cost at the initial reference volume Amp@ RN.

OLT [Amp@RN]						
Optical Devices	**current unitary COST per year (€)**	**Type of learning cost (1-9)**	**QUANTITY per ONU**	**QUANTITY of user**	**Unitary cost**	**Cost**
1550nm DFB Laser Diode	950	2	96	1000000	102	102,475,686
MZ EO Modulator	1,900	2	96	1000000	205	204,951,373
Photodiode	124	2	96	1000000	13	13,408,135
1x96 AWG	2,850	2	2	20833.33333	449	9,354,185
Raman Amplifier	2,850	2	0	0	2,850	0
Optical Circulator	154	1	1	10416.66667	23	234,501
RF/Electrical Devices	0			0	0	0
RF 1:5 power splitter	87	4	96	1000000	17	17,169,109
OFDM modem	0			0	0	0
FPGA board	1,300	4	96	1000000	257	256,549,908
2DAC/2ADC board	4,000	2	96	1000000	431	431,476,574
IQ-Mixer	800	4	384	4000000	130	519,412,890
LO	50	4	384	4000000	8	32,463,306
LPF	25	4	384	4000000	4	16,231,653
BPF	45	4	288	3000000	8	22,728,830
Tx Amp	50	4	96	1000000	10	9,867,304
Rx Amp	50	4	96	1000000	10	9,867,304
LTE	0		0	0	0	0

BPF	25	4	96	1000000	5	4,933,652
Low-noise Amp	232	4	96	1000000	46	45,784,291
WiMAX	0			0	0	0
DX250	200	4	96	1000000	39	39,469,217
BPF	25	4	96	1000000	5	4,933,652
Low-noise Amp	232	4	96	1000000	46	45,784,291
UWB	0			0	0	0
BPF	32	4	96	1000000	6	6,315,075
UWB Amp	850	4	96	1000000	168	167,744,171
– inc. ADC/DAC	4,000	2	96	1000000	431	431,476,574
–Centralised Management Subsystem	1,300	4	1	10416.66667	664	6,919,139
–inc. channel sounding	4,000	4	96	1000000	789	789,384,334
Prototype Components Total				0	0	0
	2,089,615					0
Total	1,000,000					3,188,935,156
Port cost						3,189

3.5.3 RN –Amplifier at OLT

In this part we calculate total price of RN when amplifiers located at OLT. For developing of the model we can use all the prices in following Table 3.14.

Table 3-14: Baseline cost estimation for RN without amplifier.

Component	Unit Cost (€)	Quantity	Total Cost (€)
Band Splitter	100	1	100
AWG	2850	2	5700
Total			5800

This price is for one lab buddy device and of course for implementation some mechanic and wiring part and also electronic part need to be removed. However next Table 3.15 shows the different evolution of their relative cost as a function of the production volume.

Table 3-15. Unitary cost at the initial reference volume Amp @ OLT

OLT [Amp@OLT]						
Optical Devices	**current unitary COST per year (€)**	**Type of learning cost (1-9)**	**QUANTITY per ONU**	**QUANTITY of user**	**Unitary cost**	**Cost**
1550nm DFB Laser Diode	950	2	96	1000000	77	76,856,765

MZ EO Modulator	1,900	2	96	1000000	154	153,713,530
Photodiode	124	2	96	1000000	10	10,056,101
1x96 AWG	2,850	2	2	20833.33333	337	7,015,639
Raman Amplifier	6,300	2	4	41666.66667	663	27,627,571
Optical Circulator	154	1	1	10416.66667	17	175,875
RF/Electrical Devices				0	0	0
RF 1:5 power splitter	87	4	96	1000000	13	12,876,832
OFDM modem				0	0	0
FPGA board	1,300	4	96	1000000	192	192,412,431
2DAC/2ADC board	4,000	2	96	1000000	324	323,607,431
IQ-Mixer	800	4	384	4000000	97	389,559,668
LO	50	4	384	4000000	6	24,347,479
LPF	25	4	384	4000000	3	12,173,740
BPF	45	4	288	3000000	6	17,046,623
Tx Amp	50	4	96	1000000	7	7,400,478
Rx Amp	50	4	96	1000000	7	7,400,478
LTE	0		0	0	0	0
BPF	25	4	96	1000000	4	3,700,239
Low-noise Amp	232	4	96	1000000	34	34,338,219
WiMAX				0	0	0
DX250	200	4	96	1000000	30	29,601,913
BPF	25	4	96	1000000	4	3,700,239
Low-noise Amp	232	4	96	1000000	34	34,338,219
UWB				0	0	0
BPF	32	4	96	1000000	5	4,736,306
UWB Amp	850	4	96	1000000	126	125,808,128
–inc. ADC/DAC	4,000	2	96	1000000	324	323,607,431
–Centralised Management Subsystem	1,300	4	1	10416.66667	498	5,189,354
– inc. channel sounding	4,000	4	96	1000000	592	592,038,250
Prototype Components Total				0	0	0
						0
Total						2,419,328,937
Port cost						2,419

3.5.4 RN –Remote node with amplifier

Here we calculate total price of RN when amplifiers located at RN. For developing of the model we can use all the prices in following Table 3.16.

