POLITECNICO DI TORINO

Engineering College

Master degree course in Communications and Computer Networks Engineering

Master Degree Thesis

Planning an FTTH network and estimate its capacity evolution in the long term

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Abstract

For years copper-based cable has been the standard for network connectivity. As services such as video streaming and wireless communication become ubiquitous, and concern over network security grows, traditionally copper cabling has become weak. Advances in Passive Optical Network (PON) and Active Ethernet (AE) technologies offer new, cost-effective option that allows the transition to fiber-optic cabling.

The targert of this thesis is to adapt a pre-existing topological network (that is not primary designed for optical fiber communication) in order to build a Fiber-To-The-Home (FTTH) network, taking into account the evolution of the network with respect to the bitrate demands of coming years.
The thesis focused on techno-economico analysis, comparing the different solutions in terms on ‘Capital Expenditures (CAPEX) and OPerating EXpenditures (OPEX) costs.

The project has been developed with the Wireless Internet Service Provider (WISP) Fastalp s.r.l., located in Pont-Saint-Martin (Aosta, Italy).

After a thorough techno-economic analysis of the two fiber technologies Passive Optical Network (PON) and Active Ethernet (AE), we choose to use the PON solution.
As we can see in Fig. 1 the main reason behind that are the unitary costs per Point of presence (POP), building (BL), Deploy of fiber per km (KM) and client of the two technologies:

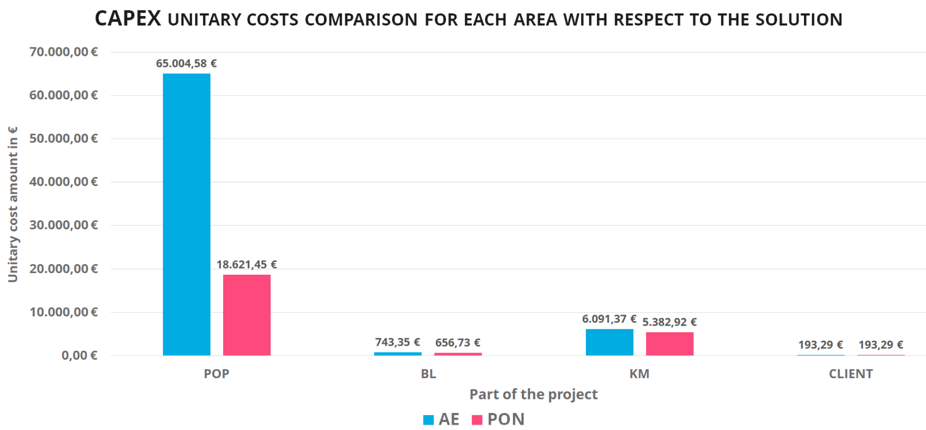

Figure 1. Capital Expenditures (CAPEX) unitary costs comparison with respect to the technology

Another important reason for choosing Passive Optical Network (PON) technology is the co-existence between different PON technologies, so that by changing the transmitter, receiver and the end user devices, and employing Wavelength Division Multiplexing (WDM) CoEXistence multiplexer, it is possible to upgrade the network without changing all the outside plant optical distribution equipment. This obviously is reflected in the lower cost in upgrading PON technology.

In Fig. 2 we can see an example of why it is possible the PON co-existence:

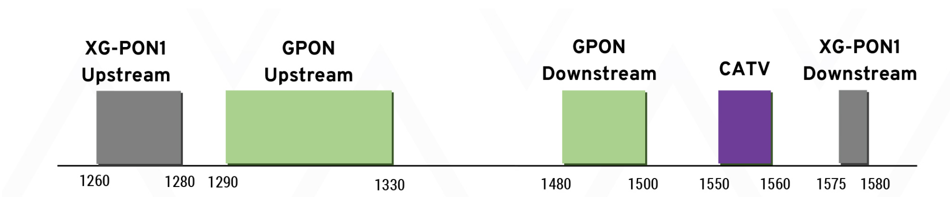

Figure 2. Optical spectrum utilized in passive optical network with implemented GPON and XG-PON1 standards and RF overlay for broadcasting TV service (CATV). Figure taken from [10].

The last key topics of this thesis are the estimation of the cost/income in the long term and the estimation of the network evolution based on the Cisco VNI Global Fixed and Mobile Internet traffic forecasts 2017-2022.

The cost/income estimation was performed to do a bottom line analysis. The bottom line is the enterprise's net income, or the "bottom" figure on a company's income statement. More specifically, the bottom line is an enterprise's income after all the expenses have deducted from revenues. With the bottom line analysis we can predict after which year all the revenues cover all the previous costs leaving profit margin to the company

In Fig. 3 we can see that between the sixth and the seventh year the incomes overcome the costs taking also into account the previous years:

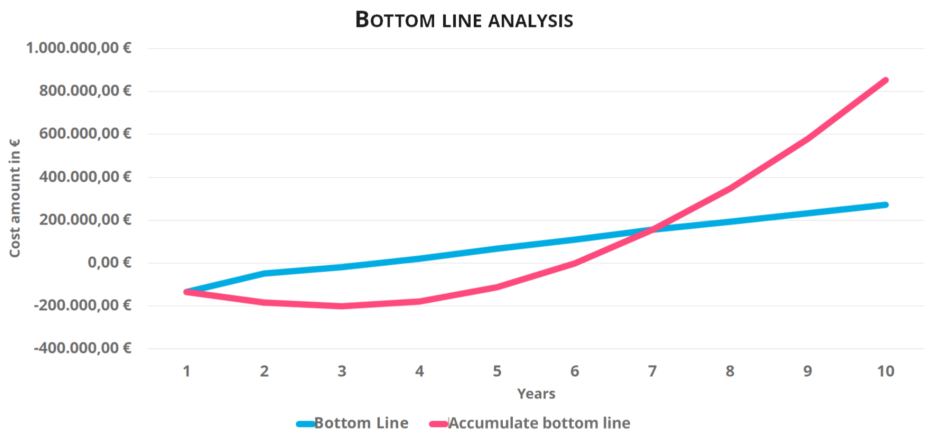

Figure 3. Bottom-line and Accumlate bottom-line analysis

In order to estimate the project network evolution, in the last part of this manuscript is estimated the entire project bitrate demand evolution taking into account a customer growth of 30% per year, the increasing Minimum Cell Rate (MCR) estimated for each internet profile and the network infrastructure branch of the pilot area.

Two different evolution scenarios are proposed for the project network evolution:

- **PON co-existence:** The first scenario consists in upgrading the PON to Gigabit Passive Optical Network (GPON) technology with the co-existence between the two.
- **Reducing the split ratio:** The second scenario consists in reducing the initial split ratio of the Optical Line Termination (OLT) of the PON network.

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Acronyms

AE Active Ethernet iii, viii, 1, 2, 5–7, 18, 28–39, 41, 54, 55, 57, 93, 97–99

ARPU Average Revenue Per User ix, 1, 59, 61, 73, 79, 100

ATM Asynchronous Transfer Mode 1, 9

BOM Bill of Materials 1, 32–35, 37, 44, 46–49

CAGR Compound Annual Growth Rate 1, 82–85, 89, 104, 105

CAPEX Capital Expenditures iii, iv, viii, xii, 1, 2, 38, 39, 50–52, 65, 79, 102, 107

CO Central Office 1, 6, 17, 28, 96

CPE Customer Premise Equipment 1, 36, 37, 49, 56, 87, 88

EPON Ethernet Passive Optical Network 1, 9–11

FTTH Fiber-to-the-Home ix, 1–3, 5, 18, 19, 27, 56, 91, 93, 96, 107

Gbps Gigabits per second 1, 9–13, 33

GPON Gigabit Passive Optical Network v, 1, 9, 10, 12, 14, 86, 88

ISP Internet Service Provider 1, 13

Mbps Megabits per second 1, 9, 33, 85

MCR Minimum Cell Rate v, 1, 85, 86, 90, 106

NG-PON1 Next-Generation Passive Optical Network 1, 9, 15

NG-PON2 Next-Generation Passive Optical Network 1, 11, 12, 15, 46

NID Network Interface Device 1, 34, 48

ODF Optical Distribution Frame 1, 32, 45

ODN Optical Distribution Network 1, 12

OFDM Orthogonal Frequency Division Multiplexing 1, 9, 14

OLT Optical Line Termination v, 1, 8, 9, 45, 88

ONT Optical Network Termination 1, 6, 9

ONU Optical Network Unit 1, 8, 9, 13, 14

OPEX OPerating EXpenditures iii, ix, 1, 61, 65, 67, 69, 79, 102, 107

OSP Outside Plant 1, 33–35, 46–48, 55, 56

OSS Operations Support System 1, 37

OTDR Optical Time Domain Reflectometer 1, 56

P2MP Point-to-multi-point xii, xiii, 1, 5, 8, 11, 13, 17, 18, 42, 46, 93, 98

PCR Peak Cell Rate 1, 85

PON Passive Optical Network iii–v, viii, 1, 2, 5, 8, 9, 11–15, 17, 18, 28, 29, 41, 42, 44–52, 54–57, 86–88, 90, 93, 94, 96, 98, 106, 107

POP Point of presence iii, 1, 6, 31–33, 41, 44–46, 54, 55, 57, 69, 98

PTP Point-to-point 1, 5, 6, 8, 11, 13, 17, 18, 30, 46, 97, 98

SFP Small form-factor pluggable 1, 32, 46, 56, 88

TDM Time Division Multiplexing 1, 8, 9, 11, 13

TWDM Time and Wavelength Division Multiplexing 1, 9, 11–13

TWDM-PON Time and Wavelength Division Multiplexing Passive Optical Network 1, 11

UHD Ultra-High-Definition 1, 85

WDM Wavelength Division Multiplexing iv, 1, 9, 11, 13, 87, 90, 106

WISP Wireless Internet Service Provider iii, 1, 2

XG-PON Ten-Gigabit-Capable Passive Optical Network 1, 9, 10, 12

XGS-PON Ten-Gigabit-Symmetric Passive Optical Network 1, 9, 10

Chapter 1

Scope of the project

1.1 Introduction

This Chapter gives an overview of how this thesis is organized and which are the objectives that will be achieved.

1.2 Objectives

The main scope of the project is to design a Fiber-to-the-Home (FTTH) network, taking into account its evolution with respect to the bit-rate demands of coming years.

The specific objectives are:

- Analyze and evaluate the topological and mechanical constraints due to the pre-existing district heat network.
  The district heat network (also known as heat networks or teleheating) is a system for distributing heat generated in a centralized location through a system of insulated pipes for residential and commercial heating requirements. In the city of Aosta, the district heat network spread over all the city with a pipe network that link all the most important buildings of the city with the centralized heating plant. By exploiting this pipe network the cost of the fiber deployment is very low.
  The downside of this approach and the challenging part of this project is to adapt a pipe network (that is not primary designed for optical fiber communication) in order to build Fiber-to-the-Home (FTTH) network.

- Analyze and choose the best FTTH technology for this project. In order to design the Fiber-to-the-Home (FTTH) network, we have to analyze the capabilities, standards and advantages and disadvantages of the two main fiber technology Active Ethernet (AE) and Passive Optical Network (PON).
- Define the network resources for the entire FTTH network. In order to choose the best fiber solution, we have to define the network resources needed for each technology and we have to compare their unitary Capital Expenditures (CAPEX) costs.
- Estimate the cost/income in the long term. This part is very important to understand when all the expenses will be covered by the revenues of the project. This is done by performing a bottom-line analysis.
- Estimate the network evolution with respect to the grow of bit-rate demand of coming years. This is one of the key point of this thesis and it affects also the choice of the fiber technology.

1.3 Description of the host company

The thesis has been developed in partnership with FastAlp srl, an Italian company located in Pont-Saint-Martin, Aosta Valley, Italy.

Figure 1.1. FastAlp srl logo.

FastAlp srl is a Wireless Internet Service Provider (WISP) built in 2005 with the mission to provide broadband wireless internet access in the "Digital Divide" areas. The company is rooted in the Aosta Valley territory and it provides services from Aosta Valley to the Canavese territory of Piedmont.
With this project FastAlp is trying to fit in the optical fiber telecommunication world.

1.4 Organization of the thesis

The manuscript is subdivided in six Chapters.

1.4.1 Fiber-To-The-Home (FTTH) technologies

In the first Chapter there is an overview of the main Fiber-to-the-Home technologies and for each technology are highlighted the advantages and the disadvantages.

1.4.2 Constraints Evaluation

In the second Chapter the topological and mechanical constraints of the network are evaluated with respect to the pre-existing district heat network.

1.4.3 Planning of the network resources

In the third Chapter the network resources needed to build the network are defined. In particular, for each FTTH technology the cost to deploy the FTTH project are analyzed. In the last part is presented the motivation of the technology chosen and the software used to design the network.

1.4.4 Estimation of the cost/income in the long term

In the fourth Chapter the cost/income in the long term are estimated, taking into account the expected grow of the customer per year and the expected costs and revenues for each year.

1.4.5 Estimation of the project network evolution

In the fifth Chapter the evolution of the project network with respect to the bitrate demand scenario and the costs that will affect the entire project are estimated.

1.4.6 Conclusions

In the last Chapter the key points and the achievements of each previous part are summarized and discussed.

Chapter 2

Fiber-To-The-Home (FTTH) technologies

2.1 Introduction

This Chapter describes the two main families of Fiber-to-the-Home technologies.The standard architecture and the advantages and the disadvantages of Active Ethernet (AE) and Passive Optical Network (PON) are explained.

2.2 FTTH technologies

When optical communications entered in the field of telecommunication, the fiber was much more expensive than copper and also the cost to deploy the fiber on the field (primary civil work) was very high.
To deploy a FTTH network we have to choose which type of architecture we want to design:

- **Point-to-point (PTP):** the simplest way to deploy fiber access is to replace copper wires with fiber strands. This solution is usually called **Active Ethernet (AE)**.

- **Point-to-multi-point (P2MP):** another way to deploy fiber access is to split (in a passive way) one fiber strand into a maximum of 64 split ratio. This solution is called **Passive Optical Network (PON)** because of the absence of active devices along the fiber link.

2.3 Active Ethernet (AE)

The simplest way to deploy fiber access is to replace copper wires with fiber strands, resulting into a PTP fiber network. With this approach there is a raw fiber strand from the Central Office (CO) (or POP) to each customer. This means that every user has a dedicated pipe between the Point of presence (POP, where the core switches are located) and the Optical Network Termination (ONT, the customer location).
Since it is a PTP connection, the capacity is limited only by the capability of the optical equipment located in the endpoints. This leads to good performance and network capabilities, but in an higher capital investment to build the network.

2.3.1 AE architecture

The Active Ethernet (AE) solution provides two main architectures:

- **Point-to-Point:** in this architecture a fiber strand is reserved for each subscriber. This solution tends to be the most expensive because the number of fiber strands needed is equal to the number of the network subscribers (Fig. 2.1).

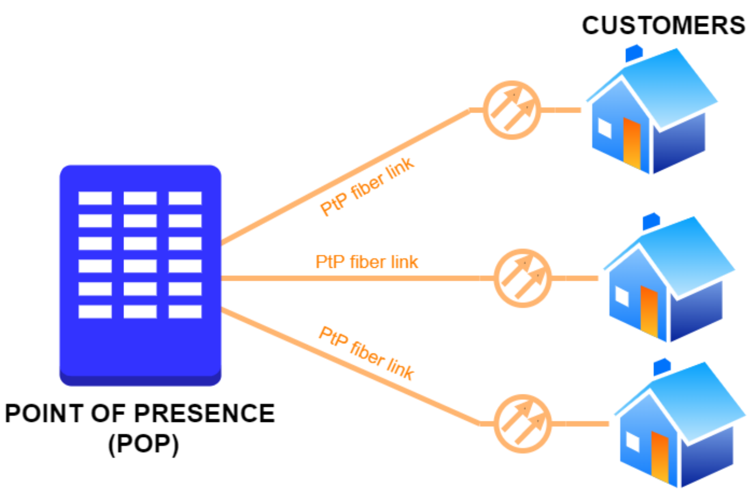

Figure 2.1. Optical access network based on Active Ethernet (AE) Point-to-point solution.

- **Active Star Point-to-Point:** to overcome the fact to have one fiber strand for each subscriber, the solution is to implement electronic concentration, typically using an active ethernet switch, at a remote terminal user near the subscribers (Fig. 2.2)

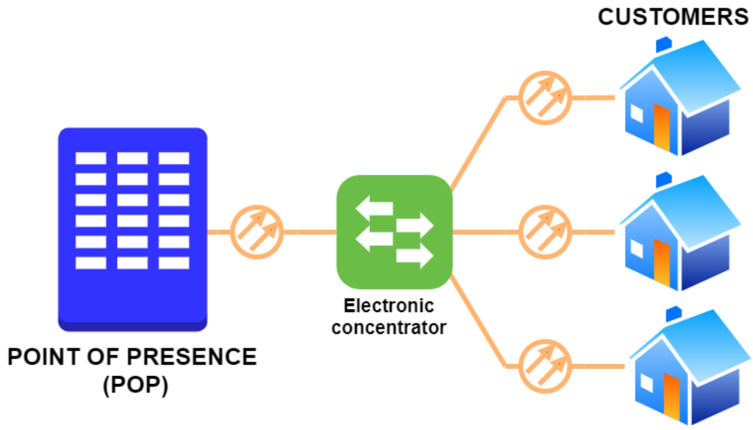

Figure 2.2. Optical access network based on Active Ethernet (AE) Active Star point-to-point solution.

2.3.2 AE capabilities and standards

In Table 2.1 the current AE capabilities and the related IEEE standards are summarized.

Technology	Downlink	Uplink	Standard	Year
1000BASE-SX/LX	1 Gbps	1 Gbps	802.3z	1998
10GBASE-SR/SW/LR/LW/ER/EW/LX4	10 Gbps	10 Gbps	802.3ae	2002
40GBASE-T/KR4/CR4/SR4/FR/LR4/ER4	40 Gbps	40 Gbps	802.3bm	2015

Table 2.1. Active Ethernet (AE) capabilities and standards

2.3.3 Advantages and disadvantages of AE

The Active Ethernet solution have some advantages and disadvantages:

- It uses Active Electronic Switches to provide fiber access aggregation. Because of that, it includes full management and troubleshooting capabilities, but it arise the problem of power requirements.
- It can reach 80km (and more) regardless of the number of subscribers been served.

- It has a PTP architecture, so each user has a dedicated "pipe" that provides full bi-directional bandwidth.
- It requires a huge number of fiber strands.

2.4 Passive Optical Networks (PON)

Passive Optical Network (PON) it is a Point-to-multi-point architecture that uses passive (non-powered) optical splitters and couplers to provide fiber aggregation.

