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Deliverable D2.2.p

(Public version of Deliverable D2.2)

"Techno-economical analysis for the identified capacity upgrade, dynamic capacity allocation, aggregate transport of wired-wireless signals and infrastructure convergence solutions"

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Executive Summary

This ALPHA Deliverable (D2.2.p) is a summary of the key messages of the Deliverable D2.2, which performed a preliminary techno-economic analysis of the solutions proposed in ALPHA Workpackage 2 “Access Networks”.

For the access architectures, the following technical research directions are considered in ALPHA:

- An optical access network, typically Fibre-to-the-Home (FTTH), capable to interconnect a large number of subscribers, optimised in terms of CapEx and OpEx, and adapted to the future bit-rate needs. Two technical alternatives are proposed to meet this goal:
    - A WDM extension of the next generation of GPON (WDM 10G GPON), with special attention for dynamic capacity allocation.
    - An Ethernet-based active optical network (AON).
- A Radio-over-Fibre (RoF) solution put on the top of a PON to eliminate the need for deployment and associated costs for a dedicated RoF infrastructure.

This deliverable describes the first steps towards a techno-economic analysis of the above concepts:

- State-of-the-art study for the techno-economic aspects of FTTH, consisting of two main parts:
    - Examples of existing techno-economic studies for FTTH, that we map on the architectures proposed in ALPHA to deduce some general trends. The costs are dominated by the civil works (digging), so that the cost of the technical solutions represents only a fraction of the overall cost (typically 50%, in an urban zone).
    - Status on the introduction of FTTH in different European countries, with three typical cases: France, Sweden/Denmark and Poland.
- Preliminary results in terms of techno-economics for the different ALPHA architectures with a clear indication of their possible techno-economic advantages compared with other technologies, either quantitatively (for WDM 10G GPON and RoF over PON) or qualitatively (for AON).
    - *WDM 10G GPON*: first results comparing a set of 10G GPON and a WDM 10G GPON clearly show cost advantages for the WDM 10G GPON solution.
    - *RoF over PON*: the cost of upgrading the RoF equipment for using it over PON instead of a dedicated infrastructure has been estimated to be in a range of a few percent of the overall costs of a “classical” RoF implementation. The upgrade allows totally avoiding the dedicated RoF fibre infrastructure and eliminating all the costs associated with it.
    - *AON*: different advantages are qualitatively considered, like the addition of redundancy, better support for local traffic, allowing an open access network model.

This deliverable gives in general the base to draw some preliminary conclusions and identifies the scope of the next studies of the project.

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Table of Contents

1 Introduction

1.1 Purpose and Scope

The successful deployment of Fibre to the Home (FTTH) technology in the Asia and Pacific (APAC) region with more than 19 Millions of connections today opens new perspectives in terms of broadband applications and creates a need for a deployment of this technology in Europe and the USA. However the deployment of this technology is facing considerable problems with respect to the initial investment. The objective of this ALPHA Deliverable D2.2.p, summarising the content of the D2.2, will be to identify the factors that are limiting its introduction.

The choice of the technical solution is also an issue. To summarise, we have the choice between three main categories as described in Figure 1-1 (and also described in ALPHA Deliverable D2.1 [1]). Each of these solutions has advantages and drawbacks. Each of them is seriously considered by different operators and their adoption depends on the deployment strategy of each operator.

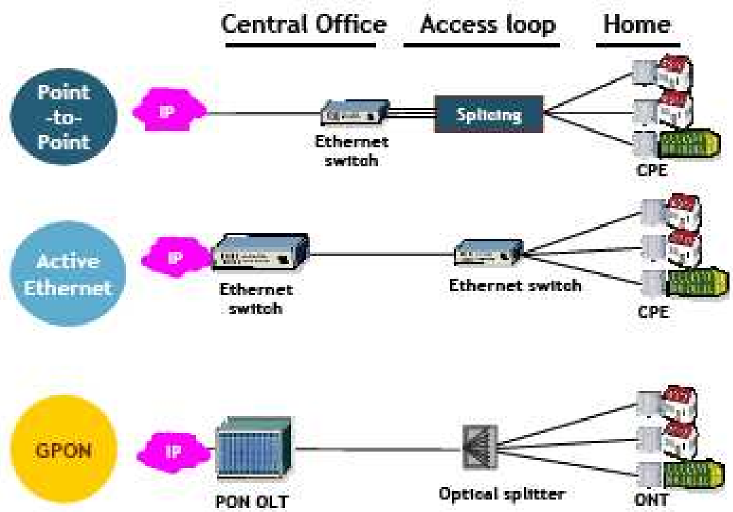

Figure 1-1: Three categories of FTTH technologies: (1) Home Run Fibre or Point-to-Point (P2P), (2) Active Star or Active Ethernet and (3) xPON architectures like GPON and EPON

The techno-economic advantages of the different solutions, mainly AON and PON, and completed with an analysis of RoF technologies over PON have been analysed. After the description of the methodology (section 2), an overview of the state-of-the-art is given, to analyse existing techno-economic studies and to deduce some general trends (section 3). Then, the proposed ALPHA architectures introduced in ALPHA Deliverable D2.1 [1] for AON (section 4), WDM/TDM PON (section 5) and RoF over PON (section 6) are analyzed in more detail with a clear indication of their possible techno economic advantages compared with other technologies, either quantitatively (for WDM/TDM PON and RoF over PON) or qualitatively (for AON).

- For AON, an approach where the access network is more integrated in the rest of the network is proposed. In this way, more meshed topologies can add redundancy to the network and can lead to better utilisation of resources. Only a quantitative evaluation is given in D2.2.
- For PON, a positioning of a WDM 10G GPON with respect to a 10G GPON is considered and supported with quantitative cost results. The objective of the WDM 10G GPON is to propose an access network capable to have an aggregation level to simplify the network infrastructure of this access part. Also special attention is given to dynamic capacity allocation.

- For RoF over PON, a convergent scenario for delivering a RoF overlay over a PON is proposed by adopting the RoF technology for compensation of power losses. In this manner an existing PON can be reused instead of installing a new dedicated fibre network.

Performance aspects are not included in this deliverable, but this will be considered in the next phase of the project to really have a more robust picture of the cost per user.

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1.2.2 Acronyms and Abbreviations

Most frequently used acronyms in the Deliverable are listed below. Additional acronyms can be specified and used throughout the text.

2G	Second Generation
3G	Third Generation
ADSL	Asymmetric DSL
AE	Active Ethernet
ALF	Alcatel Lucent France (project partner)
AN	Access Node
AON	Active Optical Network
APD	Avalanche Photodiode
ARPU	Average Revenue Per User
ATFI	Andrew Wireless Systems Srl (project partner)
ATM	Asynchronous Transfer Mode
AWGR	Arrayed Wavelength Grating Router
B&S	Broadcast and Select
B3G	Beyond third Generation
BMOFA	Burst Mode Optical Fibre Amplifier
BMRX	Burst Mode Receiver
BMTRX	Burst Mode Transceiver
BMTX	Burst Mode Transmitter
BPON	Broadband Passive Optical Network
BSC	Base Station Controller
BTS	Base Transceiver Station
CapEx	Capital Expenditures
CATV	Cable Television
CO	Central Office
CPE	Customer Premises Equipment
CPON	Composite PON
CWDM	Coarse WDM
DAS	Distributed Antenna System