Table 3-16. Baseline cost estimation for RN.

RN [Amp@RN]			
Component	**Unit Cost (€)**	**Quantity**	**Total Cost (€)**
Optical Amplifiers	2200	4	8800
Optical Circulator	154.41	3	463.23
Band Splitter	100	2	200
AWG	2850	2	5700
Total			15163.23

This price is for one lab buddy device and of course for implementation some mechanic and wiring part and also electronic part need to be removed.

In consequence, in the access network deployment, every element of the system is categorized depending on this classification (from type 0 to 7), and then, depending on the network scenario, topology, architecture, solution and expected deployment coverage, the unitary cost is calculated. We can observe that many factors can effect on this; the more one makes use of an element for a production, the lower is its cost.

Table 3-17. Unitary cost at the initial reference volume for RN with amplifier.

RN cost Amp@RN							
	current unitary COST per year (€)	**Type of learning cost (1-9)**	**Number for each RN**	**QUANTITY per ONU**	**QUANTITY of user**	**Unitary cost**	**Cost**
Optical Amplifiers	2,200	2	4	41666.66667	1000000	309	12,863,631
Optical Circulator	154	1	3	31250	1000000	20	637,679
Band Splitter	100	1	2	20833.33333	1000000	14	284,658
AWG	2,850	2	2	20833.33333	1000000	449	9,354,185
Total							23,140,153
Port cost							2,221

3.5.5 ONT

In this part we estimate the price of ONT when amplifiers located at RN. For developing of the model we can use all the prices in following Table 3.18.

Table 3-18. Baseline cost estimation for ONT.

ONT			
Component	**Unit Cost (€)**	**Quantity**	**Total Cost (€)**
Optical Devices			
Photodiode	124.3	1	124.3
DML			
– Current source & Temp contr (per channel)	2525	1	2525
– Interconnection cables	150	1	150
– Laser mount (per channel)	1746	1	1746
Prototype Components Total			
– MQW-DFB laser	950	1	950
Band Splitter	100	1	100
RF/Electrical Devices			
RF 1:5 power splitter	87	1	87
Baseband GbE OFDM modem			
FPGA board	1300	1	1300
2DAC/2ADC board	4000	1	4000
IQ-Mixer	800	4	3200
LO	50	4	200
LPF	25	4	100
BPF	45	3	135
Tx Amp	50	1	50
Rx Amp	50	1	50
LTE			
BPF	25	1	25
Low-noise Amp	232	1	232
WiMAX			0
DX250	200	1	200
BPF	25	1	25
Low-noise Amp	232	1	232
UWB			
BPF	32	1	32
UWB Amp	850	1	850
Antenna	10	4	40
Control (Inc, Channel Sounding)	1300	1	1300
(ADC/DAC board)	4000	1	4000
Prototype Components Total			21653.3

This price is for one lab buddy device and of course for implementation some mechanic and wiring part and also electronic part need to be removed. However next Table 3.19 shows the different evolution of their relative cost as a function of the production volume.

Table 3-19. Unitary cost at the initial reference volume ONT.

ELEMENT	current unitary Cost per year (€)	Type of learning cost (1-9)	Quantity per ONU	Quantity of user	Unitary cost	Cost
ONT						
				1000000	0	0
Optical Devices					0	0
Photodiode	124	1	1	1000000	14	13,739,619
DML	0		0	0	0	0
–Controller Mainframe (1 channels)	722	4	1	1000000	142	142,483,872
–Current source & Temp contr (per channel)	2,525	4	1	1000000	498	498,298,861
–Interconnection cables	150	3	1	1000000	93	93,494,487
–Laser mount	1,746	5	1	1000000	486	485,620,641
Prototype Components Total	0		0	0	0	0
–MQW-DFB laser	950	2	1	1000000	102	102,475,686
Band Splitter	100	1	1	1000000	11	11,053,595
RF/Electrical Devices	0			0	0	0
RF 1:5 power splitter	87	4	1	1000000	17	17,169,109
Baseband GbE OFDM modem	0			0	0	0
FPGA board	1,300	4	1	1000000	257	256,549,908
2DAC/2ADC board	4,000	2	1	1000000	431	431,476,574
	0			0	0	0
IQ-Mixer	800	4	4	4000000	130	519,412,890
LO	50	4	4	4000000	8	32,463,306
LPF	25	4	4	4000000	4	16,231,653
BPF	45	4	3	3000000	8	22,728,830
Tx Amp	50	4	1	1000000	10	9,867,304
Rx Amp	50	4	1	1000000	10	9,867,304
LTE	0			0	0	0
BPF	25	4	1	1000000	5	4,933,652
Low-noise Amp	232	4	1	1000000	46	45,784,291
WiMAX				0	0	0
DX250	200	4	1	1000000	39	39,469,217