2.4.1 PON architecture

PON architecture is based on optical splitters as shown in Fig.2.3:

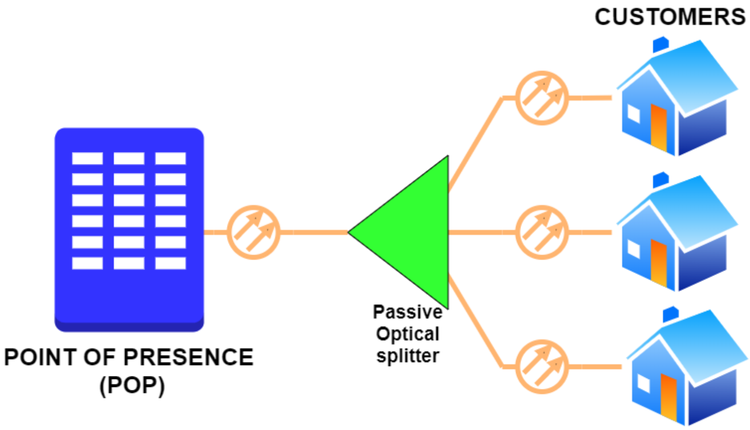

Figure 2.3. Optical access network based on P2MP Passive Optical Network (PON) solution

All PON technologies enable a single port on a central distribution unit known as an Optical Line Termination (OLT) to be connected to multiple subscriber terminals, known as Optical Network Units (ONUs). Passive optical splitters provide connectivity between multiple ONUs and single OLT port over a single optical cable (a single fiber strand). The typical splitting ratio of a PON network for each single strand is 1:32 or 1:64.

Depending on the data multiplexing, PON is subdivided into different families:

- Time Division Multiplexing (TDM) PONs (by far the most common).

- Time and Wavelength Division Multiplexing (TWDM) PONs (recently standardized, but not very commonly deployed).

- Wavelength Division Multiplexing (WDM) PONs (at research level only).

- Orthogonal Frequency Division Multiplexing (OFDM) PONs (at research level only).

2.4.2 Time Division Multiplexing (TDM) PONs

The TDM PON solution is today and by far the most commonly deployed type of PON, with hundreds of million of users in the world.
In TDM PON traffic from/to ONUs are TDM multiplexed onto upstream/downstream wavelengths. In upstream direction each ONT transmit for an assigned time-slot, so the OLT can communicate with one ONT at any point in time. In downstream direction the OLT transmits all the traffic to all the OLT, again with a TDM approach (Broadcast transmission).

There are three main families of TDM PON:

- **APON/BPON:** ATM PON is the initial PON specification based on ATM for long-haul packet transmission. Since ATM is no longer used, a newer version was created and called Broadband PON (BPON). Designated as ITU-T G.983, this standard provided 622 Mbps in downlink and 155 Mbps in uplink. It exploits the wavelength O-Band (from 1260 nm to 1360 nm) and the wavelength S-Band (from 1460 nm to 1530 nm). In particular it uses the 1490 nm wavelength for downstream and 1310 nm wavelength for upstream. It was the first standardized PON, but today it is not deployed.

- **GPON:** Designated as ITU-T G.984, Gigabit Passive Optical Network (GPON) provides 2.5 Gbps in downlink and 1.25 Gbps in uplink. It is by far the most commonly used together with EPON. It accommodates three transport layer (L2) networks: ATM for voice, Ethernet for data and proprietary encapsulation for video, thus enabling GPON with full service support. GPON evolved in NG-PON1 to provide higher bandwidth provisioning. Standardized as ITU-T G.987, NG-PON1 specifies asymmetric 10G-PONs (also referred as XG-PON1 and shown in Fig.2.4) and it provides 9.9528 Gbps in downlink and 2.488 Gbps in uplink. To provide 9.9528 in both uplink and downlink, it was defined XGS-PON and standardized as ITU-T G.9807.1.

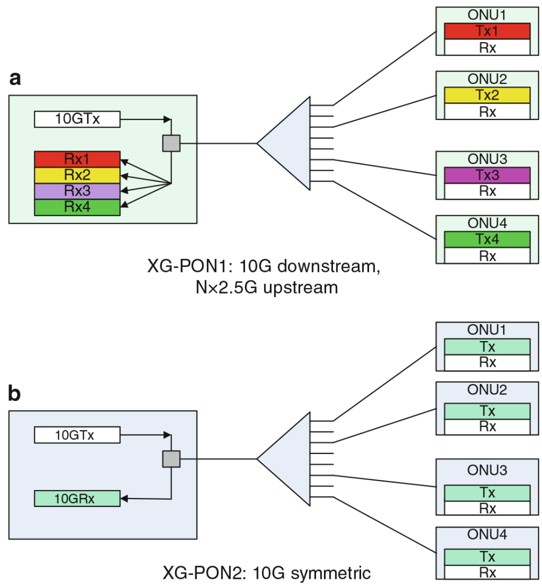

Figure 2.4. (a) TDM PON XG-PON: 10 Gbps downlink, 2.5 uplink (b) TDM PON XGS-PON: 10 Gbps symmetric. Figures taken from [2].

GPON exploits the wavelength O-Band (from 1260 to 1360 nm) and the wavelength S-Band (from 1460 to 1530 nm). In particular it uses the 1490 nm wavelength for downstream and 1310 nm wavelength for upstream.
XG-PON and XGS-PON exploit the wavelength O-Band (from 1260 nm to 1360 nm) and the wavelength L-Band (from 1565 nm to 1625 nm). In particular they use the 1575-1580 nm wavelength range for downstream and 1260-1280 nm wavelength range for upstream.

- **EPON:** Ethernet Passive Optical Network (EPON) is developed based on Ethernet technologies, and it enables seamless integration with IP and Ethernet technologies. Owing the advantages of fine scalability, simplicity, multicast convenience and the capability of providing full-service access, EPON has been rapidly adopted in Asia. Exploiting the Ethernet standard, upstream signals are combined by using again time division multiple access (TDMA). As compared to GPON, the burst sizes and physical layer overhead are large in EPON. The IEEE 802.3ah standardized the 1G-EPON that provides 1.25 Gbps in both uplink and downlink. To provide higher bandwidth provisioning, the IEEE 802.3av standardized the 10G-EPON that provides

10.3125 Gbps in downlink and it can provides symmetric data rate (10.3125 Gbps) or asymmetric data rate (1.25 Gbps) in uplink. The upstream and the downstream EPON traffic exploits different wavelengths with respect to the technology:
EPON exploits the wavelength O-Band (from 1260 to 1360 nm) and the wavelength S-Band (from 1460 to 1530 nm). In particular it uses the 1490 nm wavelength for downstream and 1310 nm wavelength for upstream.
10G-EPON exploits the wavelength O-Band (from 1260 nm to 1360 nm) and the wavelength L-Band (from 1565 nm to 1625 nm). In particular it uses the 1575-1580 nm wavelength range for downstream and 1260-1280 nm wavelength range for upstream.

2.4.3 Time and Wavelength Division Multiplexing (TWDM) PONs

Hybrid TDM and WDM (TWDM-PON) technology shown in Fig.2.5 was selected as the multiplexing technique for NG-PON2. It was standardized as ITU-T G.989. According to the ITU-T G.989.2 standard, NG-PON2 is a PON system that consists of a set of TWDM channels and/or a set of PTP WDM channels. The TWDM channel is a pair of one downstream and one upstream wavelength channel that enable P2MP connectivity. Whereas the PTP WDM channel is a pair of one downstream and one upstream wavelength channel offering PTP connectivity.
TWDM-PON combines the advantages of the high capacity provided by TDM and the large number of wavelengths provided by Wavelength Division Multiplexing into one architecture by transmitting TDM frames to several users over several wavelengths.

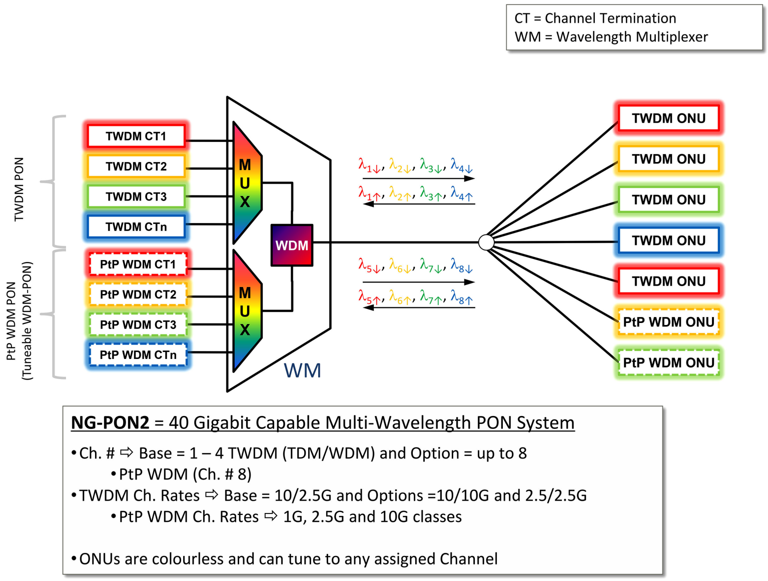

Figure 2.5. NG-PON2 Architecture. Figure taken from [6].

The basic structure of TWDM PON consists of four techniques of XG-PON. They are stacked by utilizing four pairs of wavelength: {λ1, λ5}, {λ2 ,λ6}, {λ3, λ7}, {λ4, λ8}. Each XG-PON provides 10 Gbps and 2.5 Gbps of data rate in downlink and uplink, resulting in a 40 Gbps and 10 Gbps aggregate data rate for TWDM PON in downlink and uplink.

TWDM PON exhibits the following advantages:

- Spectral flexibility: it allows the system to support different types of customer over the same ODN.
- Co-existence: NG-PON2 network use wavelength that are not used by pre-existing PON network. This allows co-existence with GPON and XG-PON.
- ODN re-use: NG-PON2 physical layer has been designed to re-use the deployed PON infrastructure.
- Pay as you grow: Wavelength channels are added to the system one by one.

NG-PON2 exploits the wavelength S-Band (from 1460 nm to 1530 nm), the wavelength C-Band (from 1530 nm to 1565 nm) and the wavelength L-Band (from 1565 nm to 1625 nm). In particular it uses the 1524-1544 nm wavelength range for downstream and 1596-1603 nm wavelength range for upstream.

TWDM PON is not yet commonly deployed today, but it is expected to be the future evolution in PON deployment when user bitrate demands will further grow, as discussed in the last chapter of this thesis.

2.4.4 Wavelength Division Multiplexing (WDM) PONs

WDM PON uses multiple wavelengths to provision bandwidth to ONUs as shown in Fig.2.6. With respect to the TDM multiplexing, WDM multiplexing:

- It allows each user to have a dedicated "pipe" of communication and to access the full wavelength bandwidth.
- It provides better security and scalability.
- It does not require P2MP media access controllers used with other PON networks.
- Each wavelength provides effectively a PTP link.
- It can provide higher than 40 Gbps data rate and even Terabits (even though this has been proved only in laboratory experiments).

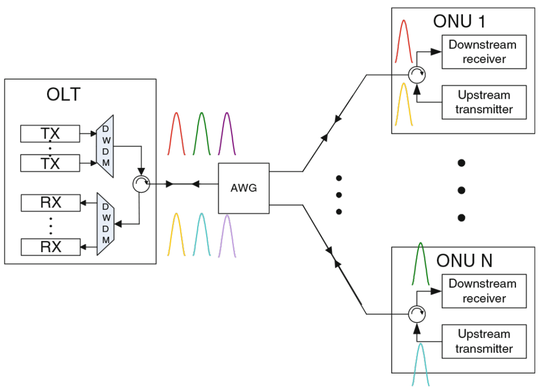

Figure 2.6. WDM PON Architecture. Figure taken from [2].

WDM PON exploits the wavelength L-Band (from 1565 nm to 1625 nm). In particular it uses the 1606-1625 nm wavelength range for downstream for upstream. Even if it offers some advantages than PON, it requires cost-prohibitive devices that lead the ISP to choose TDM solutions.

2.4.5 Orthogonal Frequency Division Multiplexing (OFDM) PONs

OFDM PON employs OFDM as modulation scheme to transmit traffic from/to ONUs. It uses a large number of closely-spaced orthogonal sub-carriers to carry data traffic. It exhibits the following advantages:

- Enhanced spectral efficiency: OFDM makes effective use of spectral resources and improves spectral efficiency.

- The allocation of each sub-carrier is executed in real time according to access distance, subscriber type and access service.

For the moment, OFDM PON is strictly limited to laboratory demonstrations.

2.4.6 PON Wavelengths plans

Typically, PON networks are built using optical fibers that cover at least the 1270-1610nm spectrum range. GPON exploit only the 1290-1330 nm range (upstream) and 1480-1500 nm range (downstream).
The adapted approach in IEEE and ITU-T standards for new PON technologies is to obtain co-existence exploiting all the unused spectrum by GPON using different wavelengths.

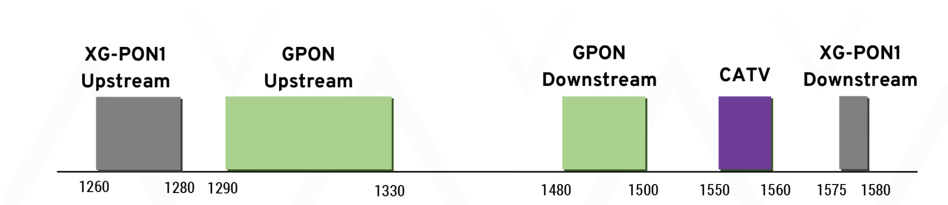

Figure 2.7. Optical spectrum utilized in passive optical network with implemented GPON and XG-PON1 standards and RF overlay for broadcasting TV service (CATV). Figure taken from [10].

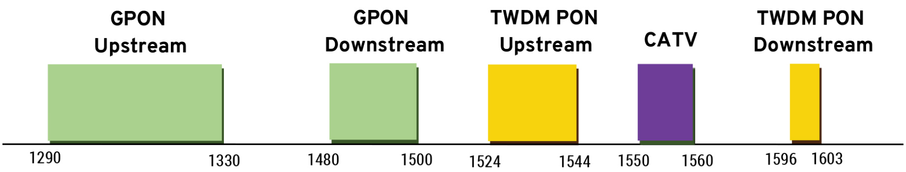

Figure 2.8. Optical spectrum utilized in passive optical network with implemented GPON and NG-PON2 (TWDM PON) standards (Wide Range option for upstream transmission) and CATV overlay. Figure taken from [10].

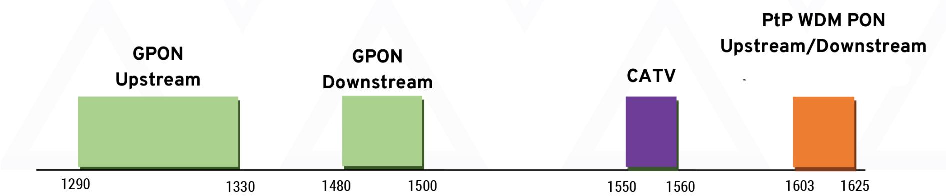

Figure 2.9. Optical spectrum utilized in passive optical network with implemented GPON and NG-PON2 (PtP WDM PON) standards. Figure taken from [10].

The co-existence between different PON technologies is possible with xWDM (or xPON) multiplexers and de-multiplexers. By installing them, telecom operators can make sure that future upgrade in the PON technologies will be possible without impacting on the optical physical infrastructure. Futures upgrades will only require to change few core elements in the endpoints.
In the ITU-T recommendation, xWDM multiplexers are divided into different groups, depending on the standards or services they support. The WDM1r multiplexers should be used when adding new-generation services to an existing PON network. CEx multiplexers should be used in implementations of NG-PON1 and NG-PON2 standards.

2.4.7 PON Capabilities and Standards

In Table 7.2 the main PON capabilities and the standards are summarized.

Technology	Dl	Up	Standard	Year	UpSR	DlSR
APON/BPON	0.622	0.155	ITU-T G.983	1995	1290-1330	1480-1500
GPON	2.488	1.244	ITU-T G.984	2003	1290-1330	1480-1500
1G-EPON	1.25	1.25	IEEE 802.3ah	2004	1290-1330	1480-1500
10G-EPON	10.3125	1.25	IEEE 802.3av	2009	1260-1280	1575-1580
10G-EPON S	10.3125	10.3125	IEEE 802.3av	2009	1260-1280	1575-1580
XG-PON1	9.9528	2.488	ITU-T G.987	2010	1260-1280	1575-1580
TWDM-PON	40	10	ITU-T G.989	2013	1596-1603	1524-1544
XGS-PON	9.9528	9.9528	ITU-T G.9807.1	2016	1260-1280	1575-1580

Table 2.2. Passive Optical Network (PON) capabilities and standards

Where:

- **Dl** is the downlink speed in Gbps.
- **Ul** is the uplink speed in Gbps.
- **UpSR** is the uplink spectral range in nm.
- **DlSR** is the downlink spectral range in nm.

2.4.8 FSAN PON Standards Roadmap

Figure 2.10 highlights the Full Service Access Network (FSAN) group Roadmap for future standardization and technology development about optical access.
The Full Service Access Network (FSAN) Group is a forum for the world's leading telecommunications services providers, independent test labs, and equipment suppliers to work towards a common goal of truly broadband fibre access networks. The group has contributed to ITU-T in standardising a number of passive optical network (PON) systems including GPON (ITU-T G.984 series) XG-PON (G.987 series) and NG-PON2 (G.989 series).

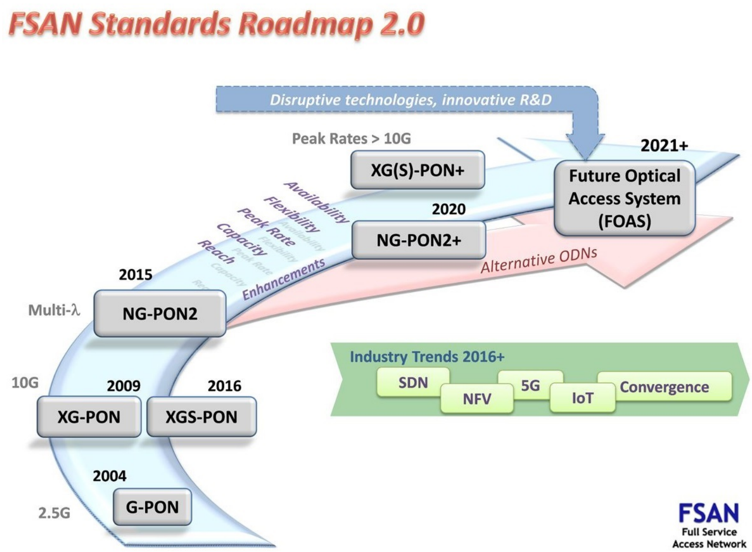

Figure 2.10. FSAN PON Standards Roadmap 2.0. Figure taken from [8].