DBA	Dynamic Bandwidth Allocation
DBR	Distributed Bragg Reflector
DCS	Digital Cellular System
DEMUX	Demultiplexer
DFB	Distributed FeedBack
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DWA	Dynamic Wavelength Allocation
DWDM	Dense WDM
EAM	Electro-Absorption Modulator
ECL	External Cavity Laser
EDFA	Erbium Doped Fibre Amplifier
EDGE	Enhanced Data rates for GSM Evolution
EPON	Ethernet Passive Optical Network
FA	Fibre-based Amplifier
FBG	Fibre Bragg Grating
F-DAS	Fibre-DAS
FP	Fabry Perrot
FSR	Free Spectral Range
FTRD	France Telecom R&D (project partner)
FTTB	Fibre to the Building
FTTC	Fibre to the Curb / Cabinet
FTTH	Fibre to the Home
FTTP	Fibre to the Premises
FTTx	Fibre to the x
GbE	Gigabit Ethernet
GEM	GPON Encapsulation Method
GMPLS	Generalized MultiProtocol Label Switching
GPON	Gigabit Passive Optical Network
GW	Gateway
HDTV	High Definition Television
HFC	Hybrid Fibre-Coaxial
ICT	Information and Communication Technologies
IP	Internet Protocol
IPTV	Internet Protocol Television
ISP	Internet Service Provider
IT	Information Technology
LAN	Local Area Network
LARNET	Local Access Router Network
LD	Laser Diode
LED	Light Emitting Diode
LLU	Local Loop Unbundling
MAC	Medium Access Control
MDU	Multi Dwelling Unit
MMF	Multi Mode Fibre
MUX	Multiplexer
NG-PON	Next-Generation PON
OA	Optical Amplifier
OLT	Optical Line Termination
ONT	Optical Network Termination
ONU	Optical Network Unit
OpEx	Operational Expenditures
OSP	Outside plant
OTN	Optical Transport Network

P2MP	Point-to-MultiPoint
P2P	Point-to-Point
PIN	Positive-Intrinsic-Negative
PLC	Planar Lightwave Circuit
POF	Plastic / Polymer Optical Fibre
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PS-PON	Power Splitting – PON
PSTN	Public Switched Telephone Network
PTP	Point-to-Point
RAU	Remote Antenna Unit
REAM	Reflective Electro-Absorption Modulator
RF	Radio Frequency
RITENET	Remote Interrogation of Terminal Network
RN	Remote Node
RNC	Radio Network Controller
ROADM	Reconfigurable Optical Add/Drop Multiplexers
RoF	Radio over Fibre
RSOA	Reflective Semiconductor Optical Amplifier
RX	Receiver
SDH	Synchronous Digital Hierarchy
SFP	Small Form-factor Pluggable
SFR	Single Family Residential
SFU	Single Family Unit
SME	Small and Medium Enterprise
SMF	Single Mode Fibre
SOA	Semiconductor Optical Amplifier
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TR	Take Rate
TRX	Transceiver
TV	Television
TX	Transmitter
UMTS	Universal Mobile Telecommunication System
VDSL	Very high bit rate Digital Subscriber Line
VLAN	Virtual LAN
VoD	Video on Demand
VoIP	Voice over IP
WDM	Wavelength Division Multiplexing
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WP	Work Package

1.3 Document History

Version	**Date**	**Authors**	**Comment**
00	2009-03-31	D. Chiaroni	First version
02	2009-04-15	D. Chiaroni	Second version
03	2009-04-30	D. Chiaroni	Third version
04-05	2009-05-06 – 2009-05-08	B. Lannoo, M. Popov, D. Chiaroni	Final version

2 Scope of the techno-economic studies

2.1 General approach

A techno-economic positioning to deploy the FTTH technology is fundamental to understand well the impact of each element in a global cost evaluation and derive specifications at the technology level.

All network operators around the world are evaluating the different FTTH technology options since the deployment of a FTTH network requires significant upfront capital investments. Building a detailed economic model that optimises their capital expenditures (CapEx), operational expenditures (OpEx) and payback period is fundamental but difficult to establish due to the diversity of topologies, and the specificity of the operator demands. Planning for a deployment or upgrading existing networks is made particularly difficult by rapidly changing network components and a multitude of system architecture alternatives.

By the above facts several calculations, assumptions and techno-economic models can be built. Such a model should satisfy some requirements, e.g.:

- Scenarios valuation - the comparison of network evolutions
- The cost evolution through years - the evolution of network (infrastructure, content of service) is forecast on a “x”- year period
- Simplicity - the models must be easy to handle, clear and all parameters must be clearly identified. Assumption of scenarios valuation

Figure 2-1 represents a general model with its ingredients influencing the network cost and profitability of the network.

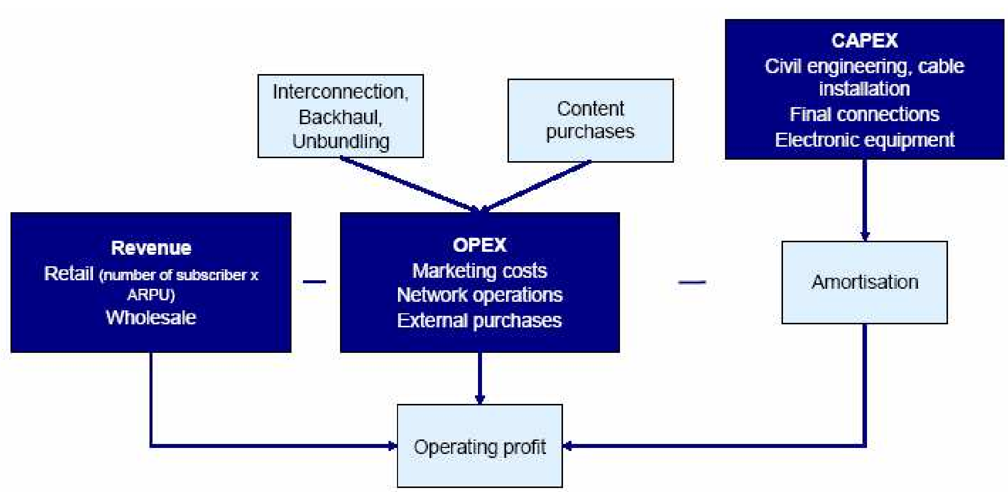

Figure 2-1: General model for evaluating the profitability of an FTTH deployment

By the mentioned difficulties of building a full economic model, in this deliverable we will limit the economic modelling (in this first preliminary study) to the CapEx evaluation for the proposed architectures in section 5 of ALPHA Deliverable D2.1 [1]. The scope is thus related to equipment and installation costs, and does not cover any OpEx aspects (such as maintenance, repair, energy consumption, pricing & billing, helpdesk…). In addition, the performance aspects will not be addressed in this report.

2.2 Methodology for the CapEx analysis

The costs for the CapEx evaluation can be divided in three main categories:

- *First category*: the cost of the civil works (e.g. digging)
- *Second category*: the cost of the transmission and interconnection elements (shared optical layer): fibre, tubes, connectors, patch panels
- *Third category*: the cost of the network elements, mainly the OLT, the ONUs, the optical couplers and splitters and the regenerative box (if required).

The techno-economic analysis will then identify the different cost figures, and their impact on the cost per user.

3 State of the art: FTTH architectures & existing techno-economic studies

3.1 Summary of FTTH architectures

As mentioned in ALPHA Deliverable D2.1 [1], to satisfy all future high-bandwidth and interactive multimedia applications, optical fibre based access networks can be considered as the most future-proof solution exceeding the current xDSL and Cable networks by far. There exist several implementations of an optical access network, depending on the end point of the fibre path and commonly indicated as Fibre to the x (FTTx). In the case of Fibre to the Home (FTTH) or Fibre to the Building (FTTB), the fibre reaches the user's house or building. Fibre to the Curb or Cabinet (FTTC) on the other hand brings the fibre to a service node (e.g. a street cabinet) near the user. In the latter case, the fibre does not reach the user itself, and the remaining gap has to be bridged by another technology, either wired (e.g. VDSL or HFC) or wireless (e.g. WiMAX, WiFi, 3G). In the remainder of this deliverable, we will mainly use the term FTTH, but this can easily be extended to any other FTTx implementation.