BPF	25	4	1	1000000	5	4,933,652
Low-noise Amp	232	4	1	1000000	46	45,784,291
UWB						
BPF	32	4	1	1000000	6	6,315,075
UWB Amp	850	4	1	1000000	168	167,744,171
Antenna	10	4	4	4000000	2	6,492,661
Control (Inc, Channel Sounding)	1,300	4	1	1000000	257	256,549,908
(ADC/DAC board)	4,000	2	1	1000000	431	431,476,574
				0		
				0		
	22,375	0				0
Total						3,672,417,134
ONT cost						3,672

3.5.6 Analysis CapEx cost for FIVER Network

As shown in the last section, several scenarios are targeted for FIVER, depending on the coverage, number of served homes, distance reach (feeder-drop), bandwidth, etc. among the infinite possible combinations. They stress the FIVER system in different ways, reach and can cover different new connectivity requirements.

We have defined two high dense urban and dense urban scenarios, shown in following table. Everyone uses different combination of elements, affecting the total cost, and may also affect the unitary cost.

Table 3-20. Case study

Name	Area (km²)	Population	Pop/Area (1/km²)	radius	Customer
Dense urban	4900	1000000	200	70	262000
High dense urban	1000	1000000	1000	32	262000

AS FIVER supports 100 km area we can have several urban+rural scenarios. We used Aveiro province as a real scenario with different take rates that presented in Table 3.1.
It is very difficult to estimate adoption user for OFDM-PON and next generation PON. Within this section, we are trying to utilise commonly-used models for consumer adoption in order to forecast future demand for FTTH and NG-PON and specially FIVER services, which may therefore provide an estimate of the number of potential subscribers available to a service provider at any given time. Based on a calibration heuristic [20], if we assume adoption user for FTTH is early adopters and GPON could be early majority.

For FIVER as a late majority we can implement following diagram with the inflection point of the adoption curve of 10-15 years as shown in Fig. 3.28.

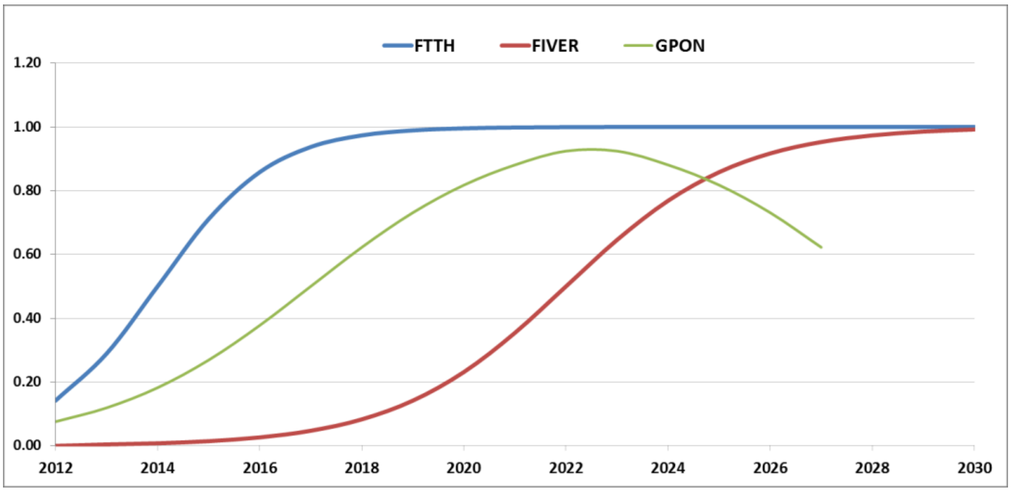


Figure 3-28. Expected chances of FTTH adoption.

As seen with our learning curve, the access technologies based on semiconductors will follow a cost reduction with increasing of volume number of components in each prototype. Now we have to consider that the cost reduction of optical components over the years as the underlying technology has advanced and manufacturing volumes have increased. A precise learning curve is defined as the percentage decline in the price of a product as the (cumulative) product volume doubles in case of time or volume of products. [20, 24].

When only a few observations are available and even if historical costs are partially or totally absent we can use the learning curve as follow: [24]

$$C(t)=C(0).\left[\frac{1}{n(0)}.\left\{1+\exp\left(\left[\ln\left(\frac{1}{n(0)}-1\right)-\frac{\ln(81)}{\Delta T}.t\right]\right\}^{-1}\right]^{\log_2^k}, \qquad (38)$$

Where

- *n(0)* is the relative accumulative volume (equal to 0.5 according to statistical data for components that exist in the market and their price is expected to be further reduced due to aging rather than due to production volume: *n(0)* could be 0.1 for mature products and 0.01 for new components in the market.
- *C(0)* is the component's price in the reference year 0, ΔT is the time for the accumulated production volume to grow from10 to 90 %,
- k is the learning curve coefficient.