The FSAN Standards Roadmap 2.0 emphasises a smooth evolution from previously standardised and deployed PON systems through re-use of the existing fibre infrastructure. System enhancements of most interest to the FSAN operator members are identified as: increased capacity, longer reach, improved reliability, enhanced flexibility and peak service rates beyond 10 Gb/s.

2.4.9 Advantages and disadvantages of PON

The Passive Optical Network solution has some advantages and disadvantages compared to PTP:

- Lower cost than PTP.
- One fiber strand can reach up to 64 customers.
- Lower power requirements of OLT at CO
- The maximum physical reach is 20km.
- Splitters have no intelligence, so they cannot be managed.
- Since it is a P2MP architecture, it arise a big security problem and each subscriber gets the same bandwidth.

- Inflexibility in identifying the faults since the optical terminations are passive.
- Different PON technologies can co-exist in the same network.
- Upgrading PON technology is possible without changing all the core and the optical fiber distribution network components.

2.5 Conclusion

In this Chapter we have evaluated the two different architecture of an FTTH network. As we will see in detail in Chapter 4, Point-to-point (AE) technology is more expensive than Point-to-multi-point (PON). Even if in AE solution each user has a dedicated "pipe" that provides full bi-directional bandwidth, we have to face with different problems:

- Upgrading the technology means changing a lot of network equipments and it is more expensive than PON.
- It requires a huge number of fiber strands.
- It uses Active Electronic Switches to provide fiber access aggregation. Because of that, it includes full management and troubleshooting capabilities,but it arise the problem of power requirements.

In the opposite side, in PON solution different users share the same "pipe" and they share the "pipe" bandwidth, but:

- It requires a lower number of fiber strands. One fiber strand can reach up to 64 customers.
- Different PON technologies can co-exist in the same network.
- Upgrading PON technology is possible by changing few core equipments in the endpoints.

Chapter 3

Constraints evaluation

3.1 Introduction

In this Chapter the topological and mechanical constraints of the network are evaluated with respect to the pre-existing district heat network.
The district heat network (also known as heat networks or teleheating) is a system for distributing heat generated in a centralized location through a system of insulated pipes for residential and commercial heating requirements. In the city of Aosta, the district heat network spread over all the city with a pipe network that link all the most important buildings of the city with the centralized heating plant.

By exploiting this pipe network the cost of the fiber deployment is very low.
The downside of this approach and the challenging part of this project is to adapt a pipe network (that is not primary designed for optical fiber communication) in order to build Fiber-to-the-Home (FTTH) network.

3.2 Topological constraints

The Area of interest of the project is Aosta (AO, IT). Related to the pre-existing district heat network service, the City has been subdivided in 8 main Areas as shown in Fig.3.1.

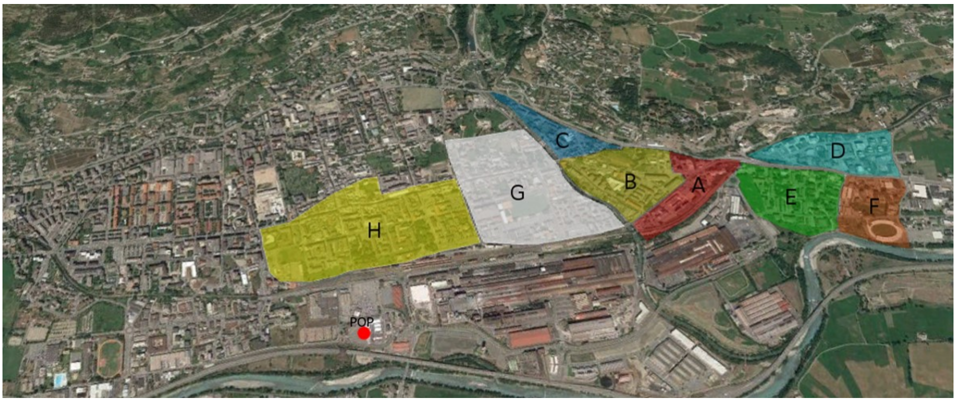

Figure 3.1. Topological areas that will be covered by the fiber infrastructure in the city of Aosta (IT).

The Areas highlighted will be covered by the fiber infrastructure in 3 years. The G and H areas are the "Pilot Area", i.e. the areas that will be implemented in the short term. The Pilot Area should have been covered in the end of 2018. The Area that is not taken into account ("West Area") is a "Work in progress", because is not fully joined by the district heat network.
In order to predict the cost of the entire project, we decided to group the topological areas of the city (Fig. 3.1) into 3 different lots:

- **Lot 1:** G and H areas.

- **Lot 2:** B, D, E and F areas.

- **Lot 3:** A and C areas.

3.2.1 Potential customers

In the highlighted Area of Fig.3.1 there are customers that are reached from the district heat network, so they can be potentially be joined by the fiber network, and potential customers that are not yet reached from the district heat network.

Buildings to be covered

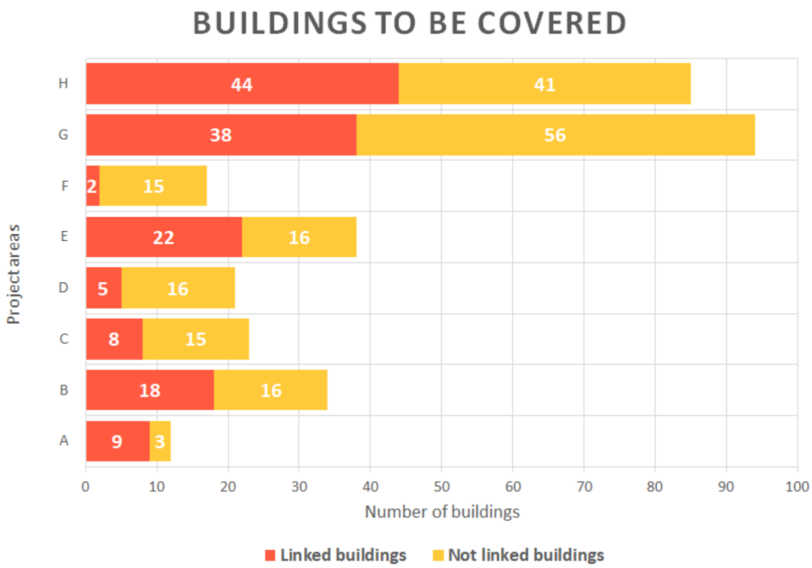

Figure 3.2. Buildings to be covered with respect to the Area that they belong

In Fig.3.2 we can see the number of the buildings that are linked to the district heat network, so they can be reached from the fiber network, and the number of the buildings that are not linked, so they can't be reached yet from the fiber network, with respect to the Area that they belong.

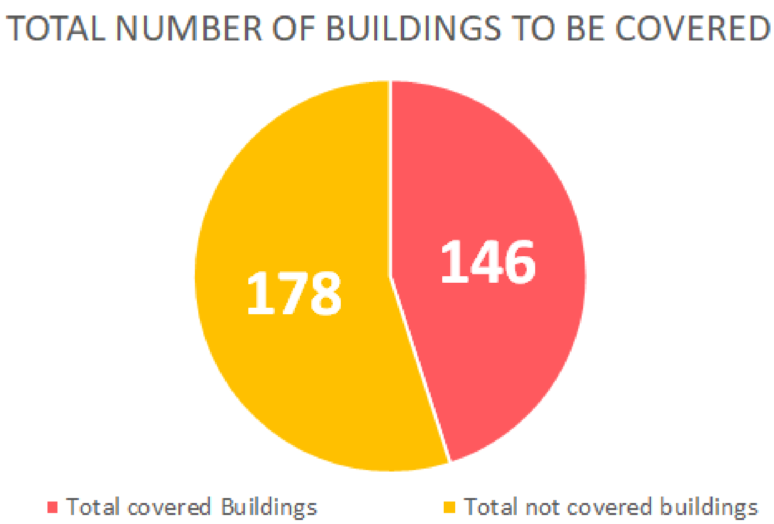

Figure 3.3. Total number of buildings to be covered

In Fig.3.3 we can see the total number of the buildings that are linked to the district heat network and the total number of the buildings that are not linked.

Customers to be covered

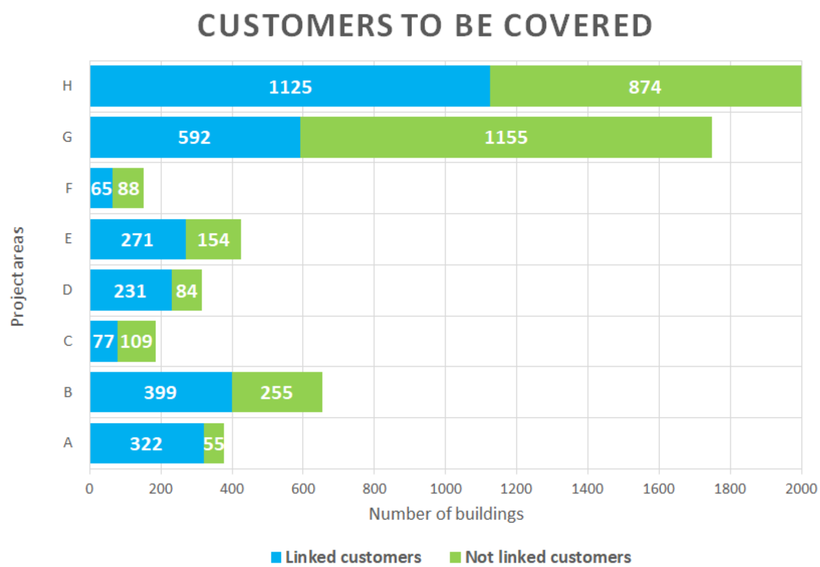

Figure 3.4. Customers to be covered with respect to to the Area that they belong

In Fig.3.4 we can see the number of the customers that are linked to the district heat network and the number of the customers that are not linked with respect to the Area that they belong.

Figure 3.5. Total number of customers to be covered

In Fig.3.5, we can see the total number of the customers that are linked to the district heat network, so they can be reached from the fiber network, and the total number of the customers that are not linked, so they can't be reached yet from the fiber network,
As we can see from the previous charts, the reason why the Areas G and H has been chosen as the "Pilot Area" is because they are the two Areas that have the higher number of potential customers.

3.2.2 Project Area Timeline

The entire project started in 2017 and will last till 2020. In Fig.3.6 we can see the project Area timeline:

- 2017: Evaluation of the constraints and project planning
- mid-2018: Coverage of "Pilot Area"
- mid-2019: Coverage of "2nd Area"
- mid-2020: Coverage of "3rd Area"

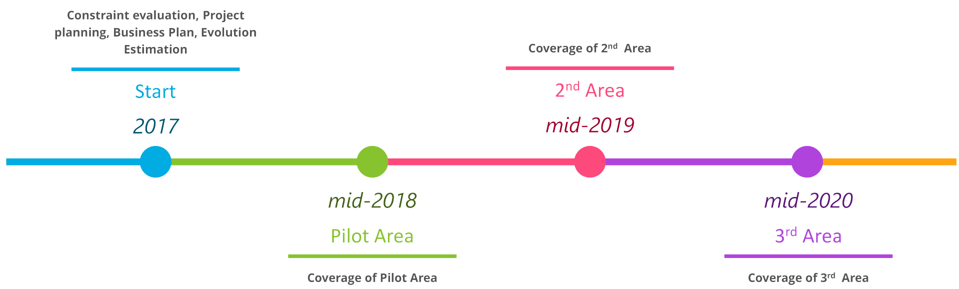

Figure 3.6. Project Area Timeline

3.3 Mechanical constraints

The district heat network was not originally designed to meet optical fiber communication needs. For this reason it shows mechanical constraints that affects the choice of the fiber infrastructure, such as:

- **Pipe Diameter**: The available pipes where the fiber cables will be placed have a diameter of 125 mm. This affect the choice of the fiber cable for what concerns the protection film of the buffer tubes and also the number of fiber that can be used.
- **Pipe Curves**: Each pipe have curves of 90°. This affect the choice of the fiber for what concern the bending radius and the torque force.
- **Manhole Size**: The manhole size is 500mm-500mm-540mm. This affect the choice of the splice closure and the amount of slack loop (fiber richness to manage fault) that can be used.

3.3.1 Optical fiber cables

In Table 3.1 we can see the comparison of different types of fiber supplied by Brugg Cable Inc. We evaluated different fiber companies and we have chosen Brugg Cable Inc. because it can provide the amount of fiber that we need for the entire project in less time than other companies.

Model	N. of fibers	Diameter	Bending R	Tensile F	Rodent P.	Crush P.
SG 12D18	144	10.6 mm	159mm	1000 N		
BC 150	12/24	7.5 mm	112.5 mm	2000 N	X	X
BC 300 2.5	96	14 mm	210 mm	5000 N	X	X
BC 600 3.0	144	14.6 mm	219 mm	8000 N	X	X

Table 3.1. Comparison with different types of fiber

Between these different cables we have chosen the **BC 600 3.0** for the backbone cable and the **BC 150** for the drop cable.
The reason behind that is because they are crush and rodent resistant, they have a stronger tensile force and they have a sufficient bending radius to overcome the pipe diameter constraint of the pipe network.

3.4 Conclusion

In this Chapter we have seen that this project has a very important potential for what concern the total customers that it will cover.
We have also seen that even if we exploit a pre-existing pipe network, we have to face down with different constraints such as pipe diameter, pipe curves and manhole size. These constraints affect the choice of the fiber cables that need a stronger tensile force and a sufficient bending radius to overcome the pipe diameter constraint.

Even if we have different constraints, the advantage of exploiting the pre-existing pipe network lower the cost of the fiber infrastructure, because the pipe have been already laid down.

Chapter 4

Planning of the network resources

4.1 Introduction

In this Chapter we define the network resources needed to build the network. In particular, for each FTTH technology we analyze the cost to deploy the FTTH project. In the last part we highlight the motivation of the technology chosen and the software used to design the network.

To plan the network resources and the cost analysis for each solution, it was estimated a success rate of 20% of the potential customer in the pilot area.The success rate gives the number of expected customer that will subscribe a fiber contract in the first year of the deployment of the infrastructure. In other words, is the percentage of customers that we will expect to gain in the first year of the project with respect to the total number of potential customers that will be reached from the fiber network.

In Fig.4.1 we can see the basic structure of the project:

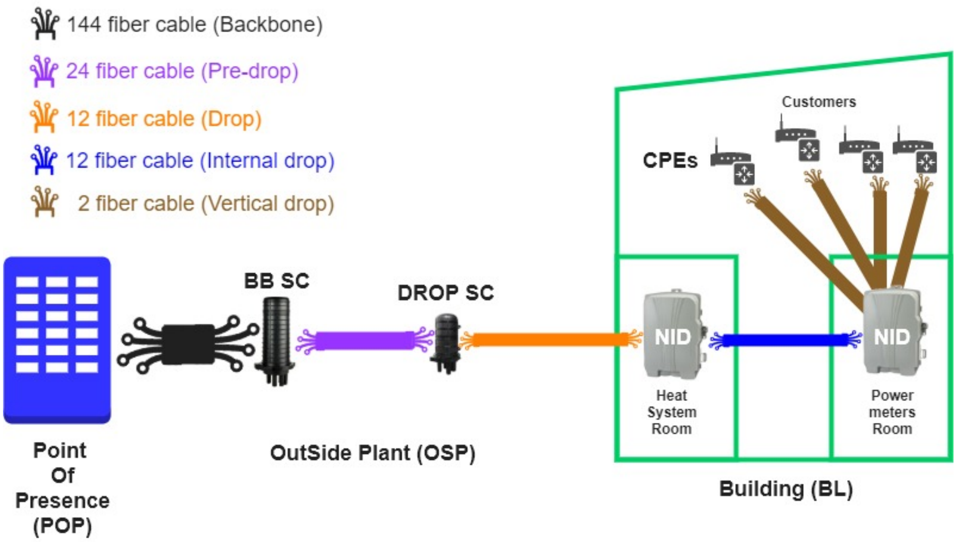

Figure 4.1. Simplified structure of the project

The project has three main parts:

- **Point of Presence (POP)**: in this part the core equipment of the project is located such as core swicth and patch panel to link the fiber infrastructure. It is often indicated as "Central Office (CO)" in the PON terminology.
- **OutSide Plant (OSP)**: in this part the fiber infrastructure and its related equipment are located.
- **Building**: in the last part the equipment to link the final customer to the fiber infrastructure is located.

Even if we choose the AE or the PON technology, we decide to keep the same structure for what concern the OutSide Plant. The reason behind is that we want to build a physical infrastructure that can support both technologies, without impacting on the fiber infrastructure for future upgrade in the technology.

4.1.1 Constraints and pre-existing network

To keep infrastructure cost low and not to disrupt the pre-existing pipe network, we had to find a way to exploit the existing manhole that will contain the splice closure to link the fiber infrastructure to the final customers. Since the manhole size is not suitable to host a splice closure for the 144 fiber cable, its drop cables and the slack loops, we decide to do a "pre-drop" splicing. By using this approach we will modify only three manholes since we will have three 144-fiber cables (the ones where will be spliced the 144 fiber cable with the "pre-drop" 24 fiber cables).

Figure 4.2. Backbone splice closure to splice the 144 fiber cable with the 24 fiber cable and drop splice closure to splice 24 fiber cable with 12 fiber cable.

As we can see from Fig.4.2, the 144 Backbone fiber cable will be spliced into a backbone splice closure, with the 24 pre-drop fiber cables. The backbone splice closure can manage up to 144 fiber strands. The 24 pre-drop fiber cables will be spliced into a drop splice closure, with the 12 drop fiber cables. The drop splice closure can manage up to 24 fiber strands.
Even if we choose AE or PON technology, each building will be reached by two fiber strands. Since there is not a big difference in cost and to provide fiber richness for futures links, we decide to use a 12 strands to reach a building.

4.2 Project Analysis for AE solution

In this Section we will highlight the network resources chosen for the AE solution. After a brief introduction on the AE solution, in the first part we will evaluate the Power budget in order to choose the proper optical transceiver for the project. In the following parts there we will highlight the network resources chosen for each part of the project (POP, OSP and Building). In the last part of this Section we will do a recap of the cost of the AE solution.

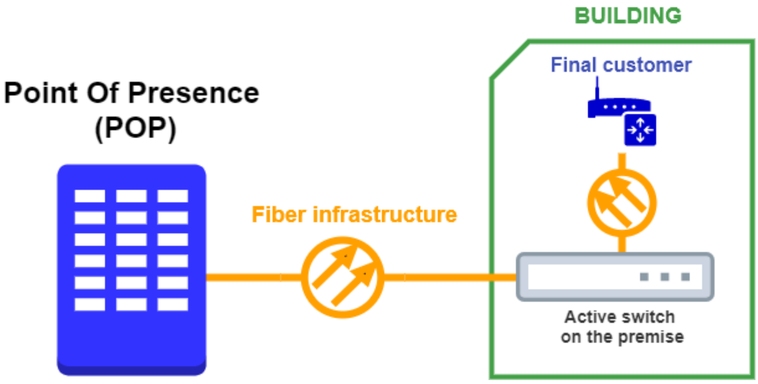

Figure 4.3. Active Ethernet project scheme.