There are two main categories of FTTH technologies, either active or passive. Active Optical Networks (AONs) provide a (logical) point-to-point (P2P) connection between the Central Office (CO)[1] and each user. Commonly used active topologies are home run fibre (with a dedicated fibre from the CO to each user, also known as P2P network) and active star (with a switch or router installed between the CO and the user, e.g. Ethernet switch in the street cabinet). More meshed topologies, however, could also be envisaged for an AON. Passive Optical Networks (PONs) on the other hand are point-to-multipoint (P2MP) networks, where the access fibre is shared by several users (e.g. 32, 64…), typically through a branched tree topology. Nowadays, the most used PON configuration is a (power splitting) Time Division Multiplexing (TDM) PON, with Gigabit PON (GPON) and Ethernet PON (EPON) as the two most important standards. Wavelength division multiplexing (WDM) PONs can be considered as a strong candidate for next-generation PONs. Additionally, a combined fibre-wireless network, e.g. using radio-over-fibre (RoF) techniques, could be considered as a cost and energy efficient solution to provide a high-bandwidth access network.

Regardless of the used architecture, the CO contains an Optical Line Terminal (OLT), which is, among other things, responsible for packet processing, medium access control (MAC), etc. In the CO, the termination and aggregation of the different fibre lines from the users is done and it then connects the users to the different Internet Service Providers (ISPs). The exact OLT functionality however differs for an AON and a PON, as the former delivers a dedicated connection and the latter uses a shared medium. On the user side an Optical Network Unit / Terminal (ONU / ONT) translates the optical signal to the in-house equipment signal and vice versa.

3.1.1 Active Optical Networks (AONs)

Common for all AON deployments is that they use Ethernet as a service carrier (for e.g. IP packets; Layer 2) and as transport means between all active equipment. However, due to different technical backgrounds, different practical and geographical constraints, AONs differ with respect to the design and business models. Consequently, there is no single "right" design as for AON, but a generic design is depicted in Figure 3-1 comprising access nodes, distribution nodes and core nodes. The nodes are either of the Layer 2 (L2, Ethernet switch) or Layer 3 (L3, IP-router) type as discussed in ALPHA Deliverable D2.1 [1].

The "ideal" AON access network comprise redundant connections to the core network, a redundant distribution network built as a ring or a mesh, and a number of access rings connected to different

[1] The central office (CO) corresponds to the location of the DSLAM in a DSL network and the OLT in a PON, but for an AON, the definition is what vague since the active equipment is spread over the network. More attention will be given to this issue in the next phase of the ALPHA project by proposing a general framework for different network architectures.

distribution nodes for redundancy. An access ring typically comprises two – five access nodes. From the access nodes there are Ethernet connections to the home gateways (which include the ONTs), either transported over fibre or copper cables

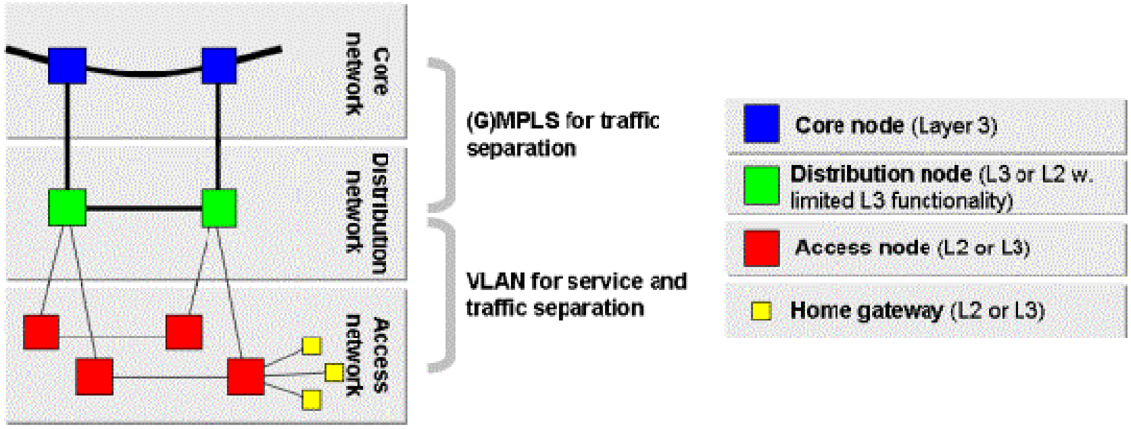

Figure 3-1: Generic design of an active optical network (AON)

Section 4 gives a more detailed description of an AON architecture, together with some techno-economic considerations.

3.1.2 Passive Optical Networks (PONs)

A PON is a shared medium where the optical fibre is passively (i.e. without the need for external electric power) split to several end users.

Time Division Multiplexing (TDM) PONs

Nowadays, the most used PON configuration is a (power splitting) Time Division Multiplexing (TDM) PON, like Gigabit PON (GPON) and Ethernet PON (EPON). A TDM PON is characterized by the concept of sharing wavelengths. One shared wavelength for all customers in the downstream direction and another wavelength for the upstream. Various end users in homes or businesses are all linked to the central node by a single fibre. The key element in a TDM-PON network light path is a splitter, which divides optical power among several end users. Moreover, multiple end users can be connected to a PON through one or more splitters, which are cascaded - considering optical power budget. The splitter is a passive element, which means that it does not require any power supplying. In a TDM PON, the downstream 1490nm and the upstream 1310nm wavelengths are used to transmit data and voice. The downstream 1550nm wavelength can be used for analogue video overlay.

From the CO, the OLT “broadcasts” data packets downstream to all the end users’ ONTs, using an addressing scheme. The ONT at the premise then intercepts data from the OLT bearing the appropriate address. The ONTs send data to the central unit in burst, and the OLT controls when the ONTs burst their data to avoid collisions between upstream packets form different ONTs. Moreover, each ONT has a dedicated time slot within each upstream frame.

Table 3-1 summarizes the characteristics of the different TDM-PONs having a standard reference [2],[3],[4]. Note that GPON can transport Asynchronous Transfer Mode (ATM) frames or Ethernet frames under a GPON Encapsulation Method (GEM) protocol. Currently, the 10G GPON variant is also standardized.

Table 3-1: Characteristics of BPON, GPON, EPON and 10G EPON

Relevant values	**BPON**	**GPON**	**EPON**	**10G EPON**
Bit rate (Gbps) down/up	0.622/0.155	2.488/1.244	1.25/1.25	10.3 / 10.3 (1.25)
Max. Total link loss (dB)	25	28	20	29
Splitting ratio	16(64)	32(128)	16 or 32	32
Distance (km)	20	20	10 or 20	10 or 20
Protocol	ATM	GEM for Ethernet and TDM, native ATM	Ethernet	Ethernet
Standards references	ITU-T G.983 series [2]	ITU-T G.984 series [2]	IEEE 802.3ah [3]	IEEE 802.3av [4]
Video transport	RF in WDM overlay	RF in WDM overlay or inband IPTV	RF in WDM overlay or inband IPTV	RF in WDM overlay or inband IPTV

<u>*Reference architecture: GPON*</u>

The Gigabit PON (GPON) belongs to the category of TDM-PONs and is often used as reference architecture in this deliverable. Figure 3-2 illustrates the GPON network architecture, with the product line of ALU. The GPON includes an OLT (7342 P-OLT or 7342 ISAM FTTU), different ONTs (7342 for the O – I or B series and a 7342/7352 for the M Series). The splitter is a 1:64 device. An option for a CATV box (7340 V-OLT) is available at 1550 nm. The upstream traffic is at 1.244 Gbps at 1310 nm whereas the downstream traffic is at 2.488 Gbps at 1490 nm. The network is controlled with a network management tool: 5526 AMS including an OSS interface, an alarm monitoring compliant with all ALU access products. The OLT has Gigabit Ethernet (GbE) and 10 GbE bidirectional links to be interconnected with a metro network.