The k factor as well as the actual or fore-cast ΔT can be obtained from the production industry, mainly the suppliers. As this model has been used for TONIC project, the RACE-TITAN and ADSL price estimation, similar cost evolution models have been used in all cases presented hereafter. The FIVER port cost for each user forecast modelling gave the estimates: We have C (2012) = 8800 €, ΔT = 15years, n (2012) = 0.1 % and K = 0.8.

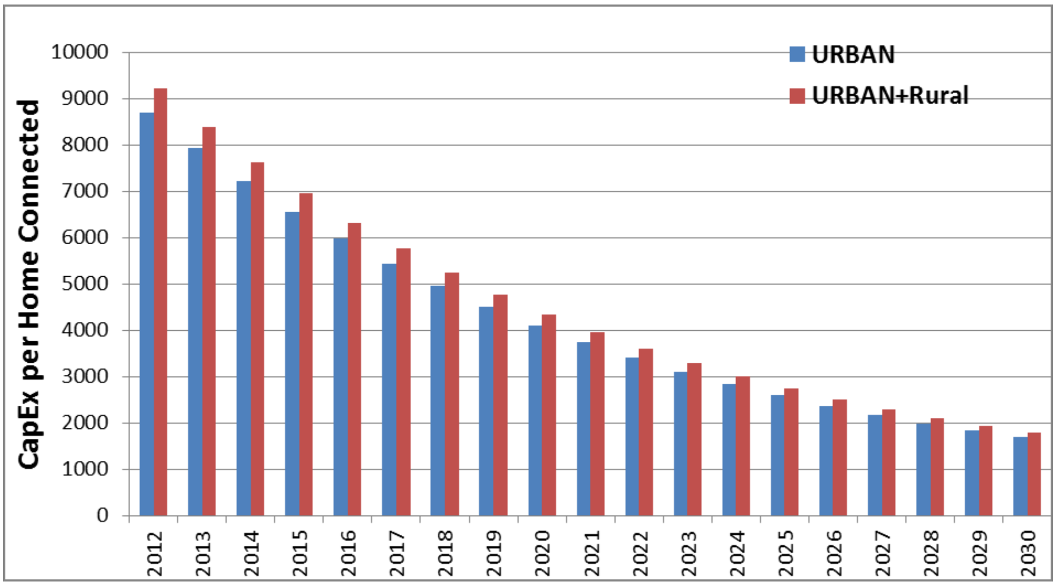


Figure 3-29. CapEx per home connected for urban and urban+rural up to 2030.

Figure 3.29 and 3-30 show the forecasting results based on the assumptions for amplification in RN and OLT with Raman amplifier, respectively.

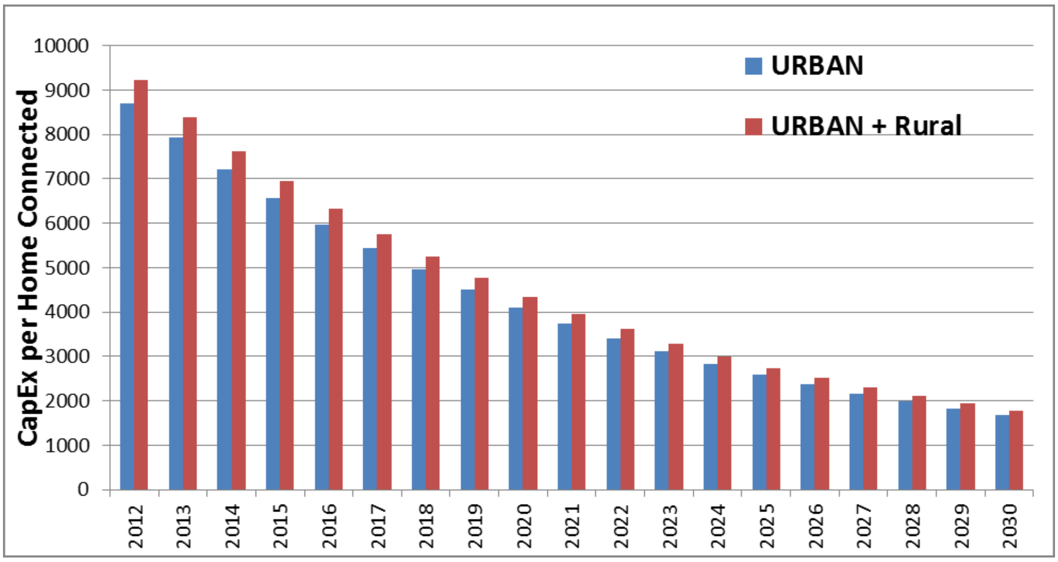


Figure 3-30. CapEx per home connected for urban and urban+rural up to 2030.

Figure 3.29 shows the forecasting results based on the assumptions.

And for amplification in OLT with Raman amplifier we have:

As for rural case the number of user can start from low take rate, it is interesting to see the cost per user for each take rate in current time. As take rate is increasing, because of OLT efficiency and number of user for volume production is increasing and cost of PON and OLT part is decreased.