The AE solution consists in a PTP connection between the POP and the switch located in the premise of the building. From the POP two fiber strands goes out that reach the active switch located in the premise of the customer building via the fiber infrastructure network. From the active switch, the final customer is reached by another PTP link with two fiber strands.

4.2.1 Power budget for the AE solution

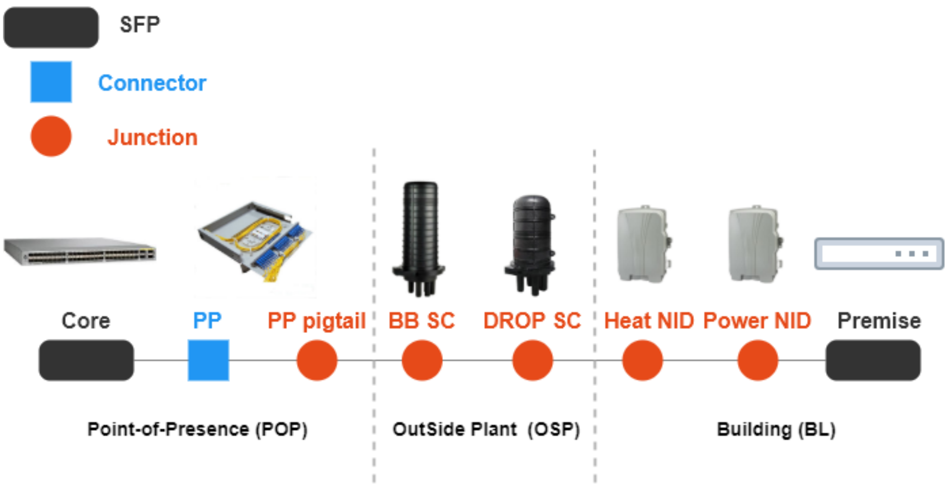

Figure 4.4. Power budget scheme with all the equipments.

The farthest point of the network in the pilot Area is located at 2225,42 m from the POP. By taking into account slack loops and to do a worst case analysis to evaluate the power budget of the project, we can take as distance for the fiber cable 5 km. As we can see from Fig.4.4, we have to take into account the loss of 5 junctions and 1 connector. In addition we impose a loss margin of 3 dB.

Type of loss	Theoretical loss
Fiber loss	0,27 dB/km
Junction loss	0,2 dB/junction
Connectors loss	0,3 dB/connector

Table 4.1. Recap of theoretical loss

With the theoretical loss of Table 4.1 data we can compute the loss budget:

$$\alpha = \alpha_{dB} * L + \alpha_j * J + \alpha_c * C + \mu = 5{,}85 dB$$

Where:

α is the total loss budget
α_{dB} is the fiber loss per km
L is the link length in km
α_j is the junction loss per junction
J is the number of junction
α_c is the connector loss per connector
C is the number of connectors
μ is the loss margin

With the loss budget, we can estimate the power budget:

$$A_{budget} = P_{Tx,dBm} - P_{Rx,sens,dBm} > \alpha$$

Where:

A_{budget} is the total power budget
$P_{Tx,dBm}$ is the transmitted power
$P_{Rx,sens,dBm}$ is the optical receiver sensitivity

From the power budget, now it is possible to choose the right optical transceiver for the AE solution.

4.2.2 Point-Of-Presence network resources

In this Section the Bill of Materials (BOM) of the AE solution for the Point of presence part of the project are shown.
The POP is the heart of a network, the place where connections come together and where all the core equipments of the fiber network are kept.
In this project the BOM of the POP are the rack cabinets, the ODF rack, the optical subracks, the core switch the SFP and the fiber patches.

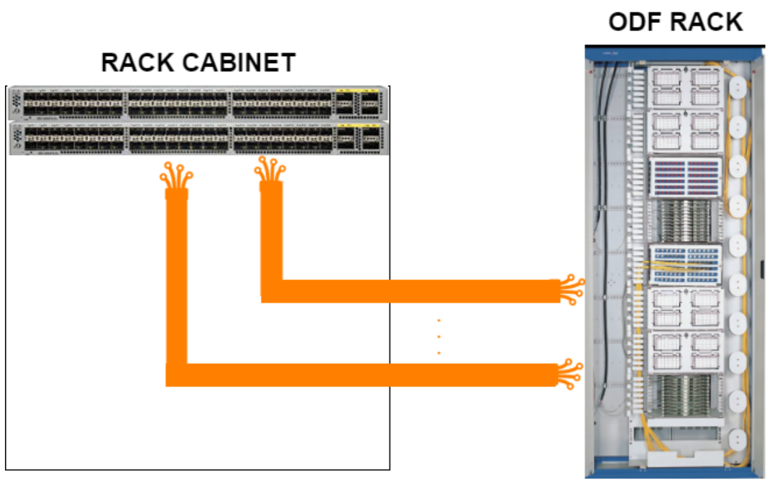

Figure 4.5. Point of Presence of Active Ethernet Solution with the Rack cabinet and ODF rack equipments.

As we can see from Fig.4.5, the POP for the AE solution is composed by:

- **Rack cabinet**: it is the cabinet where all the core switches that link the final customer to the POP through the optical fiber network distribution are stored.

- **ODF Rack**: it is the cabinet where the optical subracks are located. They are used for connecting the optical fiber network distribution to the core switches. They have different cassettes for splicing fiber cables with pigtails.

The Cisco Nexus 3064-X was chosen to be the core switch for the AE solution.

Figure 4.6. The Cisco Nexus 3064-X core switch. Figure taken from [11]

The reason behind that is because it is the less expensive core switch with a large number of SFP+ ports. It has 48 SFP+ ports, which means that each port can operate in 100-Mbps, 1-Gbps or 10-Gbps mode. It has also 4 QSFP+ port (40-Gbps each). Last but not least, it is very thin and it occupies only one rack cabinet unit.
The optical transceiver Cisco Compatible GLC-LH-SMD 1-Gbps was chosen for the Cisco Nexus 3064-X. From target data, this transceiver has power budget of 10 dB. From the previous formula, we can see that we satisfy the power budget requirements and we have 4,15 dB of extra margin.

In Table 4.2 we can see the complete list of the BOM for the POP part of the AE solution:

Description	Unitary cost	Quantity	Total
Rack cabinet	950,00 €	1	950,00 €
ODF Rack	1020,08 €	1	1020,08 €
Optical sub-racks	1273,50 €	3	3820,50 €
Switch Nexus 3604-X	26000,00 €	2	52000,00 €
SFP GLC-LH-SMD	19,00 €	164	3166,00 €
Patches	4,00 €	164	656,00 €

Table 4.2. BOM of the pop part for the AE solution

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4.2.3 OutSide Plant network resources

In this Section the BOM of the AE solution for the OSP part of the project is shown.

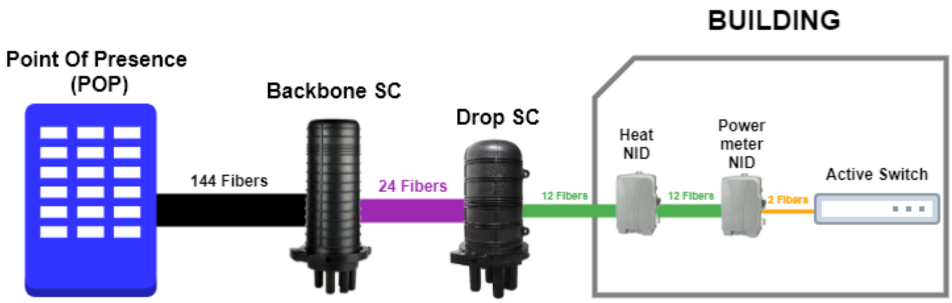

Figure 4.7. OutSide Plant Active Ethernet equipments

As we can see from Fig.4.7, the OSP for the AE solution is composed by:

- **Fiber infrastructure**: this part is composed by the backbone cable, the pre-drop cable and the drop cable.
- **Splice closures**: to splice the different fiber cables there are a backbone splice closure and a drop splice closure.
- **Premise equipment**: in the premise of each building there are two Network Interface Device (NID) to link the fiber infrastructure with the active switch located in the premise of the building.

In Table 4.3 we can see the complete list of the BOM for the OSP part of the AE for what concern the Fiber infrastructure:

Description	Unitary cost	Quantity	Total
12 Fiber Cable	0,50 €/m	10331 m	5165,50 €
24 Fiber Cable	0,81 €/m	4178 m	3384,18 €
144 Fiber Cable	3,15 €/m	9340 m	29421,00 €

Table 4.3. BOM of the OSP Fiber infrastructure part for the AE solution

In Table 4.4 we can see the complete list of the BOM for the OSP part of the AE for what concern the Splice Closures:

Description	Unitary cost	Quantity	Total
Backbone Splice Closure	446,64 €	3	1339,92 €
Drop Splice Closure	316,37 €	18	5694,66 €

Table 4.4. BOM of the OSP Splice closures part for the AE solution

In Table 4.5 we can see the complete list of the BOM for the OSP part of the AE for what concern the Premise equipment:

Description	Unitary cost	Quantity	Total
NID	30,90 €	164	5067,60 €
Mikrotik CRS106-1G-10S	171,05 €	82	14026,10 €
SFP Mikrotik s-31dlc20d	17,75 €	425	7543,75 €
2 Fiber cable	0,41 €/m	10296 m	4221,36 €

Table 4.5. BOM of the OSP Premise equipment part for the AE solution

In Table 4.6 we can see the total costs of each part concerning the OSP part for the AE solution:

Part	Total
Fiber Infrastructure	37970,68 €
OutSide Plant	7034,58 €
Premise Equipment	30768,81 €

Table 4.6. total cost of each part of the AE solution

4.2.4 Building network resources

In this Section the BOM of the AE solution for the building part of the project is shown.

Figure 4.8. Building Active Ethernet equipments

As we can see from Fig.4.8, the building part for the AE solution is composed by:

- **SFP Media converter**: the device that transparently connects copper to SFP for multimode or single mode fiber.
- **Customer Premise Equipment**: the device that link the final customer to the infrastructure via cable or wireless connection.

The Mikrotik RFBTC11 was chosen to be the SFP media converter for the AE solution.

Figure 4.9. The Mikrotik RFBTC 11 media converter. Figure taken from [12]

The reason to use a media converter and not to use a Customer Premise Equipment (CPE) with an SFP interface to directly link the fiber infrastructure to the final customer, is because we want to permit to the final customer to choose which CPE use.

The Mikrotik hAP ac2 was chosen to be the standard CPE for the AE solution.

Figure 4.10. The Mikrotik hAP ac2. Figure taken from [12]

The reason behind that is because it is fully compatible with the pre-existing Operations Support System (OSS). An OSS is a software component that enables a service provider to monitor, control, analyze, and manage the services on its network.
The Mikrotik hAP ac2 has 5 Gigabit ETH ports, it is compatible with the latest Wireless standards (802.11a/b/g/n/ac) but, more important, it supports the TR-069 protocol.
The TR-069 is a technical specification of the Broadband Forum that defines an application layer protocol for remote management of CPE connected to an Internet Protocol (IP) network. With this protocol, it is possible to auto-provision the CPE with a pre-defined template.

In Table 4.7 we can see the complete list of the BOM for the Building part of the AE:

Description	Unitary cost	Quantity	Total
Mikrotik RFBTC11	28,36 €	343	9727,48 €
Mikrotik hAP ac2	49,35 €	343	16927,05 €

Table 4.7. BOM of the Building part for the AE solution

4.2.5 CAPEX costs for the AE solution

In this Section the total Capital Expenditures costs for the AE solution is shown, including all the implementation costs.

In Table 4.8 we can see the complete CAPEX costs for the AE solution:

Description	Unitary cost	Quantity	Total
Equipment POP	60004,58 €	1	60004,58 €
Equipment OSP	75864,07 €	1	75864,07 €
Equipment BL	26654,53 €	1	26654,53 €
GIS Software + OTDR	27000,00 €	1	27000,00 €
Softwares	5000,00 €	1	5000,00 €
POP staging	5000,00 €	1	5000,00 €
Laying BB fiber	5,00 €	9340	46700,00 €
Laying D fiber	1,00 €	14509	14509,00 €
Splice Closures Junctions	25,00 €	328	8200,00 €
Heat Room Junctions	25,00 €	686	17150,00 €
Power Meter Room Junctions	25,00 €	686	17150,00 €
Client activation	100,00 €	343	34300,00 €

Table 4.8. Summary of the CAPEX costs for the AE solution

Unitary CAPEX costs for the AE solution

The previous CAPEX costs are estimated taking into account only the pilot area. To estimate the costs of the entire project taking into account the other areas, we have computed the unitary costs of the AE solution.

In Table 4.9 we can see all the unitary costs of the AE solution.

Description	Total	Quantity	Unitary cost
POP	65004,58 €	1	60004,58 €/POP
OutSide Plant	145273,07 €	23,849	6091,37 €/km
Building	60954,53 €	82	743,35 €/BL
Customer Cost	34300,00 €	343	100,00 €/client
Softwares + OTDR	32000,00 €	343	93,29 €/client

Table 4.9. Unitary costs of the CAPEX to the AE solution

Taking into account the unitary CAPEX costs and the number of customers expected in the first year, buildings to link, fiber km estimated for each area, it is possible to estimate the CAPEX costs for the entire project and the AE solution.

In Table 4.10 we can see the estimation of the CAPEX costs for the entire project and the AE solution:

Clients	BL	Fiber [km]	Area	POP cost	OSP cost	BL cost	CLIENT cost	Total
343	82	23,849	1	65004,58 €	145272,07 €	60954,53 €	66300,00 €	337532,18 €
193	47	18	2	65004,58 €	109644,65 €	37305,83 €	37305,83 €	246892,41 €
80	17	15	3	65004,58 €	91370,54 €	15463,56 €	15463,56 €	184475,59 €

Table 4.10. CAPEX costs for the entire project and the AE solution

4.2.6 Conclusion

In this Section we have highlighted the cost of the AE solution. As we can imagine and as we will see in the next Section, the unitary costs of this solution are very high. In particular we have a very high cost for what concern the POP equipments. As we have seen in Fig. 4.3, with this solution we have also to face with a big problem: the active switch located in the premise. This arise two main problems:

- Power supply: in every premise a power point would be present to provide power to it.

- Since it is an active component, it is more susceptible to faults and it requires a regular maintenance.

As we have seen in the previous Chapter, the fact that we have an active switch on the premise means that we have a fully symmetric link between the core components in the POP and it. Because of that, we could provide better internet profiles to final customers.
The last but not least problem of this solution is future upgrade of the network: it would require to change all the core components, including the core switches and consequently it would requires a huge amount of financial resources.

4.3 Project Analysis for PON solution

In this Section we highlight the network resources chosen for the PON solution. After a brief introduction for the PON solution, in the first part the Power Budget in order to choose the proper optical transceiver for the project will be estimated. In the following parts the network resources chosen for each part of the project (POP, OSP and Building) will be highlighted. In the last part of this section we will show a recap of the cost of PON solution.

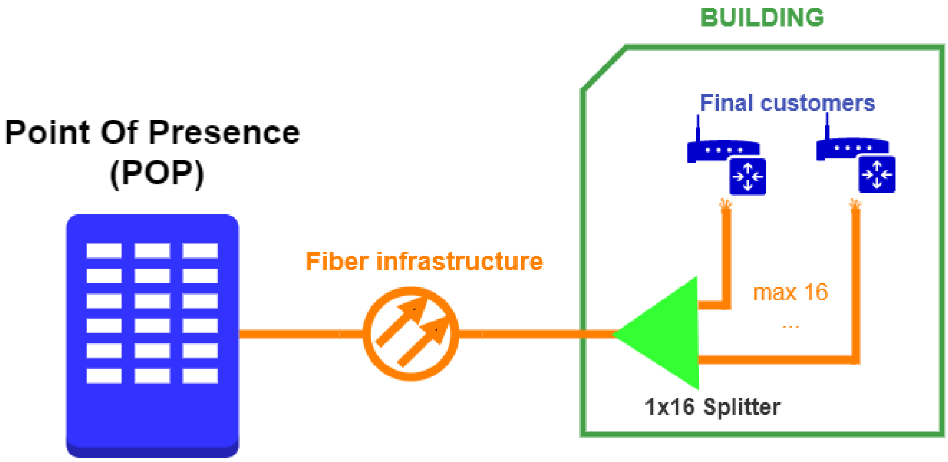

Figure 4.11. Passive Optical Network project scheme

The PON solution consists in a P2MP connection between the POP and the final customer. From the POP one fiber strand goes out and it reaches the optical splitter located in the premise of the customer building via the fiber infrastructure network. We decided to choose a splitter with 1X16 splitting ratio and in the next section there will be explained the motivation behind this choice. From the optical splitter the the final customer is reached by a single strand fiber.

4.3.1 Power budget for the PON solution

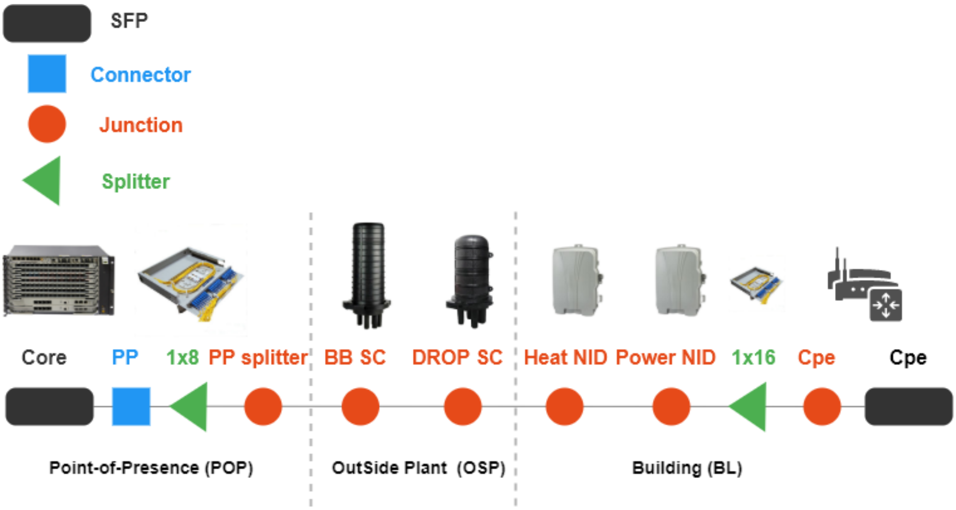

Figure 4.12. Power budget scheme with all the equipments.

The farthest point of the network in the pilot Area is located at 2225,42 m from the POP. Taking into account slack loops and to do a worst case analysis to evaluate the power budget of the project, we can take as distance for the fiber cable 5 km. As we can see from Fig.4.12, we have to take into account the loss of 6 junctions and 1 connector. In addition we impose a loss margin of 3 dB.