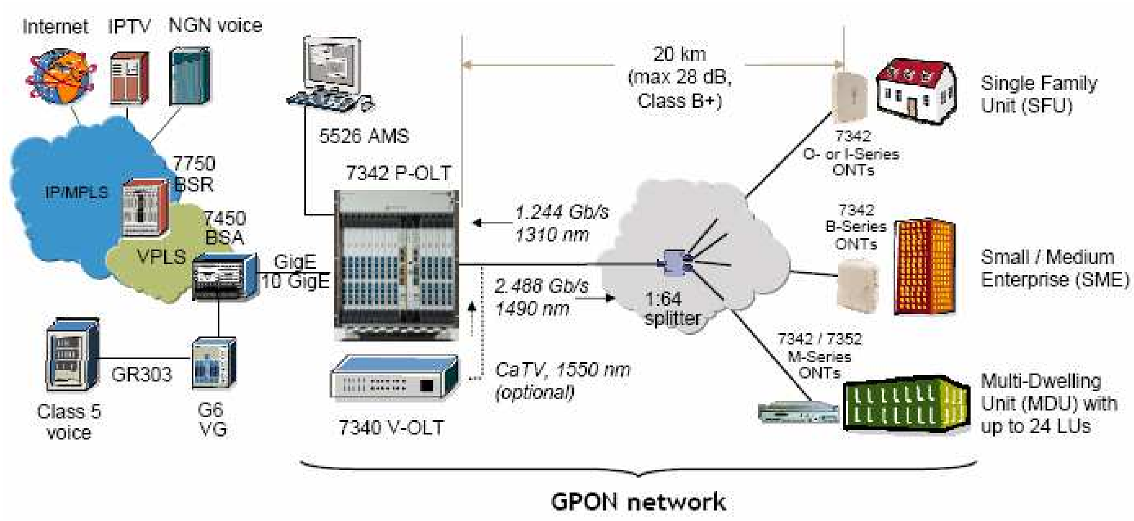

Figure 3-2: GPON network architecture

The downstream protocol is composed of contiguous frames of 1.25 µs. Each frame includes a Physical Control Bloc downstream (the header of the frame) and a payload. The payload can include two fields: one is the “Pure” ATM cells section, mostly unused in reality; and a TDM & Ethernet over a GPON Encapsulation Method (GEM) section.

The upstream is built up with bursts. Each burst is a packet sent by an ONT with an adaptation layer. Typically, each packet includes a guard band, a preamble, a header and a payload. At the OLT side a burst mode receiver is used to demodulate the packets. A burst mode receiver has a high dynamic range (close to 20 dB) to be able to detect any packet coming from any ONT. At the OLT side, a short recovery time for the clock (done in less than 26 ns), and can support long sequences of identical bits (CID >= 72 bits).

Wavelength Division Multiplexing (WDM) PONs

Wavelength division multiplexing (WDM) PONs are extensively researched as a potential technology for next-generation PONs (NG-PON) [5],[6]. They are considered to be an ideal solution for extending the capacity of PONs without drastically changing the currently deployed PON structures. Currently, WDM-PON standard contributions are prepared. A more recent evolution is the combination of TDM-PON with WDM-PON, resulting in a – either long-reach or not – hybrid WDM/TDM PON.

Section 5 gives a more detailed description of a pure WDM- PON architecture and two different implementations of a hybrid WDM-/TDM PON, both enabling dynamic capacity allocation. General techno-economic considerations and some preliminary results are provided for these architectures.

3.1.3 Radio-over-fibre networks

A Radio-over-Fibre (RoF) system is a fibre-fed distributed antenna network [7], and can be considered as a hybrid fibre/wireless technology. It is fundamentally an analogue optical transmission system because an optical fibre distributes the radio waveform, directly at the radio carrier, from a master unit to a remote antenna unit (RAU).

RoF technology can be used for implementing a Distributed Antenna System (DAS), resulting in a Fibre-DAS (F-DAS). DAS extends wireless coverage for multiple operators from multiple Base Transceiver Stations (BTS) to multiple locations and provides high coverage uniformity with low radiated power. Furthermore, F-DAS enables future proofing, supports multi-band, multi-operator in-building coverage, allows flexible cell-splitting for evolving capacity needs and planning requirements, and cell shaping with handover minimization.

Section 6 gives an indication of the extra equipment needed in a PON architecture to implement RoF over it for deploying a mobile access network.

3.2 Existing techno-economic studies for comparing FTTH architectures

A variety of techno-economic studies for comparing different FTTH architectures can be found in literature. However, based on their origin and the considered scenarios, many differences can be noticed and they have to be analysed in a critical manner. In this section, we make a distinction between research-based studies (with no or little commercial involvement) and the more commercial tinted studies, written by a company. We end this section with some general conclusions and trends.

3.2.1 Research-based studies

Towards Technologically and Competitively Neutral Fiber to the Home (FTTH) Infrastructure [Carnegie Mellon University, 2003]

This study is performed by Carnegie Mellon University in 2003, and gives a clear overview of the differences between a Home Run, Active Star and PON architecture [8]. Further this paper mainly focuses on different competition models for FTTH and the viability of each architecture for the mentioned forms of competition.

In addition, there is also performed a techno economic analysis to quantify the obtained results. The CapEx per home passed for the Home Run, Active Star and the PON architecture for each of the deployment scenarios (urban, suburban, rural), assuming a community being served by one CO, is shown in Figure 3-3. The necessity of deploying all the fibre up front, with its attendant construction costs makes FTTH a decreasing cost infrastructure with penetration. The PON appears to be the most economical FTTH architecture. For very low levels of penetration the Home Run architecture is significantly more expensive as more fibre needs to be pre-positioned in the Home Run case, while for high levels of penetration the cost difference drops to about $ 200 (at 100% penetration) per home in an urban deployment. The Cost per Home Passed (and Served) is sensitive to loop lengths especially for the Home Run architecture which has much higher costs than PON in rural areas (particularly for low penetration levels).