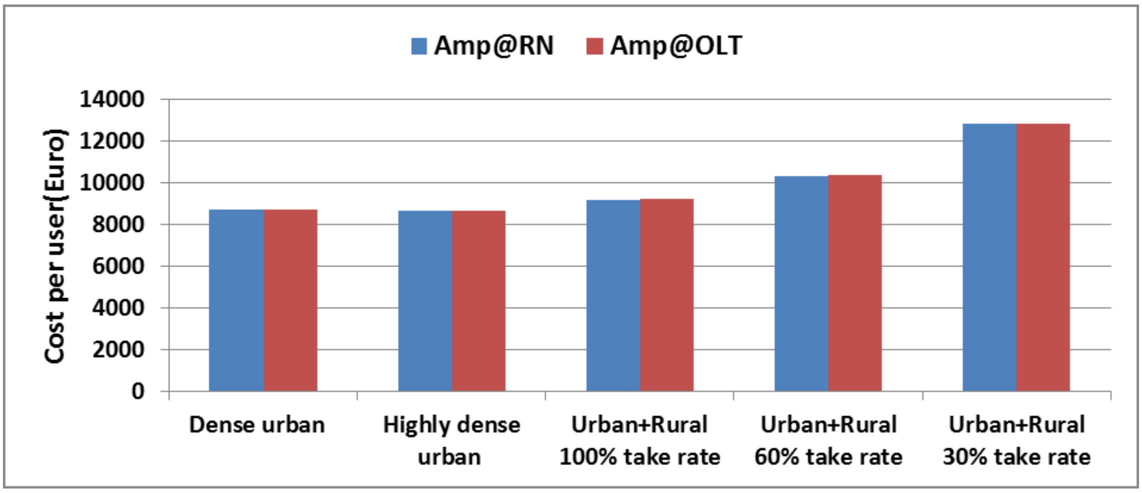


Figure 3-31. Today cost per user for different scenarios and take rates.

3.6 Concluding Remarks

In this chapter, a techno-economic model by incorporating the bottom up approach as an optimization-focus with the top-down approach as an engineering-rules based was presented. The model was implanted for GPON and Long Reach GPON in inside plant and outside plant of network to calculate the cost for several urban and rural scenarios in Portugal. The CapEx per user for both single and cascaded splitter schemes for different take rates was calculated. The intrinsic design characteristic of two configurations to serve a high number of end users with OLT efficiency was translated into saving in components in inside plant in densely as well as scarcely populated areas. A price learning curve for estimate of new components and new technologies was presented and was extrapolated in time and then for calculation of deployment costs of WDM-PON and OFDM-PON was employed.

CHAPTER 4 CONCLUSIONS AND FUTURE WORK

Summary

This final chapter presents the most important conclusions on the techno-economic of PONs deployment. Some guidelines for future research work are also presented.

4.1 Summary of the works and Contributions

Throughout the different chapters we presented several main issues to be faced by the service providers in developing and migration of existing and future access networks. We started with FTTH concepts in optical access networks to address different types of PONs providing the cost-effective, flexible and reliable improvement in deployments and development of access architectures. It was concluded that PON will offer higher bandwidths, enabling more products and services with better quality of service and increasing subscriber satisfaction.

The next step was to classify the existing PON and candidate for NG-PON2 based on their characteristics. The services and different type of users as a driver of these technologies were analysed and the required technology for each service versus time was presented. Obviously, TDM-PONs was employing different wavelengths for upstream and downstream and can share it between several subscribers. The per-user cost of TDM PONs was low as the bandwidth is shared among all the subscribers. But the PON architecture could easily support more wavelengths and allowing each user has its own wavelength. The study and classification of existing protocols enabled us to propose WDM-PON and OFDM-PON technologies with excellent scalability could support multiple wavelengths over the same fibre infrastructure.

Cost issues especially in development of access networks was the common metric and a techno-economic model was proposed based on this metric. This model drew the consequence of different ODN structures during each network implementation phase. This model also provides a guideline to compare CapEx per user for different topology and take rate. The comparison indicates that in cascaded configuration due to its access convergence and deep positioning of splitters, length of drop fibre and consequently duct and trenching are reduced which translates to great savings in terms of material and labour. Also influences of civil work and sharing outside plant have been demonstrated in high and low take rates. The intrinsic design characteristic of two configurations to serve a high number of end users with OLT efficiency was translated into saving in components in inside plant in densely as well as scarcely populated areas. The savings in fibre, number of splitters and storing areas were evident in the presented results.

The techno-economic model was implemented for GPON and Long Reach GPON considering the inside and outside plant of the networks. The CapEx for different urban and rural scenarios in Portugal was estimated.