Type of loss	Theoretical loss
Splitter 1X8	10,4 dB
Splitter 1X16	13,6 dB
Fiber loss	0,27 dB/km
Junction loss	0,2 dB/junction
Connectors loss	0,3 dB/connector

Table 4.11. Recap of theoretical loss

With the theoretical loss of table 4.11 data we can compute the loss budget:

$$\alpha = \alpha_{dB} * L + \alpha_j * J + \alpha_c * C + \alpha_{splitters} + \mu = 30{,}05dB$$

Where:

α is the total loss budget
α_{dB} is the fiber loss per km
L is the link length in km
α_j is the junction loss per junction
J is the number of junction
α_c is the connector loss per connector
C is the number of connectors
$\alpha_{splitters}$ is the total loss of the two splitters
μ is the loss margin

With the loss budget, we can estimate the power budget:

$$A_{budget} = P_{Tx,dBm} - P_{Rx,sens,dBm} > \alpha$$

Where:

A_{budget} is the total power budget
$P_{Tx,dBm}$ is the transmitted power
$P_{Rx,sens,dBm}$ is the receiver sensitivity

From the power budget, now it is possible to choose the right optical transceiver for the PON solution.

In PON technology we have two different types of optical transceiver:

SFP Class	$\mathrm{P}_{Rx,sens,dBm}$	$\mathrm{P}_{Tx,dBm}$
B+	-28 dBm	1,5 dBm
C+	-32 dBm	3 dBm

Table 4.12. PON SFP classes

Considering the loss budget α, we can see that the B+ SFP is not enough, so we have to choose the C+ SFP.

4.3.2 Point-Of-Presence network resources

In this Section the BOM of the PON solution for the POP part of the project is shown.

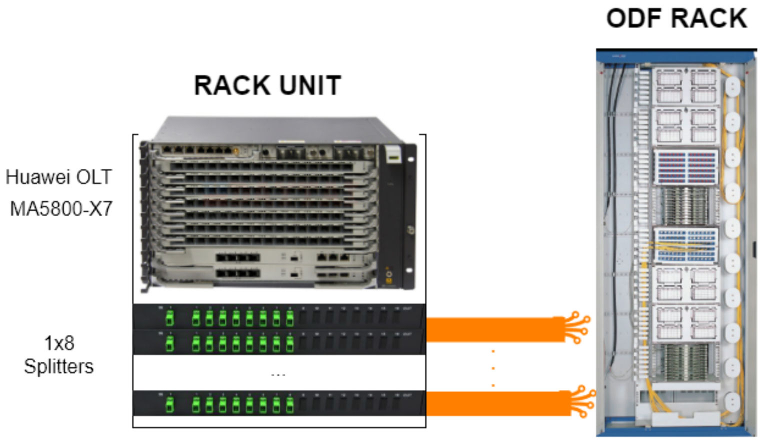

Figure 4.13. Point of Presence of Passive Optical Network Solution

As we can see from Fig.4.13, the POP for the PON solution is composed by:

- **Rack cabinet**: it is the cabinet where all the core switches that link the final customer to the POP through the optical fiber network distribution are stored. In this cabinet we have also the optical splitters.

- **ODF Rack**: it is the cabinet where the optical subracks are located. They are used for connecting the optical fiber network distribution to the core switches. They have different cassettes for splicing fiber cables with pigtails.

The Huawei OLT MA5800-X7 was chosen to be the OLT for the PON solution.

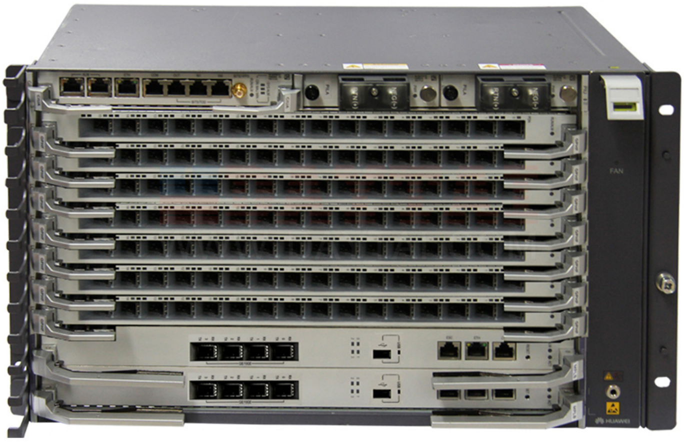

Figure 4.14. The Huawei MA5800-X7 OLT. Figure taken from [13]

The reason behind that is because it supports both PTP and P2MP solution and it has provision for NG-PON2 solutions.

The first stage of optical splitters has a splitting ratio of 1x8, in order to link 8 building per SFP PON transceiver. The final stage of the optical splitters has a 1x16 splitting ratio, so the total splitting ratio of the project is 1x128.
It is a not common splitting ratio for a PON solution, but due to the fact that the farthest point of the network is at 2,225 km and in average in every building there will be no more than 10 final customer to link, there is no problem with the bitrate capacity of the final customer and with the power budget.

Another strange approach of this project is to locate the first stage of the optical splitters in the POP and not in the OSP. The reason behind that is because of the mechanical constraints of the manhole, so to keep costs down and without made modification at the pre-existing pipe network, we decided to put them in the POP.

In Table 4.13 we can see the complete list of the BOM for the POP part of the PON solution:

Description	Unitary cost	Quantity	Total
Rack cabinet	950,00 €	1	950,00 €
ODF Rack	1020,08 €	1	1020,08 €
Optical sub-racks	1273,50 €	3	3820,50 €
Huawei OLT MA5800-X7 (*)	6932,87 €	1	6932,87 €
Splitters 1x8	22,00 €	11	242,00 €
Patches	4,00 €	164	656,00 €

Table 4.13. BOM of the pop part for the PON solution

(*) in the total price are included the power supply board, the 16-port GPON board with SFP Class C.

4.3.3 OutSide Plant network resources

In this Section the BOM of the PON solution for the OSP part of the project is shown.

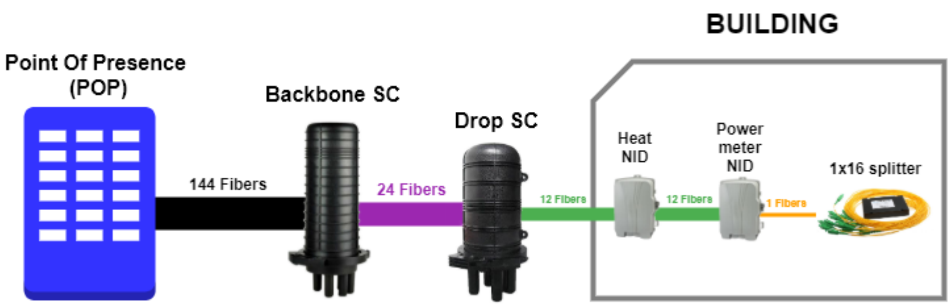

Figure 4.15. OutSide Plant PON

As we can see from Fig.4.15, the OSP for the PON solution is composed by:

- **Fiber infrastructure**: this part is composed by the backbone cable, the pre-drop cable and the drop cable.
- **Splice closures**: to splice the different fiber cables there are a backbone splice closure and a drop splice closure.

- **Premise equipment**: in the premise of each building there are two NID to link the fiber infrastructure with optical splitter with 1x16 splitting ratio.

In Table 4.14 we can see the complete list of the BOM for the OSP part of the PON for what concern the Fiber infrastructure:

Description	Unitary cost	Quantity	Total
12 Fiber Cable	0,50 €/m	10331 m	5165,50 €
24 Fiber Cable	0,81 €/m	4178 m	3384,18 €
144 Fiber Cable	3,15 €/m	9340 m	29421,00 €

Table 4.14. BOM of the OSP Fiber infrastructure part for the PON solution

In Table 4.15 we can see the complete list of the BOM for the OSP part of the PON for what concern the Splice Closures:

Description	Unitary cost	Quantity	Total
Backbone Splice Closure	446,64 €	3	1339,92 €
Drop Splice Closure	316,37 €	18	5694,66 €

Table 4.15. BOM of the OSP Splice closures part for the PON solution

In Table 4.16 we can see the complete list of the BOM for the OSP part of the PON for what concern the Premise equipment:

Description	Unitary cost	Quantity	Total
NID	30,90 €	164	5067,60 €
Splitter 1:16	57 €	82	4674,00 €
2 Fiber cable	0,41 €/m	10296 m	4221,36 €

Table 4.16. BOM of the OSP Premise equipment part for the PON solution

In Table 4.17 we can see the total costs of each part concerning the OSP part for the PON solution:

Part	Total
Fiber Infrastructure	37970,68 €
OutSide Plant	7034,58 €
Premise Equipment	13962,96 €

Table 4.17. total cost of each part of the PON solution

4.3.4 Building network resources

In this Section the BOM of the PON solution for the building part of the project is shown.
The building part for the PON solution is composed by:

- **Customer Premise Equipment**: the device that link the final customer to the infrastructure via cable or wireless connection.

We decided to have two different solution as CPE. The first is the EchoLife EG8010H, that is a simple media converter that permits to final customer to use the CPE he wants.

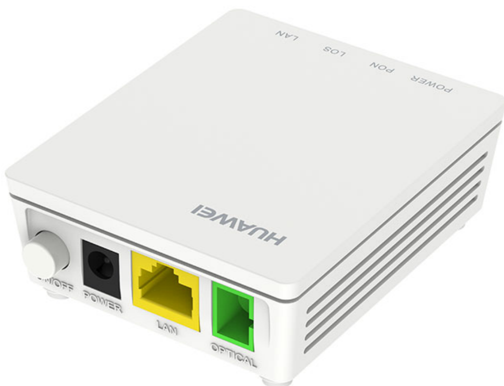

Figure 4.16. The Huawei EchoLife EG8010H. Figure taken from [13]

The second is the EchoLife EG8045H, that is a Wireless Router with pre-built VoIP support.

Figure 4.17. The Huawei EchoLife EG8045H. Figure taken from [13]

Description	Unitary cost	Quantity	Total
CPE 1 EchoLife EG8010H	33 €	144	4752 €
CPE 2 EchoLife EG8045H	74 €	200	14800 €

Table 4.18. BOM of the Building part for the PON solution

4.3.5 CAPEX costs for the PON solution

In this Section the total CAPEX costs for the PON solution are shown, including all the implementation costs.

In Table 4.19 we can see the complete CAPEX costs for the PON solution:

Description	Unitary cost	Quantity	Total
Equipment POP	13621,45 €	1	13621,45 €
Equipment OSP	58968,22 €	1	58968,22 €
Equipment BL	19552,00 €	1	19552,00 €
GIS Software + OTDR	27000,00 €	1	27000,00 €
Softwares	5000,00 €	1	5000,00 €
POP staging	5000,00 €	1	5000,00 €
Laying BB fiber	5,00 €	9340	46700,00 €
Laying D fiber	1,00 €	14509	14509,00 €
Splice Closures Junctions	25,00 €	328	8200,00 €
Heat Room Junctions	25,00 €	686	17150,00 €
Power Meter Room Junctions	25,00 €	686	17150,00 €
Client activation	100,00 €	343	34300,00 €

Table 4.19. Summary of the CAPEX costs for the PON solution

Unitary CAPEX costs for the PON solution

The previous CAPEX costs are estimated taking into account only the pilot area. To estimate the costs of the entire project taking into account the other areas, we had to compute the unitary costs of the PON solution.

In Table 4.20 we can see all the unitary costs of the PON solution.

Description	Total	Quantity	Unitary cost
POP	18621,45 €	1	18621,45 €/POP
OutSide Plant	128377,22 €	23,849	5282,92 €/km
Building	53852,00 €	82	656,73 €/BL
Customer Cost	34300,00 €	343	100,00 €/client
Softwares + OTDR	32000,00 €	343	93,29 €/client

Table 4.20. Unitary costs of the CAPEX to the PON solution

Taking into account the unitary CAPEX costs and the number of customer expected in the first year, buildings to link, fiber km estimated for each area, it is possible to estimate the CAPEX costs for the entire project and the PON solution.

In Table 4.21 we can see the estimation of the CAPEX costs for the entire project and the PON solution:

Clients	BL	Fiber [km]	Area	POP cost	OSP cost	BL cost	CLIENT cost	Total
343	82	23,849	1	18621,45 €	128377,22 €	53852,00 €	66300,00 €	267150,67 €
193	47	18	2	18621,45 €	96892,52 €	30866,39 €	37305,83 €	182686,20 €
80	17	15	3	18621,45 €	91370,54 €	11164,44 €	15463,56 €	125993,22 €

Table 4.21. CAPEX costs for the entire project and the PON solution

4.3.6 Conclusion

In this Section we have highlighted the cost of the PON solution. As we will see in detail in the next Section, the unitary costs of this solution are lower than the previous AE solution. In general all of them, but we have a huge difference for what concern the POP equipments.
On the contrary of the AE solution, PON solution has a passive optical splitter on the premise, so we do not have to face power supply and it is less susceptible to faults than an active switch.
As we have mentioned in Chapter 2 and we will see in detail in Chapter 6, for future upgrade the PON solution does not require a huge amount of financial resources, because all the new PON technologies were designed to coexist with older ones and they were designed to exploit older equipments. In this way you do not have the necessity to change all the core components.

4.4 Comparison between PON and AE solutions

In this Section the costs of the entire project are compared with respect to the solution.

4.4.1 CAPEX costs comparison for each area with respect to the solution

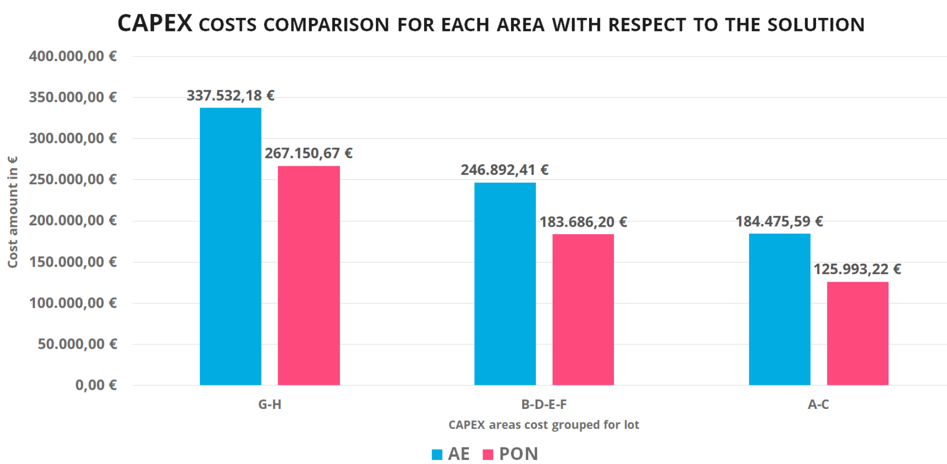

Figure 4.18. CAPEX costs comparison for each area with respect to the solution

In Fig.4.18 we can see the cost comparison of each technology with respect to the cost of building each area. For each area we can see that PON technology is cheaper than AE solution.

4.4.2 Unitary costs comparison

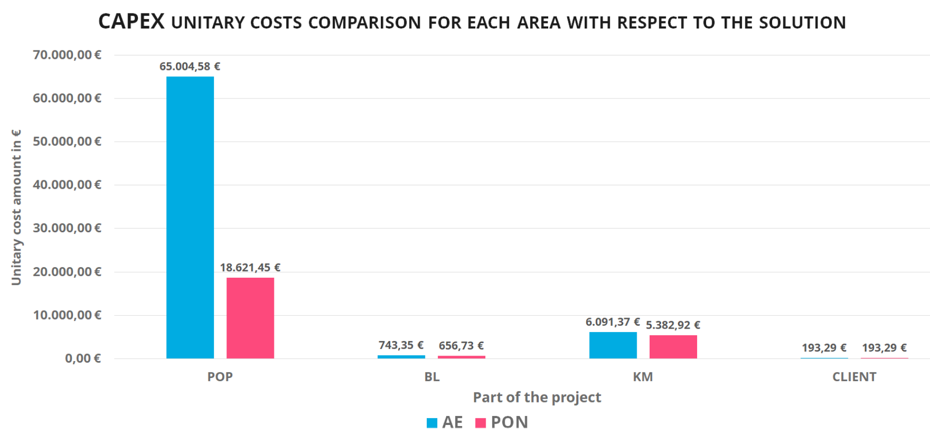

Figure 4.19. CAPEX unitary costs comparison with respect to the solution

In Fig.4.19 we can see the unitary cost comparison for each technology per POP, per building, cost of fiber per km and per client. All the unitary costs are lower for PON technology, but the most interesting of them is the POP unitary cost that is very low.

4.4.3 Choice of the FTTH solution

Even though the AE solution is more suitable in terms of the total bandwidth carried to the final customer, we decided to chose the PON solution instead for the following main reasons:

- PON is **cheaper** than AE.
- PON **does not require power supply for splitting**: it is not susceptible to power failure and it does not arise the problem to power it in the OSP.

- PON **upgrade is simpler**: to upgrade the PON technology there is simply to change the SFP at both sides of the network (POP/customer) without changing the core switch, the CPE and the outside plant optical distribution equipment.

4.5 OutSide Plant (OSP) software

In this Section what are the main needs of the OSP software solution to plan and manage the entire network are described.

4.5.1 Project needs

The main needs of the OSP software to plan and manage the entire network are the following:

- **GIS Service:** Ability to design the network and to identify all the components on a Map service.
- **Wire/Splice Info:** Ability to simply reach and see a single strand info, ports and splice diagrams.
- **Fault Tracking:** Ability to track a fault on the map starting from the OTDR trace.
- **Manhole managment:** Ability to keeping track of what is inside the manhole, the pipe and to attach a detailed documentation to it.
- **Export Data:** Ability to export detailed data to provide at the company that will implements the physical network and also other information such as BOM (bill of materials).

4.5.2 OSP solutions

After an exhaustive analysis and a long testing period, the OSP software solution chosen is 3-GIS.

4.6 Conclusion

In this Chapter we have seen all the network resources needed for each of the two FTTH technologies and the compromises that we have to take to exploit the pre-existing pipe network.

To keep infrastructure costs low and not to disrupt the pipe network, we had to find a solution which includes not only one splice closure to link the core elements with the final customers, but another one to do a pre-drop splicing. With this approach we have to modify the pipe network only where the backbone splice closures (the splice closures that can manage up to 144 fiber strands) will be placed and not where the drop splice closures (the splice closures that can manage up to 24 fiber strands) will be placed.

After a deep and attentive research, we have evaluated all the network resources needed to develop our project taking into account the AE and POP solutions.
We decided to choose the PON solution for all the advantages that has compared to the AE solution, but in particular because it is cheaper, it is not susceptible to power failure and future network upgrades do not require a huge financial resources than instead the AE solution would require.