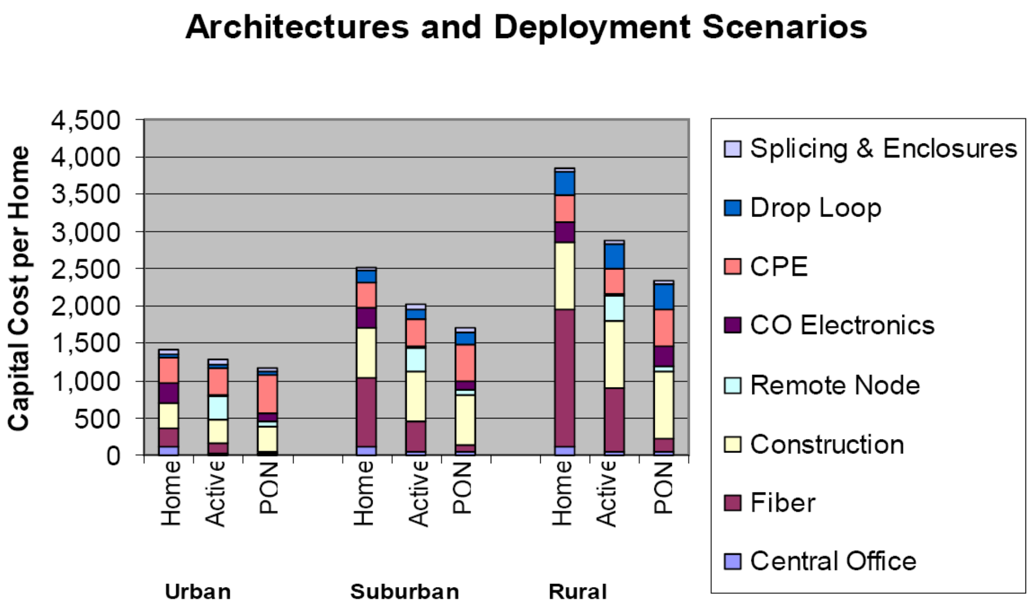

Figure 3-3: Breakdown of Capital Cost per Home for FTTH architectures [8]

PON advantages are clearly proved in this paper, and the largest influence is noticed in a rural area mainly due to the fibre and construction (i.e. civil works) costs. However, as fibre costs are drastically reduced during recent years, a similar study today could give smaller differences between the scenarios. But it is certainly true that a rollout in (less-populated) rural areas is more expensive due to higher fibre and digging distances. Note that for construction, a combination of digging and aerial rollout is considered in this study. For a rollout with 100% digging the construction cost would be much higher, as will be shown in further studies.

Techno-Economic Comparison of different architectures of Optical Access Networks [UPC, 2005]

In this study, performed at Universitat Politècnica de Catalunya (UPC) in 2005, five different FTTH architectures are analysed [9]:

1. *P2P – 2 fibres Network*: it has two fibres for every connection, which gives the complete bandwidth of the network for every direction.
2. *P2P – single fibre Network*: it is also a P2P architecture but with only a single fibre between the OLT and the ONU. It uses two different wavelength lasers for downlink and uplink directions in order to eliminate the Rayleigh backscattering effect.
3. *Single fibre Power Splitting (PS)-PON*: it is a classical PON in which all ONUs receive the same optical signal, therefore multiplexing user's transmissions in time.
4. *CWDM – PS-PON with reflective ONU*: it uses M Distributed Feedback (DFB) lasers in the OLT to address through the AWG a specific power splitter, creating a virtual PS-PON for every wavelength.
5. *Multi-FSR WDM-PON with reflective ONU*: it uses tuneable lasers in the OLT to select the output port of the MxM AWG in the OLT as well as the 1xN AWG output port, which connects to a single ONU, where data is sent [10]. This architecture uses the Latin Routing

characteristic of the AWG in order to have more flexibility when transmitting information to different users.

Figure 3-4 shows the total cost of each of the studied networks with prices from 2005 (referred to as "current") and with some prices estimated for after 2005 (that optical components are expected to have in some years, considering an evolution of the prices of optical components as Moore's Law estimates the cost of semiconductor prices along time). With current prices, PS-PON is the most economic solution. Considering the expected prices of the optical components, the three PONs have very similar costs. If the take rate is high, CapEx per user of the PONs have a third of the price of a single fibre P2P network and a fourth of a two-fibre P2P network. If the take rate is low this difference can be much higher, up to nine times.

Both CWDM-TDM and DWDM, together with the bidirectional reflective transceiver in the ONU have been demonstrated to dramatically lower the CapEx and OpEx per user of the network. If the take rate is low, the difference is even greater, compared to the P2P networks, due to the low cost of the feeder and the sharing of the expensive components along many users. A study of the market bandwidth demand has to be done in order to decide if it is worth implementing P2P or PON depending on the bitrates required. Comparing the two WDM-PONs with the PS-PON, some decrease in the CapEx per user is noticed, with the advantage of having a network with high privacy that PS-PON can only achieve using very robust encryption techniques.

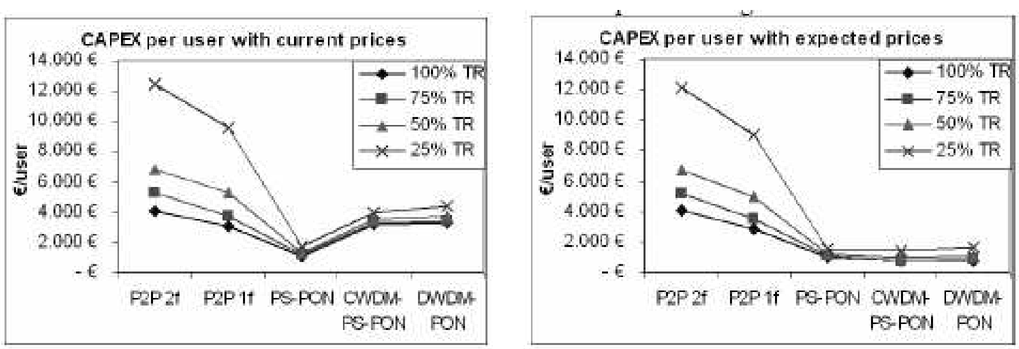

Figure 3-4: Current cost of the networks for different Take Rates (TR). Right: Expected cost of the networks [9]

In conclusion, this study clearly shows some techno economic advantages of PS-PONs and in the near future (if component prices decrease in some years) for WDM-PONs.

A Comprehensive Methodology for Comparing Different FTTP Solutions [National Taiwan University of Science and Technology, 2008]

Owing to the many operational and cost factors involved in designing and implementing any type of PON, it is difficult to make a detailed comparison of different proposed networks. A study, performed in 2008, from the National Taiwan University of Science and Technology presents a method for comparing different Fibre to the Premises (FTTP) solutions using factors such as information capacity, subscriber number, network flexibility and growth potential in order to select an optimum network design [11].

Five different FTTP architectures were compared:

1. *Point-to-point architecture*: The simplest FTTP network is based on using individual point-to-point fibres to connect subscribers to a CO. There is either one bidirectional or two unidirectional fibres running between the OLT and each subscriber. This architecture uses a large quantity of fibres, but is advantageous if the bandwidth demands of each subscriber require use of close to the full capacity of the connecting fibre link.

2. *Regular PON architecture*: Here a single bidirectional feeder fibre connects a CO with a passive optical power splitter and combiner, located at a remote node (RN). Individual distribution fibres run from the RN to subscriber locations. The regular PON architecture uses TDM for downstream (CO to ONU) and upstream (ONU to CO) transmission.

3. *Regular WDM-PON architecture*: In this architecture, a wavelength router such as a passive arrayed-waveguide grating (AWG) replaces the optical splitter at the remote node. This configuration allows each subscriber to use one or two (for up- and downstream) wavelengths for their transmission.

4. *Regular DWA WDM-PON architecture*: A regular Dynamic Wavelength Allocation (DWA) WDM-PON is a block-free architecture that uses tuneable lasers. A major advantage of this architecture is that it allows more network flexibility to assign services to subscribers, since each subscriber can receive several wavelengths. In addition, the bandwidth efficiency is increased.

5. *Cascaded TDM-WDM PON architecture*: In this architecture the traffic passes through a cascade of a wavelength router and an optical splitter. It combines the TDM techniques of a regular PON with the capacity expansion capabilities of a WDM PON. An AWG separates a multiple-wavelength stream coming from the CO into a number of individual wavelength channels. Each channel then serves a cluster of subscribers using the TDM scheme of a regular PON. The use of coarse WDM (CWDM) is considered.