When it came to WDM-PON and FIVER project the CapEx calculation per user provides tangible results for the deployment of its outside plant. The calculated cost of WDM-PON and FIVER key individual elements was extrapolated in time and then incorporated in the model for calculation of deployment costs and migration cost from GPON to WDM-PON. These computations show that FIVER architecture can be cost effective In addition; FIVER architecture provides an environmental friendly solution because of the decreased volume of fibre and overall material needed for its deployment. Besides, its flexibility allows a manageable migration from an already deployed network to this WDM solution with minimum construction labour.

4.2 Main Challenges and Future Work

When looking ahead, it is a future challenge for practical NG-PON2 implementation to develop novel optical access structure. Therefore, it seems interesting to study the potentialities of the techno-economic model PON with respective to main topics such as the increase of bit rate, reach and splitting ratio, reduce CapEx and OpEx. However many other key issues have not been covered by the model. Some of these issues are listed below and require further investigation.

Integrated optical components: Traditionally CMOS feature size is tied to Moore's Law and in future all the electrical and optical parts of ONU and OLT beside their DSP can be integrated in the single chip for having single components. This could be able to estimate total cost of components for next 20 years and this is an area not yet properly developed.

OpEx and power consumption: We implemented the model for CapEx, in next step we are going to consider OpEx and power consumption in details. In NG-PON2 technologies total cost should be calculated in detail, thus in the design of efficient model, potential OLT nodes should be selected based on incentives, energy consumption and network bandwidth. Once again this is an area full of open challenges.

User adoption model for different type of users: Services and users are key requirements for each system and architecture design. In next 5 years, global IP traffic will reach 1.4

zettabytes per year [2]. Therefore, it is very important to know in each country and each culture, how several types of user are growing. It can help to operator to have a good long term decision when they are selecting their technology.

Annex I: Portugal's present and future on FTTH

This annex summarizes the deployment situation of FTTH in the world and European countries especially in Portugal. Recently, ANACOM [29] has done a lot of researches on panorama of the Portugal fibre deployment and service requirements. In the near future of Portugal, following application and services will continue to increase dramatically over current values: real-time monitoring and widespread adoption of services such as video over Internet, online/virtual reality, IPTV, TV3D15/Home Theatre, "Super Hi- Vision", content sharing applications (peer-to-peer), 3G/4G mobile devices, "cloud computing",

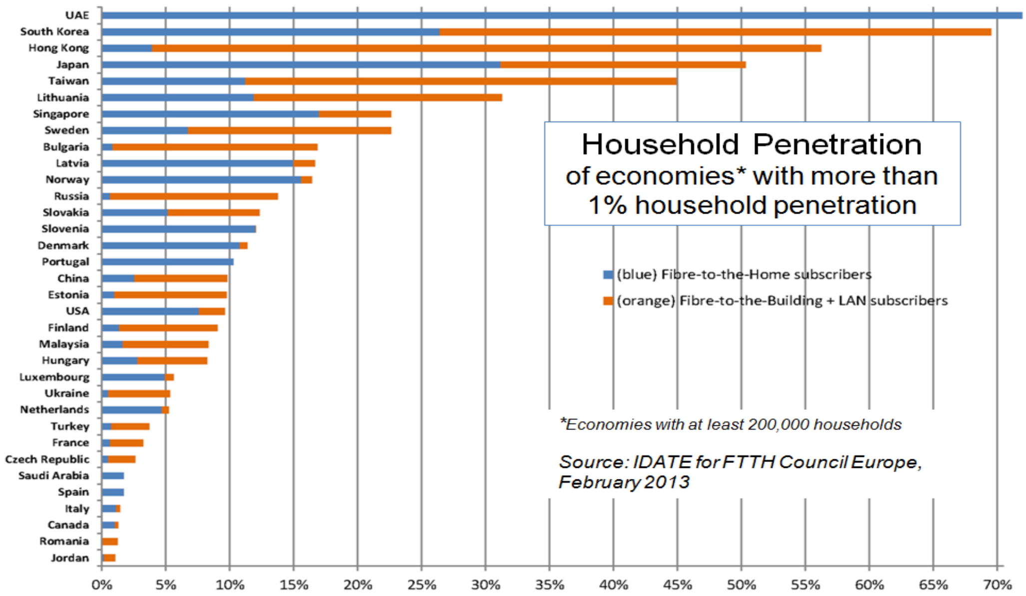


Figure 0-1. Rate of household penetration of FTTH/B+LAN in terms of homes connected [16]

e-learning, inactivity sensors, online medical consultation, home security, smart homes, access controls, electronic commerce and social networking, traffic values [29]. In Portugal Asymmetric Digital Subscriber Line (ADSL/ADSL 2+) technology and Cable TV (CATV) are current broadband access infrastructure. Although the fixed broadband penetration is about 14.8% and for mobile broadband penetration is 18%, but fixed broadband customers are about 1.57 millions in all Portugal.

Figure I.1 presents roll-out forecasts by technology in Western European countries. The total coverage will vary greatly by 2017 if operators stick to current plans.