Chapter 5

Estimation of the cost/income in the long term

5.1 Introduction

In this Chapter an estimation of the cost and the income in the long term is performed. In the following Sections the Average Revenue Per User (ARPU), the customer growth and the costs and the incomes expected in the first ten years of the project will be estimated.

5.2 Definition of internet profiles

In order to predict the incomes, in this Section the internet profile costs of the project are defined.

5.2.1 Competitor analysis

In this Section is performed a competitor analysis, so that to define the right price of each profile taking into account the other offers of the market. In Table 5.1 we can see the internet fiber profiles offered by the competitors:

Company	Profile	Price
Vodafone	Internet Unlimited +	24,90 €
Tim	Tim Connect Fibra	25,00 €
Wind	Fibra 1000 Unlimited	25,98 €
BBBell	Kiara casa 300	29,00 €
BBBell	Kiara casa 1000	32,00 €
Go	GoVerFibra	24,90 €
Fibra City	Best Seller	18,99 €
Fibra City	Best Seller Giga	23,99 €
Fibra City	Business	29,99 €
Fibra City	Top Gaming	27,90 €
Fibra City	E-sports PRO	35,00 €
Panservice	Fibra 300	29,90 €
Panservice	Fibra 500	32,90 €
Panservice	Fibra 1000	35,90 €

Table 5.1. Internet Fiber profiles of the competitors

5.2.2 Internet profiles

In this Section the internet profiles of the project are defined. After the competitor analysis, we decided to define two private customer profiles and three business customer profiles. For each one we have defined the distribution of the customers with respect to the profile that we expect.

In table 5.2 we can see the internet profiles of the project:

Name	Cost/month	Distribution
Entry	25,00 €	76 %
Plus	32,00 €	5 %
Business Entry	85,00 €	5 %
Business Plus 300	45,00 €	12 %
Business Large	60,00 €	2 %

Table 5.2. Internet fiber profiles of the project

5.2.3 Average Revenue Per User (ARPU)

Taking into account the cost of internet profiles and the distribution expected with respect to the number of customers of table 5.2, in this Section the Average Revenue Per User (ARPU) is computed.
The Average Revenue Per User, also known as Average Revenue Per Unit, is a measure used primarily by consumer communications, digital media and networking companies. It defines the total revenue divided by the number of subscribers.

The ARPU is computed with the following formula:

$$ARPU = (\sum_{i=1}^{n} P_j * D_k) * 12$$

Where:
P_j is the cost/month in € for the internet profile.
D_k is the customer distribution for the internet profile.

Computing the formula with the data of internet profiles of Table 5.2:

$$ARPU = 343{,}20 \text{ €/year}$$

This means that by average, every user generates an income of 343,20 € per year.

5.3 OPerating EXpenditures costs

In this Section the OPEX costs for the entire project are estimated.
The OPerating EXpenditures (OPEX) costs are the ongoing cost for running a product, business or system.
In Table 5.3 we can see the OPEX costs for the entire project:

Description	Unitary cost per year
Auto provisioning system	5000,00 €
IT parts	350,00 €
Cars maintenance	2000,00 €
Energy / Heat of Office	1680,00 €
Telephony	192,00 €
Mobile Telephony	500,00 €
Office assurance	500,00 €
Employees fee	30000,00 €
Field operation employees fee	22000,00 €
Provisioning/assurance employees fee	30000,00 €
Business consultant	5000,00 €
Marketing	5000,00 €
10G port annual fee	21000,00 €
Internet Bandwidth	15000,00 €

Table 5.3. OPEX costs for the entire project

5.4 Estimation of cost/income in 10 years

In this Section the cost/income of the entire project in 10 years are estimated. In the first Subsection the number of customers expected is estimated.
In the second Subsection the costs of the project are estimated taking into account the cost analysis of the previous chapter and the cost per each new customer.
In the third Subsection the revenues of the project are estimated taking into account the recurrent revenues and the customer activation fee.
In the fourth Subsection the costs are compared with the revenues.
In the last Subsection is performed a Bottom line analysis to evaluate after which year all the revenues compensate all the costs of the project.

5.4.1 Prediction of the customers growth

In order to evaluate the cost/income of the entire project, we have estimated the customers growth per each year. The new customers for each year are computed as it follows:

$$NewAreaCustomers = SR * TotalCustomersOfTheNewArea$$

Where:

SR is the success rate (30%) of the customers that we estimated for each area in the first year.

$$NewCustomers = CG * TotalCustomersOfPreviousYear$$

Where:

CG is the customer growth estimated for each year.

$$TotalCustomers = TCPY + NAC + NC$$

Where:

$TCPY$ are the Total Customers of Previous Year.
NAC are the New Area Customers.
NC are the New Customers of current year.

In table 5.4 we can see the total customers expected for each year:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Customer growth	-	30%	30%	20%	15%	15%	10%	10%	10%	10%
New Area Customers	343	193	80	-	-	-	-	-	-	-
New Customers	-	103	192	182	164	189	145	159	175	192
Total Customers	343	640	911	1093	1257	1446	1591	1750	1925	2117

Table 5.4. Customers growth of the project

5.4.2 Estimation of the costs

In order to estimate the costs, we defined three different categories of costs:

- **CAPEX:** The CAPEX costs for each Lot. We decided to estimate an amortisation of the total costs in 10 years.
- **OPEX:** The OPEX costs of the project.
- **Other OPEX:** All the other OPEX costs for which we did not estimate a constant growth.

We decided to group the topological areas of the city (Fig. 3.1) into 3 different lots:

- **Lot 1:** G and H areas.
- **Lot 2:** B, D, E and F areas.
- **Lot 3:** A and C areas.

In Table 5.5 we can see how much all the CAPEX costs for each lot influence the cost the cost of the project each year:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
CAPEX Lot 1	26715,07 €	26715,07 €	26715,07 €	26715,07 €	26715,07 €	26715,07 €	26715,07 €	26715,07 €	26715,07 €	26715,07 €
CAPEX Lot 2	18368,62 €	18368,62 €	18368,62 €	18368,62 €	18368,62 €	18368,62 €	18368,62 €	18368,62 €	18368,62 €	18368,62 €
CAPEX Lot 3	12599,32 €	12599,32 €	12599,32 €	12599,32 €	12599,32 €	12599,32 €	12599,32 €	12599,32 €	12599,32 €	12599,32 €
Total	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €

Table 5.5. Influence of CAPEX costs per each year

For the OPEX costs (OPEX1) we estimated a cost increase of 1% per each year. In Table 5.6 we can see how much all the OPEX1 costs influence the cost of the project each year:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
OPEX1	138222,00 €	139604,22 €	14100,26 €	142410,26 €	143824,37 €	145272,71 €	146725,44 €	148192,69 €	149674,62 €	151171,37 €

Table 5.6. OPEX1 costs of the project per each year

Each other OPEX cost (OPEX2) is computed in a different way than OPEX1 costs:

- **New Customer Acquisition (NCA):** is the cost for each new customers with respect to the unitary cost.

$$NCA = UCC * NewCustomers$$

  Where:
  NCA is the New Customers Acquisition.
  UCC is the Unitary Cost for each Customer.

- **Interconnection Client Cost (ICC):** is the total estimated cost of each customer per year. The Unitary Interconnection Cost (UIC) estimated is 60 € per customer.

$$ICC = UIC * TotalCustomers$$

- **Pipe Network Royalties (PNR):** is the estimated cost for the pipe network for each customer. The Pipe Unitary Royalties (PUR) is 8 €/customer for less than 500 customers, 10 €/customer for less than 1000 customers, 14 €/customer for less than 2000 customers and 16 €/customer for more or equal than 2000 customers. The PUR grows when the number of the customers grows because the PUR is not computed per pipe, but it is computed by the effective customer linked to the network. So it grows when the number of customers increases.

$$PNR = PUR * TotalCustomers$$

- **POP Rent (PR):** is the estimated cost for the POP rent. In the second year the cost double and in the third year the cost triple as in the end of the third year there will be one POP for each lot. From the fourth year we estimated that the cost of previous year will increase of 1% per year.

- **Offices Rent (OR):** is the estimated cost for the offices rent. In the second year the cost double and in the third year the cost triple as in the end of the third year. We estimate this behaviour because we expect that in the first three year, since we implement new areas, that also the office needs to grow to accomodate new employees. From the fourth year we estimated that the cost of previous year will increase of 5% per year.

In Table 5.7 we can see how much all the OPEX2 costs influence the cost of the project each year:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
NCA	-	19906,33 €	37084,22 €	35222,40 €	31700,16 €	36455,18 €	27948,97 €	30743,87 €	33818,26 €	37200,08 €
ICC	20596,90 €	38370,70 €	54666,44 €	65599,72 €	75439,68 €	86755,63 €	95431,20 €	104974,32 €	115471,75 €	127018,92 €
PNR	2746,25 €	6395,12 €	9111,07 €	13119,94 €	15087,94 €	17351,13 €	22267,28 €	24494,01 €	26943,41 €	33871,71 €
PR	3600,00 €	7200,00 €	10800,00 €	10908,00 €	11017,08 €	11127,25 €	11238,52 €	11350,91 €	11464,42 €	11579,06 €
OR	5000,00 €	10000,00 €	15000,00 €	15750,00 €	16537,00 €	17364,38 €	18232,59 €	19144,22 €	20101,43 €	21106,51 €
Total	31943,15 €	81872,15 €	126661,73 €	140600,07 €	149782,36 €	169053,57 €	172118,57 €	190707,33 €	207799,27 €	230766,29 €

Table 5.7. OPEX2 costs of the project per each year

In Table 7.4 we can see the total amount of the project costs:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
CAPEX	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €
OPEX1	138222,00 €	139604,22 €	14100,26 €	142410,26 €	143824,37 €	145272,71 €	146725,44 €	148192,69 €	149674,62 €	151171,37 €
OPEX2	31943,15 €	81872,15 €	126661,73 €	140600,07 €	149782,36 €	169053,57 €	172118,57 €	190707,33 €	207799,27 €	230766,29 €
Total	227848,16 €	279159,38 €	325345,00 €	340692,34 €	351299,73 €	372009,29 €	379527,01 €	396582,03 €	415156,89 €	439630,66 €

Table 5.8. Total costs of the project per each year

5.4.3 Estimation of the incomes

The incomes of the entire project are composed by:

- **Recurrent Revenues (RR):** are the incomes generated by the cost of the profile chosen by each customer.

  $$RR = TotalCustomers * ARPU - NewCustomers * (ARPU)/2$$

  We decided to divide by a factor two the revenues of the new customers because the new customers does not come with the beginning of the year.

- **Customer Activation Fees (CAF):** Every new customer that wish to activate a fiber internet profile has to pay an activation fee of 100 €.

In Table 5.9 we can see the total amount of the project incomes:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
RR	58907,13 €	201808,26 €	279769,95 €	343961,21 €	403372,70 €	463878,60 €	521054,34 €	573159,77 €	630475,75 €	693523,32 €
CAF	34328,17 €	29263,00 €	27159,56 €	18222,15 €	16399,93 €	18859,92 €	14459,27 €	15905,20 €	17495,20 €	19245,29 €
Total	93235,30 €	231431,25 €	306929,52 €	362183,36 €	419772,63 €	482738,52 €	535513,61 €	589064,97 €	647971,47 €	712768,61 €

Table 5.9. Total incomes of the project per each year

5.4.4 Comparison costs vs incomes

In Table 5.10 we can see the comparison between the project costs/incomes per year:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Costs	227848,16 €	279159,38 €	325345,00 €	340692,34 €	351299,73 €	372009,29 €	379527,01 €	396582,03 €	415156,89 €	439630,66 €
Incomes	93235,30 €	231431,25 €	306929,52 €	362183,36 €	419772,63 €	482738,52 €	535513,61 €	589064,97 €	647971,47 €	712768,61 €

Table 5.10. Total cost-incomes of the project per each year

In order to compare the costs/incomes of the project, in the next Subsection a Bottom line analysis is performed.

5.4.5 Bottom line analysis

The bottom line is the enterprise's net income, or the "bottom" figure on a company's income statement. More specifically, the bottom line is an enterprise's income after all the expenses have deducted from revenues. With the bottom line analysis we can predict after which year all the revenues cover all the previous costs leaving profit margin to the company.
In doing the analysis we have computed:

- **Bottom line (BL):** is the difference between the incomes and the costs for each year.
- **Accumulate Bottom Line (PBL):** is the difference between the incomes and the costs for each year and it takes into account also the previous year, by adding it to the final result.

In Table 5.11 we can see the bottom line (BL) and the accumulate bottom line (PBL) computed per each year:

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
BL	-134612,86 €	-47728,12 €	-18415,48 €	21490,02 €	68472,90 €	110729,23 €	155986,60 €	192481,94 €	232814,57 €	273137,95 €
PBL	-134612,86 €	-182340,99 €	-200756,47 €	-179266,45 €	-110793,55 €	-64,32 €	155922,28 €	348402,22 €	581218,79 €	854356,74 €

Table 5.11. Bottom line and progressive bottom line per each year

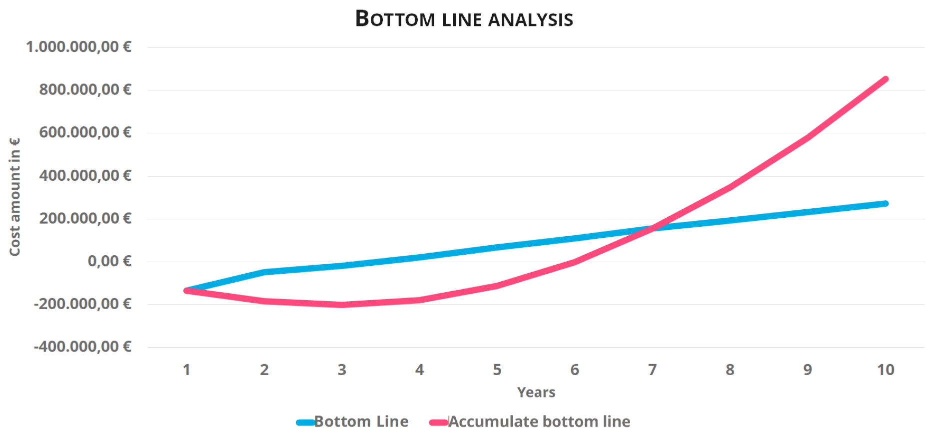

Figure 5.1. Bottom-line and Accumulate bottom-line analysis

As we can see from Table 5.11 and from Fig.5.1, between the sixth and the seventh year the incomes overcome the costs taking also into account the previous years.

5.5 Conclusion

In this Chapter we have performed a cost/income estimation expected in the first ten years of the project.

In order to predict the incomes of the project expected, we have defined the **price of the internet profiles**, the **Average Revenue Per User** (**ARPU**) equal to 343.20 €/year, the **Customer growth** expected in the first 10 years of the project and the **Customer Activation Fees**.

In order to estimate the costs of the project expected, we have defined three different categories of costs: the **CAPEX** costs for each lot, the **OPEX** costs of the project and all the **other OPEX** recurrent costs that they do not have a constant growth, such as New Customer Acquisition, Interconnection Client Cost, Pipe Network Royalties, Pop Rent and Office Rent.

Summing all the costs and all the incomes expected in the first ten years of the project, we were able to perform a bottom line analysis, that allows us to predict after which year all the revenues cover all the previous costs leaving profit margin to the company. Recalling Fig. 5.1, we can see that between the sixth and the seventh year the incomes of the project overcome the costs of the project.

Chapter 6

Estimation of the project network evolution

6.1 Introduction

Every day the number of connected devices increase and the services that run over one single devices need bandwidth. Let us think for example how much applications do we have in our mobile phone that require a connection. Let us think also to the streaming of a video. Nowadays most people watch a video from the internet. Imagine how much bandwidth requires a simple FHD video and try to think how much bandwidth will be required for a stable 4K video streaming. Consider also that every device present in our home is evolving in a Smart Device, so that it requires a connection. With these simple scenario we can only imagine how the bandwidth demand can change over only one year.
In this Chapter we will analyze the Cisco Visual Network Index (VNI) Global Fixed and Mobile Internet Traffic Forecasts 2017-2022 and then will estimated how the network can evolve in the next 5 years.

6.2 Cisco VNI Global Fixed and Mobile Internet Traffic Forecasts 2017-2022

In this Section we analyze the Cisco Visual Network Index (VNI) Global Fixed and Mobile Internet Traffic Forecasts 2017-2022.

6.2.1 Global devices growth

The first phenomenon to keep track is the global device growth and the average number of devices and connections per capita.
In Fig.7.14 we can see the forecast of the expected global device growth until 2022:

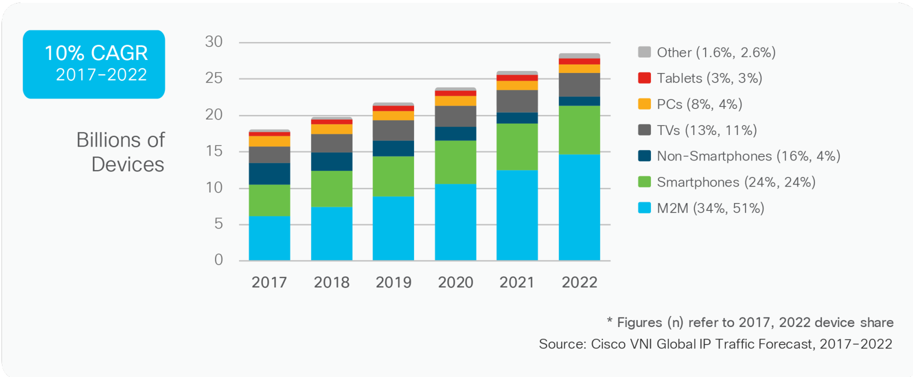

Figure 6.1. Global devices growth. Figure taken from [9].

The forecast use the Compound Annual Growth Rate (CAGR) index, that is the constant rate of return over the time period, and it estimates that from 2017 to 2022 the CAGR will be of 10%.
In Fig.6.2 we can see the forecast of how this number will grow:

	2017	2022
Asia Pacific	2.1	3.1
Central and Eastern Europe	2.5	3.9
Latin America	2.1	2.9
Middle East and Africa	1.1	1.4
North America	8.0	13.4
Western Europe	5.4	9.4
Global	2.4	3.6

Figure 6.2. Devices per capita. Figure taken from [9].