Figure 3-5 shows the maximum span distances for the various FTTP types based on the projected bandwidth requirement for future years. It is found that using the regular PON or cascaded TDM-WDM PON architecture with PIN receivers, information cannot be transmitted within the 12-year window at the desired 1 Gbps data rate. However, if every receiver of the subscribers changes into an avalanche photodiode (APD), those two PON types can span almost 20 km.

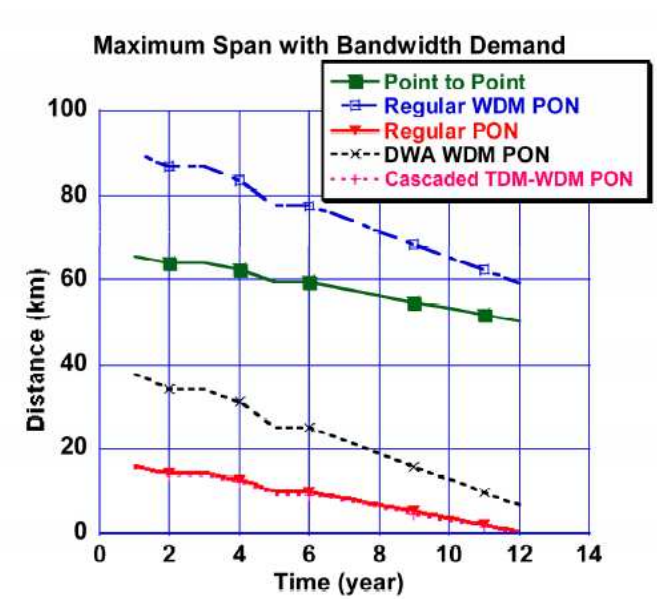

Figure 3-5: The maximum span distance with the PIN receivers [11]

The regular PON is a useful technology currently because it can serve more subscribers on a fibre and can provide enough bandwidth for their required service. However within five or six years, an upgrade of the equipment has to be done. If TDM technology is still used in a regular PON, there would be some problems. First, the optical power budget becomes smaller and we cannot use the original link to transmit the new higher data rate. On the other hand, it also means that we cannot transmit our information over a longer distance. Second, the modulation bandwidth of the light-sources located in

OLT and ONU needs to be externally high. If the data rate of each subscriber is 1.25 Gbps and we provide 32 subscribers at the same time, the modulation bandwidth of each light-source is equal to 40 Gbps. That is hardly feasible and other architectures must be considered.

The regular WDM-PON architecture is a better choice than the others. There are some advantages in the regular WDM-PON, for example, it can provide many different applications in one fibre link and the bit rate is independent of each wavelength. There is no need for the ultra-high modulation bandwidth of each light-source. On the other hand low-speed light-sources can be used to enable our application. However it potentially is more costly. In the regular WDM-PON architecture we need more light-sources in the OLT and each light-source is wavelength specific. More wavelength-stable equipment is needed, which increases the cost when we deploy this architecture. Thus, a future task for engineers to solve is to create inexpensive colourless light-sources for this application.

The costs of deploying fibre-based next-generation broadband infrastructure [Broadband Stakeholder Group, 2008]

This study, made by the Broadband Stakeholder Group in 2008, provides a detailed analysis of the deployment costs involved in deploying fixed-line infrastructure to provide next-generation broadband services in the UK [12]. It is based on realistic assumptions that are detailed, clear and transparent and has been modelled on geographical data specific to the UK. The research has been informed and validated by the key commercial players, including network operators, technology vendors, deployment specialists and other industry experts.

The cost model considers three different technological options for the provision of next-generation broadband services:

1. *FTTC/VDSL*: Fibre to the Cabinet (FTTC) using VDSL involves laying fibre-optic cables to street cabinets. Such cabinets are typically within a few hundred metres of the customer premises. Active equipment is then deployed in the street cabinet that connects to the customer premises using existing copper cables. Depending upon the length of the final copper line, download speeds of 30–100 Mbps can be expected.
2. *FTTH/GPON*: FTTH using GPON involves laying fibre-optic cables directly to the customer premises. Each fibre is theoretically capable of providing up to 2.5 Gbps of download bandwidth to the customer premises. However, this bandwidth is typically shared between more than one customer.
3. *FTTH/PTP*: FTTH can also be deployed using point-to-point (PTP) fibre connections. By using this technology each customer premises has a dedicated fibre that using current technology is capable of supporting symmetric connections of up to 1 Gbps.

The total costs for connecting 100% of the population using each technology are shown in Figure 3-6. Deployment costs for FTTC/VDSL are dominated by fibre and cabinet costs. It can be seen that both types of FTTH are dominated by the costs of civil works, which also represent the area of greatest difference between the two: The key differences between the two FTTH technologies are in the costs of civil works.

This work has shown that the costs of deploying FTTH are of the order of five times the costs of deploying FTTC, and that the costs of deploying FTTH/PTP are around 15% higher than for FTTH/GPON.

In a market where the business case for any of the technologies is not clear cut, and the availability of funds for investment is uncertain, FTTC/VDSL is likely to be the main technology in the medium term. This is consistent with the strategy announced by British Telecom (BT) on 15 July 2008.

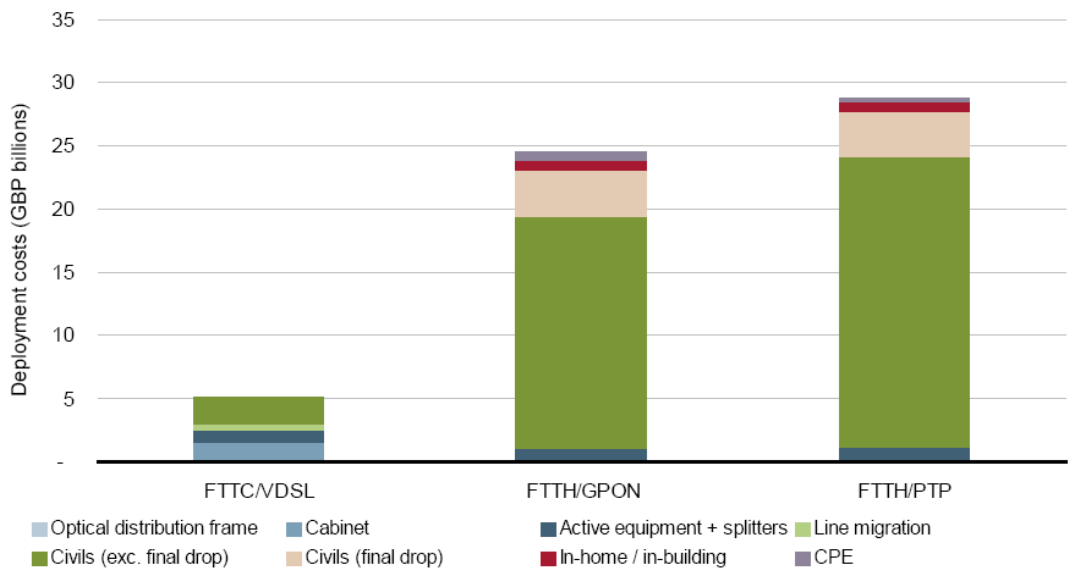

Figure 3-6: Costs for nationwide coverage of each technology [12]

3.2.2 Commercial driven studies

Comparing EPON with WDM TDM PONs [ETRI, 2006]

In a study from ETRI, dated from 2006, a techno-economic analysis for WDM/TDM PON is given [13]. ETRI compared a PON with a WDM/TDM PON and showed that the exploitation of the WDM dimension could be interesting in terms of cost.