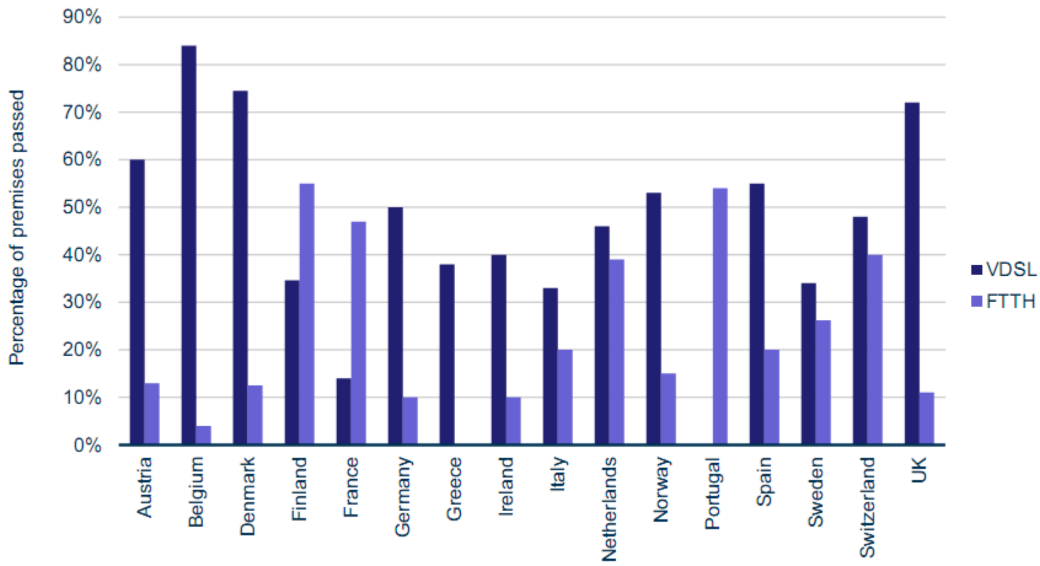


Figure 0-2 Incumbents' roll-out forecasts by technology, Western Europe, 2017 [16]

At the end of 2012, Portugal occupied 16th position in the group of world countries and 10th in European countries with highest FTTH penetration, with a penetration rate reported of around 10%, according to the FTTH Council Europe in Fig. I.2 and I.3.

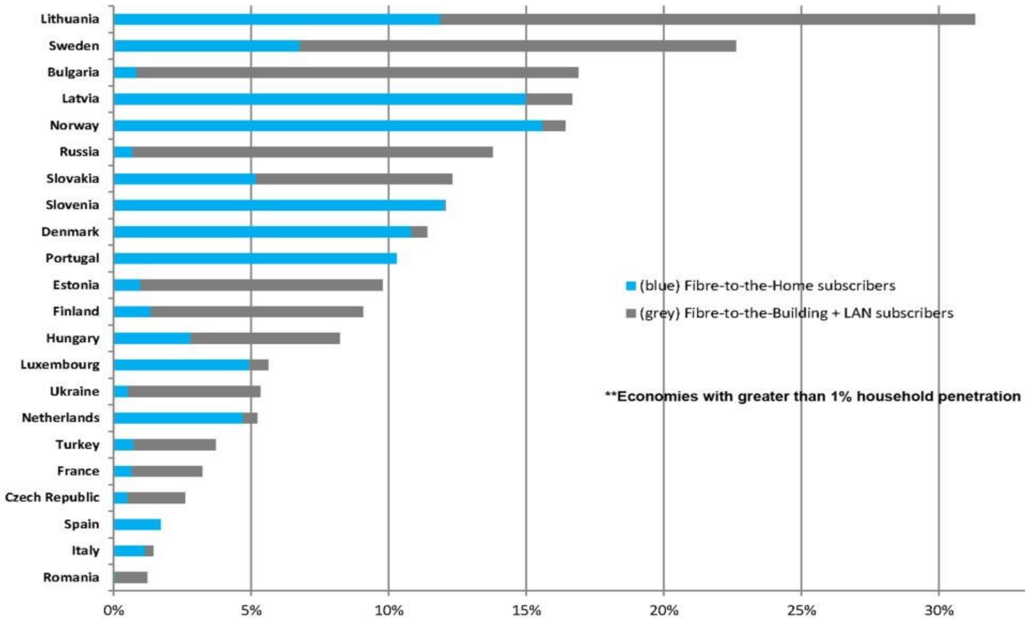


Figure 0-3. European Ranking- December 2012[16]

Also Portugal is in the Top 5 European countries in terms of home passed in total households and this will be good news for more work, research and develop of FTTH network (Fig. I.4).