6.2.2 Global internet traffic

The second phenomenon to keep track is the global internet traffic growth and how the global internet traffic change from 1992 and how it is estimated to change in 2022.
In Fig.6.3 we can see the forecast of the expected global internet traffic growth until 2022 by device:

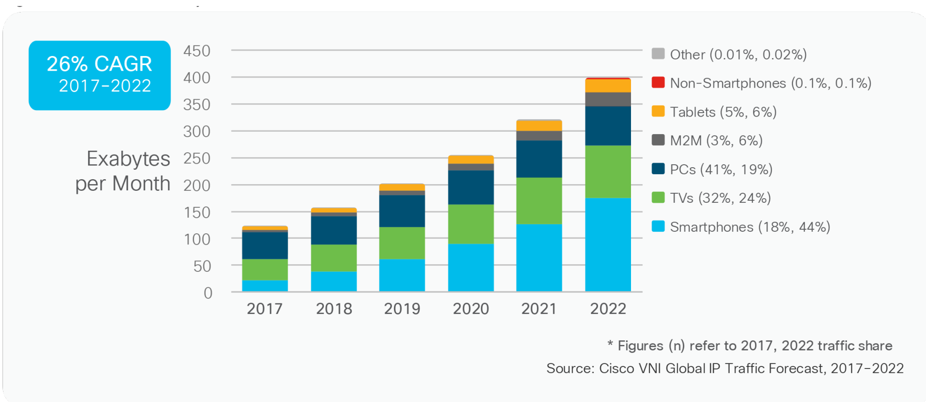

Figure 6.3. Global internet traffic by device. Figure taken from [9].

The CAGR expected from 2017 to 2022 is 26%.
In Fig.6.4 we can have an overview of how the internet traffic demand changed from 1992 and how it expected to change until 2022:

Year	Global internet traffic
1992	100 GB per day
1997	100 GB per hour
2002	100 GB per second
2007	2,000 GB per second
2017	46,600 GB per second
2022	150,700 GB per second

Figure 6.4. Global internet traffic demand growth. Figure taken from [9].

6.2.3 Video effect on global internet traffic

The last but not least phenomenon to keep track is the video effect that affect the global internet traffic.
It is expected that global video traffic will be 82% of all IP traffic by 2022.
In Fig.6.5 we can see how the video quality affects the global internet traffic:

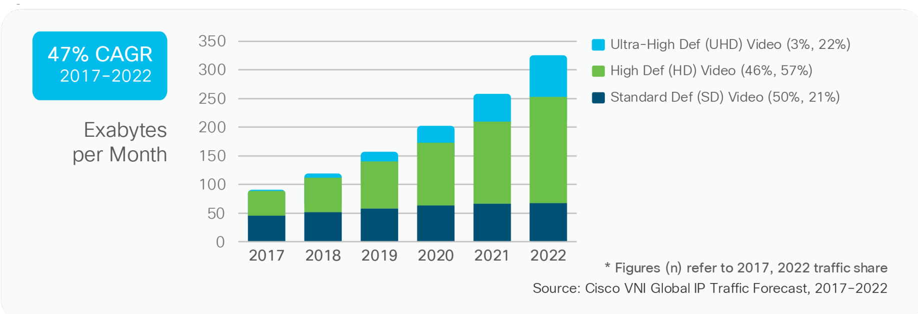

Figure 6.5. Video traffic by device. Figure taken from [9].

The CAGR expected from 2017 to 2022 is 47%.
As we can suppose, the video effect of the devices on traffic is more pronounced

by the introduction of Ultra-High-Definition (UHD), or 4K, video streaming. This video quality affect the total bandwidth required because it needs from 15 to 18 Mbps to be seen.
In Fig.6.6 we can see the growth expected of connected 4K TV sets:

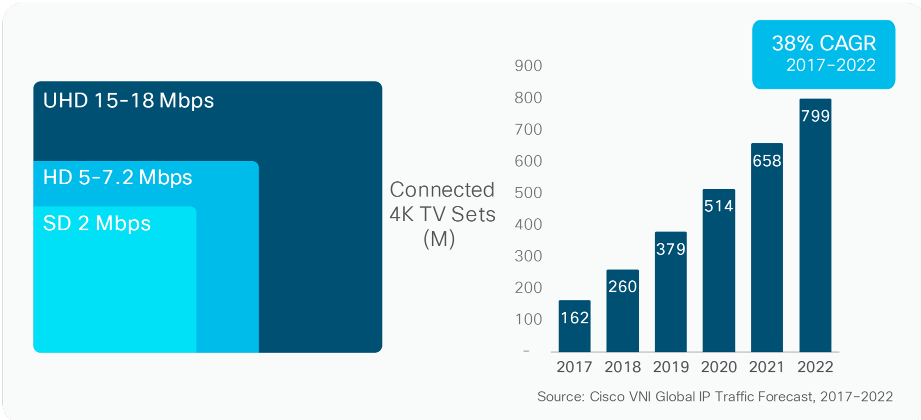

Figure 6.6. Video traffic demand growth. Figure taken from [9].

The CAGR expected from 2017 to 2022 is 38%.

6.3 Project bitrate demand evolution

In order to predict how the network can grow in the next years, in this Section the bitrate demand evolution in the first 5 years of the project network is estimated taking into the use case scenario the pilot area (Lot 1, G and H area of the project). In other words, we predict how the bandwidth of each internet profile will grow and the network resources needed to accomodate the project network evolution.

6.3.1 Internet profiles bandwidth

To predict the bitrate demand evolution at first we have defined the Peak Cell Rate and the Minimum Cell Rate (MCR) in downlink for each profile.
In Table 6.1 we can see for each profile what PCR and MCR we have defined:

Profile	Distribution	PCR DL [Mbps]	MCR DL [Mbps]
Entry	76%	50	20
Plus	5%	100	30
Business Entry	5%	50	20
Business Plus	12%	100	50
Business Large	2%	1000	100

Table 6.1. MCR and PCR defined for each profile

Taking into account:

- The pilot Area (Lot 1, G and H area of the project);
- The number of expected customers in the first year equal to 343;
- A customer growth of 30% per year;
- 11 GPON branches;
- The expected MCR in the next 5 years for each profile that we can see in table 6.2.

We can estimate the bitrate demand growth of next 5 years. In Table 6.3 we can see the total bitrate demand of one PON branch of each year (BB Yx, where x is the year):

Profile	MCR Y1	MCR Y2	MCR Y3	MCR Y4	MCR Y5
Entry	20	20	30	40	50
Plus	30	30	50	70	80
Business Entry	20	20	30	50	80
Business Plus	50	50	80	100	150
Business Large	100	100	150	200	200

Table 6.2. MCR [Mbps] of each profile in the next 5 years

Profile	BB Y1	BB Y2	BB Y3	BB Y4	BB Y5
B Entry	474	616	1201	2083	3384
B Plus	47	61	132	240	356
B Business Entry	31	41	79	171	356
B Business Plus	187	243	506	822	1603
B Business Large	62	81	158	274	356
Total B Demand	801	1042	2076	3590	6056

Table 6.3. MCR [Mbps] of each profile in the next 5 years

As we can see from Table 6.3, after the 2nd year, one PON branch is no longer able to support all the bitrate estimated with respect to the customers profiles.

6.4 Scenarios of project evolution

In this Section we will discuss the two scenarios that we have predicted fro the new project network resources needed to accomodate the predicted bandwidth demand grow of each user internet profile.

6.4.1 First scenario: PON co-existence

An interesting fact of the PON technology and one of the main reason of why we choose it, is that within a PON network can co-exist different PON technologies. This is possible because every PON technology works on different wavelengths than others:

- GPON: 1290-1330nm 1480nm-1500nm;
- XGS-PON: 1260-1280nm 1575nm-1580nm;
- NG-PON2: 1524-1544nm 1596-1603nm.

The component that make the PON co-existence possible is called WDM CEX multiplexer.
By following the PON co-existence approach and assuming:

- That we need to add two XG-PON boards;
- To upgrade each new customers to XG-PON CPE;
- To have a 20% of already customers every year that will perform the upgrade.

	Y3	Y4	Y5
New Customers	134	174	226
WDM CEX Cost	720,00 €		
CPE New cost	1471,00 €	1912,91 €	2486,78 €
CPE Upgrade cost	4927,20 €	6405,35 €	8326,96 €
XG-PON boards	1800,00 €		
Total	8918,67 €	8318,26 €	10813,74 €

Table 6.4. First scenario: PON co-existence upgrade costs

As we can see from Table 7.5 the cost of upgrading the technology is very low with respect to the total cost of the project that we can recall from Table 4.21. This is due to the fact that to upgrade the PON technology you have only to upgrade the SFP and the CPE devices at both end of the network, without changing the entire core part that would significantly affect the upgrading cost.

6.4.2 Second scenario: Reduce split ratio

The second scenario takes into account to reduce the initial split ratio of the OLT of the PON network from 8 to 4. In this way we can reduce the total number that one branch can reach. With this solution the number of branches double from 11 to 22 and also the number of GPON board required.
Doubling the number of branches, we can have a different estimate of bitrate demand growth in the next 5 years:

Profile	BB Y1	BB Y2	BB Y3	BB Y4	BB Y5
B Entry	237	308	601	1041	1692
B Plus	23	30	66	120	178
B Business Entry	16	20	40	86	178
B Business Plus	94	122	253	411	802
B Business Large	31	41	79	137	178
Total B Demand	401	521	1038	1795	3028

Table 6.5. MCR [Mbps] of each profile in the next 5 years

As we can see from Table 6.5 with respect to the first scenario, by doubling the number of branches, we will gain one year before introducing the PON co-existence as for the first scenario.

	Y1	Y4	Y5
New Customers	-	174	226
Double splitters	242,00 €	-	-
GPON boards	300,00 €	-	-
WDM CEX Cost	-	3600,00 €	
CPE New cost	-	1912,91 €	2486,78 €
CPE Upgrade cost	-	6405,35 €	8326,96 €
XG-PON boards	-	3600,00 €	-
Total	542,00 €	13238,26 €	10813,74 €

Table 6.6. Second scenario: Reducing the split ratio upgrade costs

In Table 6.6 we can see that also in this scenario, the cost of upgrading the technology is very low with respect to the total cost of the project that we can recall from Table 4.21. With respect to the previous scenario, we gain one year before needing to upgrade the technology.

6.5 Conclusion

In this Chapter we have analysed the Cisco Visual Network (VNI) Global Fixed and Mobile Internet Traffic Forecasts 2017-2022 and we have predicted the bitrate demand evolution that we expect for our project in order to propose two different scenario of the evolution of this project.

The Cisco VNI forecast highlights three phenomena to keep track:

- **Global Device Growth** and **Average number of devices and connections per capita** the Compound Annual Growth Rate (CAGR) index expected from 2017 to 2022 is equal to 10%.
- **Global internet traffic** the CAGR index expected from 2017 to 2022 is equal to 26%.
- **Video effect on global internet traffic** global video traffic is expected to be the 82% of all IP traffic by 2022.

In order to predict the network evolution in the first 5 years, we have estimated how the bitrate of each internet profile will change in the next years.

In Table 6.2 we have predicted the Minimum Cell Rate (MCR) expected for each profile for the next 5 years.

Taking into account the pilot Area (Lot 1, G and H area of the project), the number of expected customers in the first year equal to 343, a customer growth of 30% per year, the expected MCR in the next 5 years, we were able to estimate the bitrate demand growth in the next five years of the project. As we can see from Table 6.3, after the 2nd year, one PON branch will be no longer able to support all the bitrate estimated with respect to the customers profiles.

In order to accomodate the predicted bandwidth demand growth of the project, we have seen two possible upgrade scenarios of the network resources of the project:

- **PON co-existence** we exploit one of the key point of PON, i.e. the co-existence with different PON technologies thanks to WDM CEx multiplexers.
- **Reduce split ratio** reduce the initial split ratio of the OLT of the PON network from 8 to 4. In this way we gain one year before introducing PON co-existence.

Chapter 7

Conclusions

In this Chapter the key points and the achievements of each previous part are summarized and discussed.

The challenging part of this project was to adapt a pre-existing topological network (that is not primary designed for optical fiber communication) in order to build a Fiber-To-The-Home (FTTH) network, taking into account the evolution of the network with respect to the bitrate demands of coming years.

7.1 FTTH technologies

In the second Chapter we have evaluated the two different architecture of an FTTH network.

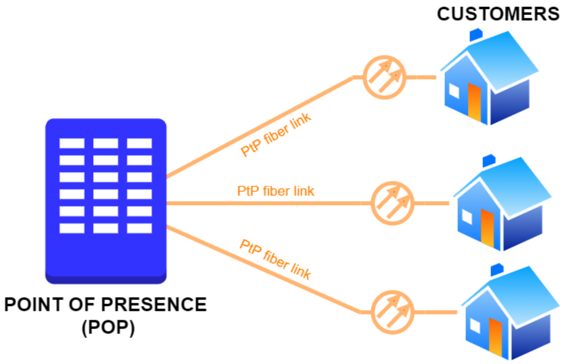

Figure 7.1. Optical access network based on Active Ethernet (AE) Point-to-point solution.

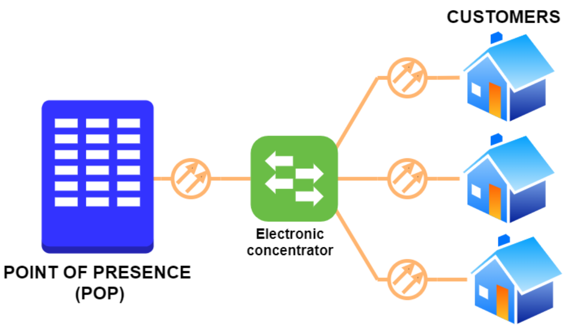

Figure 7.2. Optical access network based on Active Ethernet (AE) Active Star point-to-point solution.

Technology	Downlink	Uplink	Standard	Year
1000BASE-SX/LX	1 Gbps	1 Gbps	802.3z	1998
10GBASE-SR/SW/LR/LW/ER/EW/LX4	10 Gbps	10 Gbps	802.3ae	2002
40GBASE-T/KR4/CR4/SR4/FR/LR4/ER4	40 Gbps	40 Gbps	802.3bm	2015

Table 7.1. Active Ethernet (AE) capabilities and standards

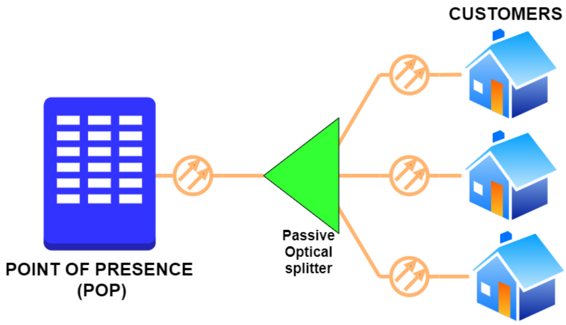

Figure 7.3. Optical access network based on P2MP Passive Optical Network (PON) solution

Technology	Dl	Up	Standard	Year	UpSR	DlSR
APON/BPON	0.622	0.155	ITU-T G.983	1995	1290-1330	1480-1500
GPON	2.488	1.244	ITU-T G.984	2003	1290-1330	1480-1500
1G-EPON	1.25	1.25	IEEE 802.3ah	2004	1290-1330	1480-1500
10G-EPON	10.3125	1.25	IEEE 802.3av	2009	1260-1280	1575-1580
10G-EPON S	10.3125	10.3125	IEEE 802.3av	2009	1260-1280	1575-1580
XG-PON1	9.9528	2.488	ITU-T G.987	2010	1260-1280	1575-1580
TWDM-PON	40	10	ITU-T G.989	2013	1596-1603	1524-1544
XGS-PON	9.9528	9.9528	ITU-T G.9807.1	2016	1260-1280	1575-1580

Table 7.2. Passive Optical Network (PON) capabilities and standards

Where:

- **Dl** is the downlink speed in Gbps.
- **Ul** is the uplink speed in Gbps.
- **UpSR** is the uplink spectral range in nm.
- **DlSR** is the downlink spectral range in nm.

Even if in AE solution each user has a dedicated "pipe" that provides full bi-directional bandwidth, we have to face with different problems:

- Upgrading the technology means changing a lot of network equipments and it is more expensive than PON.
- It requires a huge number of fiber strands.

- It uses Active Electronic Switches to provide fiber access aggregation. Because of that, it includes full management and troubleshooting capabilities,but it arise the problem of power requirements.

In the opposite side, in PON solution different users share the same "pipe" and they share the "pipe" bandwidth, but:

- It requires a lower number of fiber strands. One fiber strand can reach up to 64 customers.

- Different PON technologies can co-exist in the same network.

- Upgrading PON technology is possible by changing few core equipments in the endpoints.

7.2 Constraints evaluation

In the third Chapter we have seen that this project has a very important potential for what concern the total customers that it will cover.

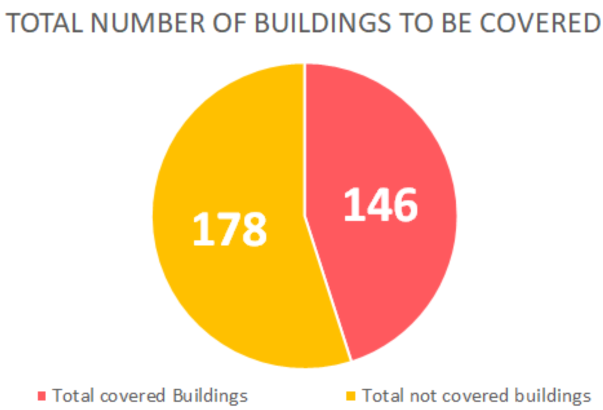

Figure 7.4. Total number of buildings to be covered

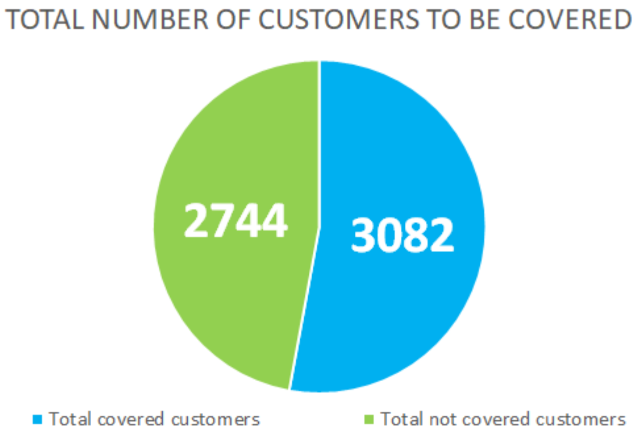

Figure 7.5. Total number of customers to be covered

In order to predict the cost of the entire project, we decided to group the topological areas of the city of Aosta into 3 different lots:

- **Lot 1:** G and H areas.
- **Lot 2:** B, D, E and F areas.
- **Lot 3:** A and C areas.