Figure 3-7 shows the architecture of the WDM/TDM PON studied by ETRI. At the ONU side each subscriber is connected to a specific wavelength. The tuneability is blocked by the optical multiplexer used before the transmission line. Each wavelength is shared among a group of 32 users through a Time Division Multiple Access (TDMA) technique. The number of wavelengths is a parameter that can be changed with respect to the capacity needs. After the optical demultiplexer, all the wavelengths are multiplexed and sent into a transmission span of 10 – 40 km. At the end, an optical demultiplexer separates the wavelengths that will be demodulated in the switch of the CO after an opto-electronic conversion.

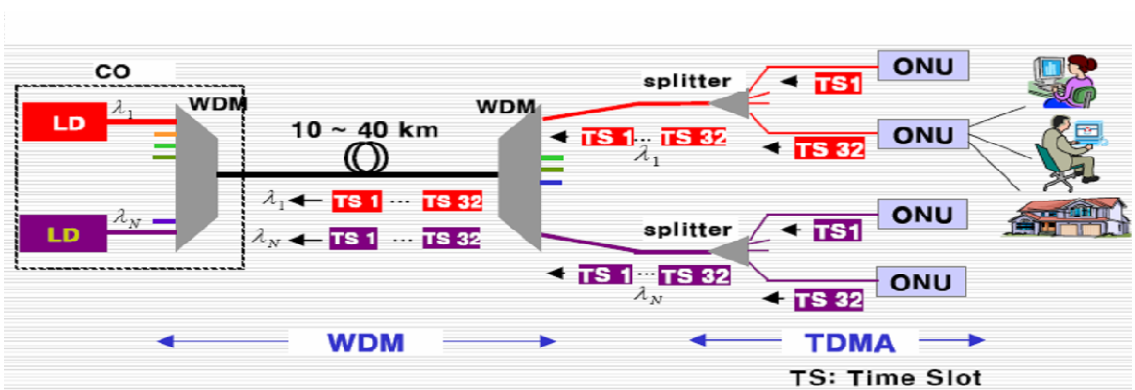

Figure 3-7: Architecture of the WDM/TDM PON studied by ETRI [13]

ETRI made a comparison between different solutions: E-PON, pure WDM PON, WDM Ethernet PON (WDM/TDM PON) for 16 and 32 wavelengths. Figure 3-8 shows the cost per channel of the considered architectures. The conclusion is that the total cost per channel of the WDM Ethernet PON with 32 wavelengths solution is very close to the Ethernet PON solution for the same minimum guaranteed bandwidth: 31 Mbps indicating that the WDM dimension can be very efficiently provided if it is combined with a TDMA technology. Otherwise, without using TDMA, the cost explodes as can be seen for the pure WDM solution. In the case of one dedicated wavelength per user, the access bit rate is much higher but because of a poor cost sharing, the total cost per channel per user is higher. The channel cost for a WDM PON is 504 $ with respect to 212 $ for the Ethernet PON.

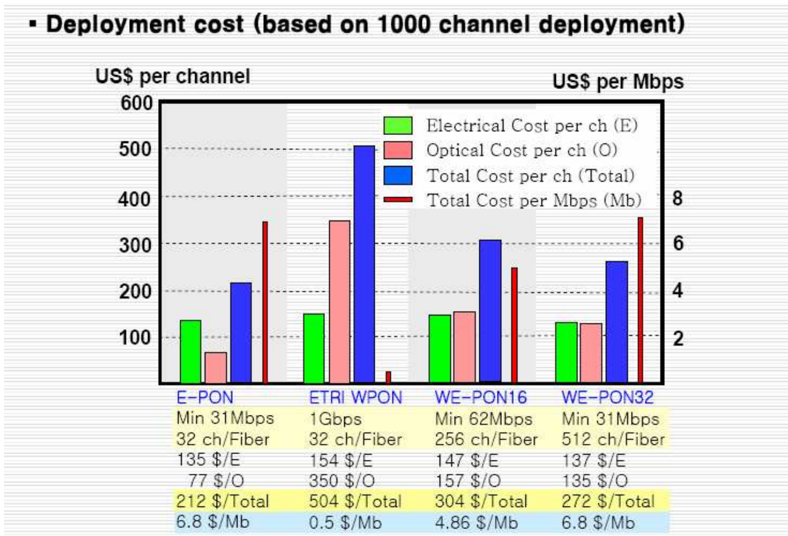

Figure 3-8: Cost analysis when comparing E-PON, W PON and WE PONs [13]

FTTH Network Economics: Key Parameters Impacting Technology Decisions [Bell Labs, 2008]

In a study from Bell Labs presented in 2008, a detailed analysis of FTTH economics across a range of different scenarios and parameters was developed comparing P2P, Active Ethernet and GPON [14]. If we compare a P2P versus an AON versus a PON architecture we can have the following tendencies:

- Point-to-point networks require 1 fibre per subscriber and many transceivers (2n). The advantage is that there is no active device in the field.
- AON networks have less fibre, but 2*(n+1) transceivers and active equipment in the field.
- PON networks have less fibre, les transceivers (n+1) and passive equipment in the field.

A business case has been studied for a German city: P2P and Active Ethernet vs. GPON. Results for some real-world customer modelling case studies were presented with sensitivity analyses. They are summarized as follows

1. *GPON vs. P2P network*

   Over a wide range of take rates and parameters, GPON provides lower CapEx/subscriber and OpEx/subscriber compared to P2P. This is primarily due to the significant outside plant (OSP) fibre investment needed on Day 1 for:

   - P2P. Average savings: CapEx = 20% and OpEx = 55-60%
   - 2-Tier GPON is more cost effective than 1-Tier (for Multi Dwelling Unit (MDU)) by 0-10%.
   - The specific results above apply to an example case of an overbuilt FTTH network deployment in MDU, but this study shows GPON savings apply to an urban/suburban Single Family Residential (SFR) deployment case as well.

Sensitivity analysis shows that the Top-3 parameters impacting CapEx are: (1) Fibre cost per meter, (2) GPON CPE cost and (3) Ethernet switch cost, and that the Top-3 OpEx parameters are: (1) Right-of-Way, (2) Cost of energy and (3) Fibre maintenance

2. *GPON vs. Active Ethernet network*

Here an operator may consider serving FTTH subscribers directly from the Digital Subscriber Line Access Multiplexer (DSLAM) chassis. In such situations, the economics of Active Ethernet (AE) and GPON will change considerably.

- An Ethernet card in the DSLAM is expected to provide a cost effective solution for FTTH in low or medium fibre deployment situations (take rates ~ 10-20%).
- The CapEx/subscriber difference between GPON and AE are small (<5%), but OpEx/subscriber is a big differentiator. GPON provides OpEx savings from 5-58% with higher savings for increasing take-rates.

In areas where no DSLAMs are deployed, GPON is expected to be more cost effective in general because of the additional cost of building the OSP cabinets for AE (Figure 3-9) and significant OpEx savings from a passive outside plant.