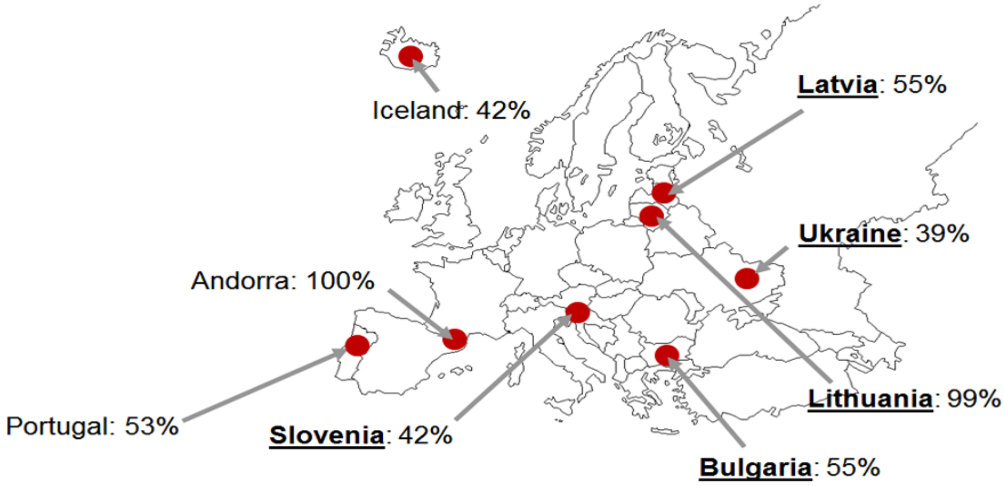


Figure 0-4. Top 5 European countries in terms of HP in total households [16].

According to forecasts from Heavy Reading, in December 2014, the penetration rate in terms of FTTH homes in Europe will be as shown in Fig. I.5. With regard to Portugal, these forecasts may be an underestimate, given the latest data on trends in the number of cabled and connected homes.

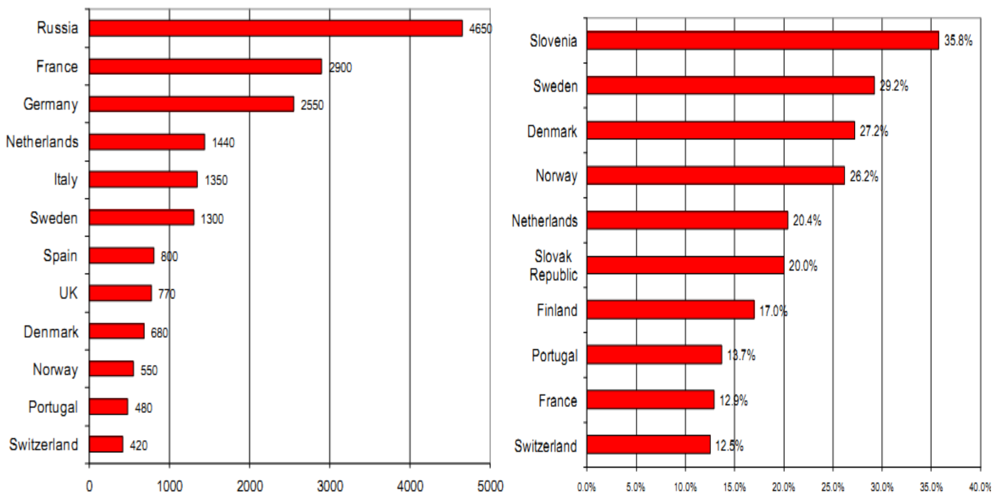


Figure 0-5. a) Connected Households b) Forecast FTTH penetration for Dec 2014 [16].

The total potential customer base in Portugal amounts to 4.9 million customers. 4.45 million are residential customers (households including second homes) and 0.45 million are business customers. Note again that these numbers include broadband customers using cable modems for internet access, mobile-only households and those not using electronic communications services at all [30]. As seen in Table I.1 the population in Portugal is not very concentrated, with 61% of it living in rural areas. The potential customer base living in high density areas (dense urban) is low (0.9%). But 19.3% live in the three urban clusters. Thus, Portugal is a country with rather strong urban and rural areas and a minor suburban population. So using some access technology with long reach and all passive equipment is felt.

Table 0-1. Population density in Portugal.[29,30]

Cluster Type	Customer Base		
	in mill.	in %	accumulated %
Urban	0.1	2.8	3.7
Less Urban	0.8	15.5	19.2
Dense Suburban	0.2	3.6	22.8
Suburban	0.3	6.9	29.8
Less Suburban 0	0.5	9.2	39.0
Dense Rural	1.2	24.4	63.4
Rural	1.8	36.6	100.0

There are parts of the national territory, mainly rural, where it is unlikely that, in the near future the market will generate the incentives necessary for operators to invest in new infrastructure for the provision of broadband access services (especially high-speed and long reach), e.g. due to factors critical to the investment, such as population density (which determines the cost of bringing the network to households) and socio-economic factors such as age, education level and per capita income (which determine the potential revenue generated by the network).

In accordance with the some tender specifications, the winning entity will be bound to ensure minimum coverage of 50% of the population of the geographic area of each of the municipalities included in the tender within twenty-four months, and guarantee a minimum speed 40 Mbps (downstream) per end-user.

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