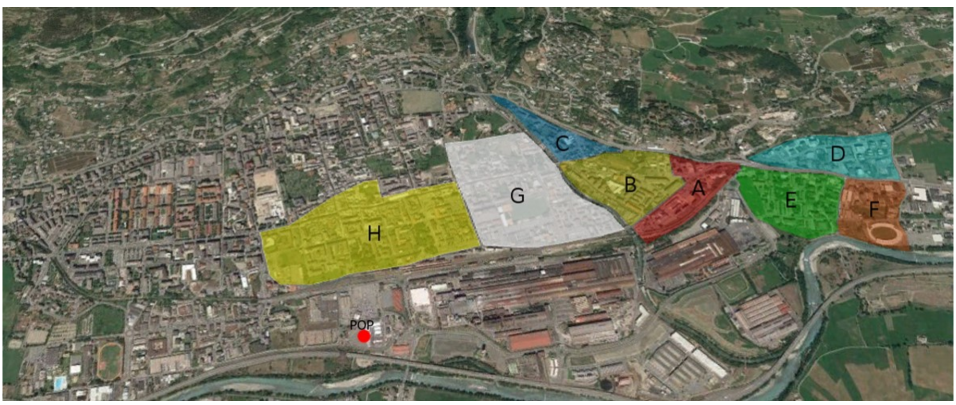

Figure 7.6. Topological areas that will be covered by the fiber infrastructure in the city of Aosta (IT).

For the fact that we exploit a pre-existing pipe network that is not primary built for telecommunications, we have to face down with different mechanical constraints such as pipe diameter, pipe curves and manhole size. These constraints affect the choice of the fiber cables that need a stronger tensile force and a sufficient bending radius to overcome the pipe diameter constraint.

Even if we have different constraints, the advantage of exploiting the pre-existing pipe network lower the cost of the fiber infrastructure, because the pipe have been already laid down.

7.3 Planning of the network resources

In the fourth Chapter we have seen all the network resources needed for each of the two FTTH technologies and the compromises that we have to take to exploit the pre-existing pipe network.
The project has three main parts:

- **Point of Presence (POP)**: in this part the core equipment of the project is located such as core switch and patch panel to link the fiber infrastructure. It is often indicated as "Central Office (CO)" in the PON terminology.

- **OutSide Plant (OSP)**: in this part the fiber infrastructure and its related equipment are located.

- **Building**: in the last part the equipment to link the final customer to the fiber infrastructure is located.

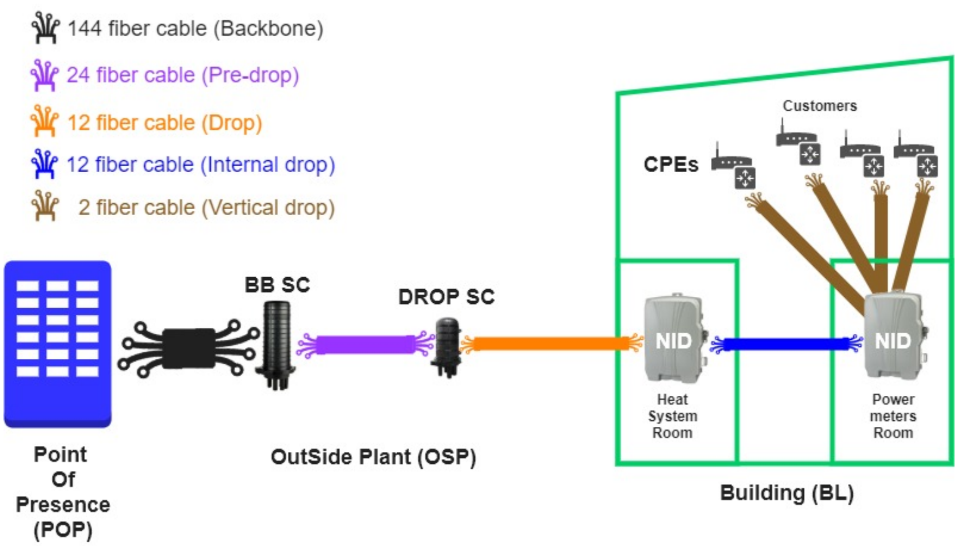

Figure 7.7. Simplified structure of the project

To keep infrastructure costs low and not to disrupt the pipe network, we had to find a solution which includes not only one splice closure to link the core elements with the final customers, but another one to do a pre-drop splicing. With this approach we have to modify the pipe network only where the backbone splice closures (the splice closures that can manage up to 144 fiber strands) will be placed and not where the drop splice closures (the splice closures that can manage up to 24 fiber strands) will be placed.

Figure 7.8. Backbone splice closure to splice the 144 fiber cable with the 24 fiber cable and drop splice closure to splice 24 fiber cable with 12 fiber cable.

The AE solution consists in a PTP connection between the POP and the switch located in the premise of the building. From the POP two fiber strands goes out that reach the active switch located in the premise of the customer building via the fiber infrastructure network. From the active switch, the final customer is reached by another PTP link with two fiber strands.

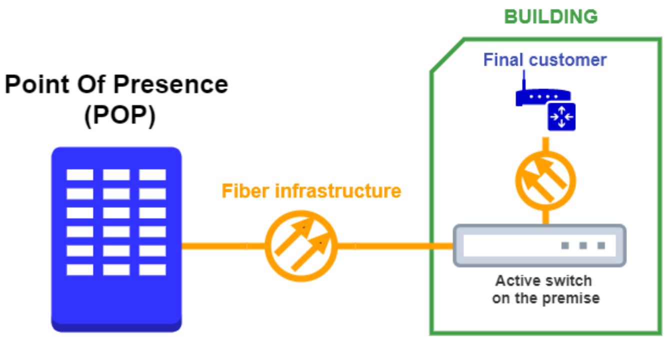

Figure 7.9. Active Ethernet project scheme.

The PON solution consists in a P2MP connection between the POP and the final customer. From the POP one fiber strand goes out and it reaches the optical splitter located in the premise of the customer building via the fiber infrastructure network. We decided to choose a splitter with 1X16 splitting ratio and in the next section there will be explained the motivation behind this choice. From the optical splitter the the final customer is reached by a single strand fiber.

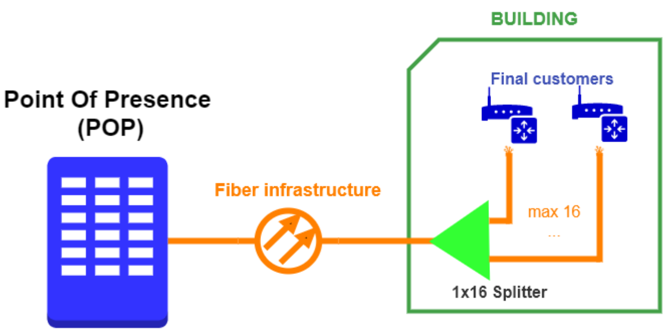

Figure 7.10. Passive Optical Network project scheme

After a deep and attentive research, we have evaluated all the network resources needed to develop our project taking into account the AE and POP solutions. We decided to choose the PON solution for all the advantages that has compared to the AE solution, but in particular because it is cheaper, it is not susceptible to power failure and future network upgrades do not require a huge financial resources than instead the AE solution would require.

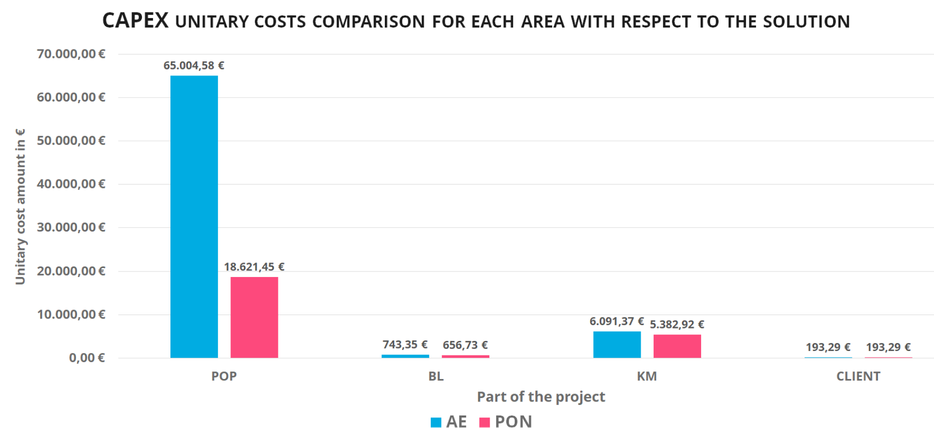

Figure 7.11. CAPEX unitary costs comparison with respect to the solution

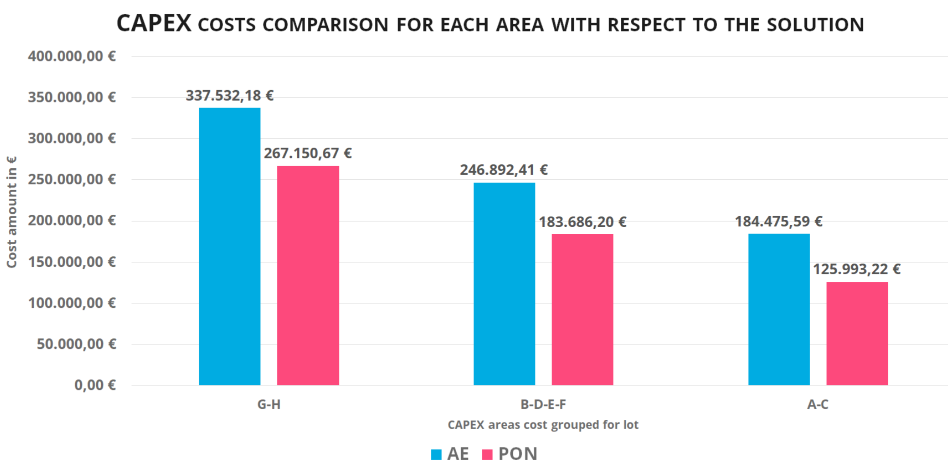

Figure 7.12. CAPEX costs comparison for each area with respect to the solution

7.4 Estimation of the cost/income in the long term

In the fifth Chapter we have performed a cost/income estimation expected in the first ten years of the project.

The incomes of the entire project are composed by:

- **Recurrent Revenues (RR):** are the incomes generated by the cost of the profile chosen by each customer.

  $$RR = TotalCustomers * ARPU - NewCustomers * (ARPU)/2$$

  By average, every user generates an income (ARPU) of 343,20 € per year. We decided to divide by a factor two the revenues of the new customers because the new customers does not come with the beginning of the year.

- **Customer Activation Fees (CAF):** Every new customer that wish to activate a fiber internet profile has to pay an activation fee of 100 €.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
RR	58907,13€	201808,26 €	279769,95 €	343961,21 €	403372,70 €	463878,60 €	521054,34 €	573159,77 €	630475,75 €	693523,32 €
CAF	34328,17 €	29263,00 €	27159,56 €	18222,15 €	16399,93 €	18859,92 €	14459,27 €	15905,20 €	17495,20 €	19245,29 €
Total	93235,30 €	231431,25 €	306929,52 €	362183,36 €	419772,63 €	482738,52 €	535513,61 €	589064,97 €	647971,47 €	712768,61 €

Table 7.3. Total incomes of the project per each year

The costs of the entire project are composed by:

- **CAPEX:** The CAPEX costs for each Lot. We decided to estimate an amortisation of the total costs in 10 years.
- **OPEX:** The OPEX costs of the project.
- **Other OPEX:** All the other OPEX costs for which we did not estimate a constant growth.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
CAPEX	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €	57683,01 €
OPEX1	138222,00 €	139604,22 €	14100,26 €	142410,26 €	143824,37 €	145272,71 €	146725,44 €	148192,69 €	149674,62 €	151171,37 €
OPEX2	31943,15 €	81872,15 €	126661,73 €	140600,07 €	149782,36 €	169053,57 €	172118,57 €	190707,33 €	207799,27 €	230766,29 €
Total	227848,16 €	279159,38 €	325345,00 €	340692,34 €	351299,73 €	372009,29 €	379527,01 €	396582,03 €	415156,89 €	439630,66 €

Table 7.4. Total costs of the project per each year

Summing all the costs and all the incomes expected in the first ten years of the project, we were able to perform a bottom line analysis, that allows us to predict after which year all the revenues cover all the previous costs leaving profit margin to the company.

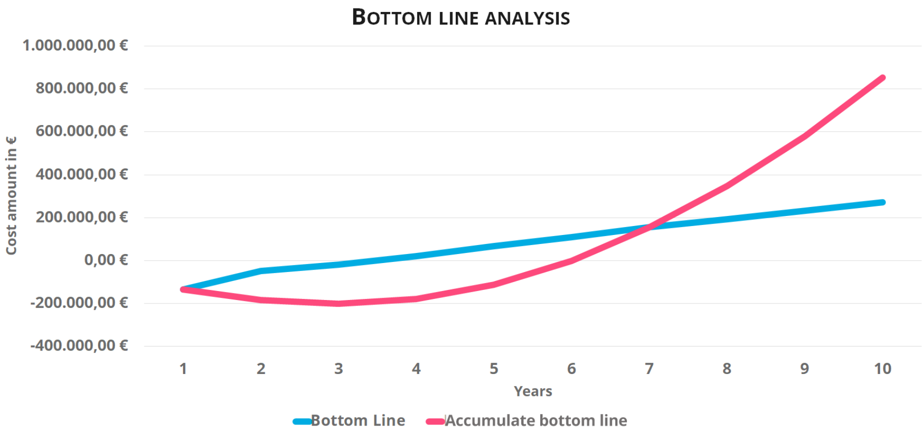

Figure 7.13. Bottom-line and Accumulate bottom-line analysis

In Fig. 7.13, we can see that between the sixth and the seventh year the incomes of the project overcome the costs of the project.

7.5 Estimation of the project network evolution

In the sixth Chapter we have analysed the Cisco Visual Network (VNI) Global Fixed and Mobile Internet Traffic Forecasts 2017-2022 and we have predicted the bitrate demand evolution that we expect for our project in order to propose two different scenario of the evolution of this project.

The Cisco VNI forecast highlights three phenomena to keep track:

- **Global Device Growth** and **Average number of devices and connections per capita** the Compound Annual Growth Rate (CAGR) index expected from 2017 to 2022 is equal to 10%.

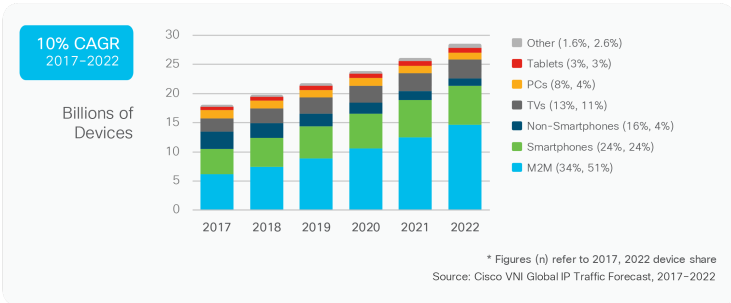

Figure 7.14. Global devices growth. Figure taken from [9].

- **Global internet traffic** the CAGR index expected from 2017 to 2022 is equal to 26%.

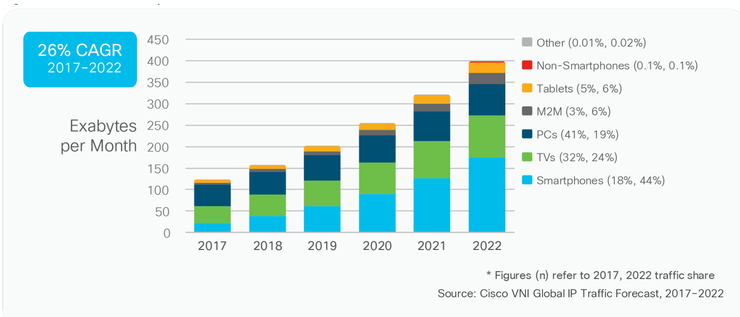

Figure 7.15. Global internet traffic by device. Figure taken from [9].

- **Video effect on global internet traffic** global video traffic is expected to be the 82% of all IP traffic by 2022.

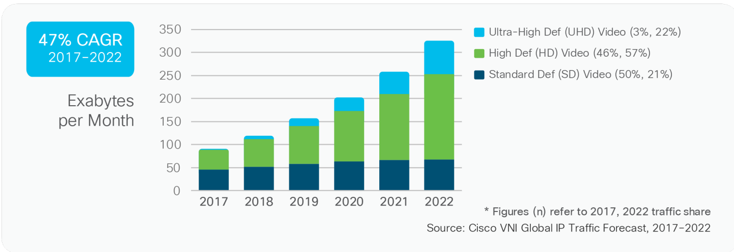

Figure 7.16. Video traffic by device. Figure taken from [9].

In order to predict the network evolution in the first 5 years, we have estimated how the bitrate of each internet profile will change in the next years.
In Table 6.2 we have predicted the Minimum Cell Rate (MCR) expected for each profile for the next 5 years.

Taking into account the pilot Area (Lot 1, G and H area of the project), the number of expected customers in the first year equal to 343, a customer growth of 30% per year, the expected MCR in the next 5 years, we were able to estimate the bitrate demand growth in the next five years of the project. As we can see from Table 6.3, after the 2nd year, one PON branch will be no longer able to support all the bitrate estimated with respect to the customers profiles.

In order to accomodate the predicted bandwidth demand growth of the project, we have seen two possible upgrade scenarios of the network resources of the project:

- **PON co-existence** we exploit one of the key point of PON, i.e. the co-existence with different PON technologies thanks to WDM CEx multiplexers.

	Y3	Y4	Y5
New Customers	134	174	226
WDM CEX Cost	720,00 €		
CPE New cost	1471,00 €	1912,91 €	2486,78 €
CPE Upgrade cost	4927,20 €	6405,35 €	8326,96 €
XG-PON boards	1800,00 €		
Total	8918,67 €	8318,26 €	10813,74 €

Table 7.5. First scenario: PON co-existence upgrade costs

- **Reduce split ratio** reduce the initial split ratio of the OLT of the PON network from 8 to 4. In this way we gain one year before introducing PON co-existence.

	Y1	Y4	Y5
New Customers	-	174	226
Double splitters	242,00 €	-	-
GPON boards	300,00 €	-	-
WDM CEX Cost	-	3600,00 €	
CPE New cost	-	1912,91 €	2486,78 €
CPE Upgrade cost	-	6405,35 €	8326,96 €
XG-PON boards	-	3600,00 €	-
Total	542,00 €	13238,26 €	10813,74 €

Table 7.6. Second scenario: Reducing the split ratio upgrade costs

7.6 Achievements

In this project we were able to overcome the topological and mechanical constraints of a pipe network not primary built for telecommunication by finding a way to exploit it without impacting to much on the pre-existing one.

We have fully analyzed the capabilities, standards and advantages and disadvantages of both FTTH technologies. We choose PON because it fits the main needs of our project.

We defined all the network resources of our FTTH project for both technologies and we analyzed the total and the unitary costs to deploy it.

After choosing the most suitable technology we predict the incomes and with the techno-economic analysis of the (CAPEX and OPEX) costs we were able to see that between the sixth and the seventh year all the project expenses will be covered by the revenues of the project.

Finally we were able to predict two scenario of the future project upgrades with their cost of deployment. As we expected from PON solution, the cost of future upgrade is very low compared to the CAPEX cost of the entire project.

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