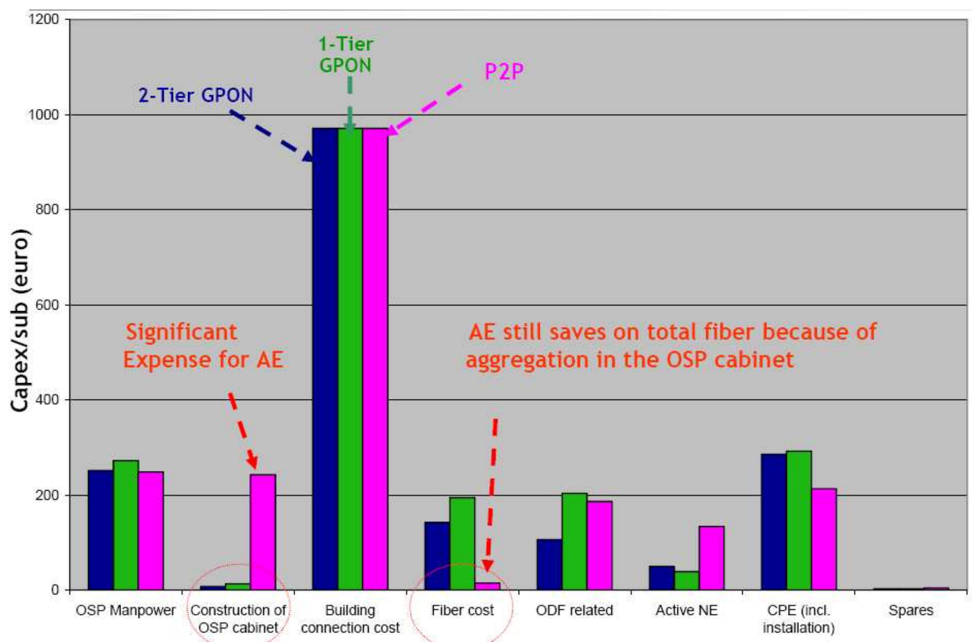

Figure 3-9: CapEx breakdown for GPON vs Active Ethernet (20% take rate) [14]

Because of a very low power consumption of the PON solution (since no active elements are in the field), this technology is positioned as a very attractive solution especially at the OpEx level. Figure 3-10 gives different OpEx terms in Euro per subscriber per year for GPON and AE. Right-of-Way and customer care are two other OpEx terms that are mentioned in the study from Bell Labs, but which are not depicted on Figure 3-10 since their value will be very case specific.

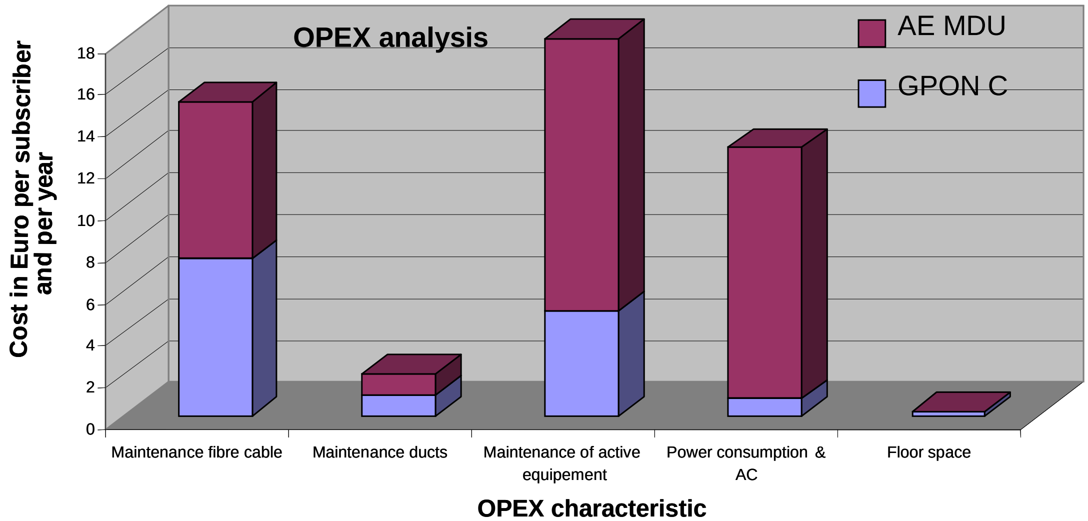

Figure 3-10: OpEx comparison between GPON (Class C) vs. Active Ethernet (used for MDUs) [14]

The conclusion is that the difference in CapEx between the technologies can be ignored, however the OpEx is in the ratio of 1:2 for GPON due to a lower maintenance cost of devices and a global lower power consumption.

Fiber to the Home: Technology Wars [Cisco, 2008]

In a study from Cisco, performed in 2008, the merits of the two main technologies competing for FTTH (GPON and Ethernet point-to-point (PTP)) are examined to determine which solution offers service providers the best competitive advantage [15].

- Many companies are using GPONs, such as Verizon in its fibre optic service (FiOS) rollout in the United States. Incumbent service providers in Europe, such as France Telecom, are also considering GPON networks.
- While Ethernet P2P costs more up front (more fibre strands deployed, larger points of presence, and so on), its performance is superior to that of GPON.

While the cost differences between Ethernet PTP and GPON are minor (Table 3-2), they are overshadowed by PTP's ability to help service providers differentiate their offerings. PTP provides customers with superior peak performance today and a simpler upgrade to even higher speeds tomorrow. Ethernet PTP, by virtue of its simpler topology, should, therefore, be considered the technology of choice for service providers in competitive market situations.

Table 3-2: Project Costs of Ethernet PTP versus GPON (the data represents the net present value (NPV) of costs over 10 years for a large European city) [15]

Variable and Hypothesis Being Tested	Scenario	PTP Cost ($M)	GPON Cost ($M)	PTP Cost as a % of GPON
Degree of civil works (when ducts are limited, GPON is favored)	· Plenty of ducts (little civil works needed for both)	137	130	+5%
	· Limited ducts (more civil works needed for PTP)	163	130	+25%
	· No ducts (civil works needed for both)	210	205	+2%
Customer density (as density falls, GPON's advantage increases)	· High-density urban areas	54	53	+3%
	· Low-density urban areas	84	79	+6%
Bandwidth (increased performance favors PTP)	· 10 Mbps upstream	137	130	+5%
	· 100 Mbps upstream	137	152	–10%

Source: Cisco IBSG Economics Practice, 2007

3.2.3 General conclusions

From the different studies in this section, it is possible to deduce some general trends:

- Although it is only briefly mentioned in this section (cf. studies from Broadband Stakeholder Group and Bell Labs), it has to be stressed that the costs for an FTTH rollout are dominated by the civil works (digging), so that the cost of the technical solutions represents only a fraction of the overall cost (typically 50%, in an urban zone). Other examples will be given in section 3.3 about the introduction of FTTH in different European countries.
- A PON typically has some cost advantages compared with Active Ethernet or AON, but what is often not mentioned is that an AON will have a higher service level and more opportunities for delivering redundancy and allowing competition.
- Introducing a WDM dimension in a PON network seems very favourable for next generation PONs. This is only a very recent trend, five years ago (in 2003) [8], WDM PON was only briefly mentioned but considered as totally unfeasible , while this perception is really changed over the last years.

We need, however, to be careful when comparing different techno-economic studies of access networks with different technologies. The different papers show a broad range of absolute cost figures, each within its own restricted application area (setup of the scenarios, input costs, etc.). E.g. in the study of Bell Labs we find an operational difference between PON and P2P, mainly caused by right of way, power consumption and fibre maintenance. Some questions that arise about this study are:

- Right of way is a dangerous cost to compare solutions because it is really depending on the circumstances. It is difficult to see a difference in a right of way between a PON and a AON network as the same network topology is used for the installation.
- Power consumption for AON is generally higher than the power consumed for a PON network, albeit not at the same bandwidth. The question here is how much this power consumption for one user impacts the final result, especially, if there is the possibility to deliver a higher service level.

3.3 Status on the introduction of FTTH in different European countries

To well understand the specificity of each region, we need to describe the business model of each representative country. In this paragraph we will distinguish three cases: France describing a Western European case, Sweden/Denmark for two specific cases in Northern Europe and Poland to have a picture on an East European case.

In each case, we will identify the current market situation, the identified FTTH solutions, some cost studies (if available) and the main tendencies observed.

3.3.1 French case

3.3.1.1 Broadband market in France

The market in France for high bit rate or broadband Internet (defined as everything above a dial-in connection) is as follows [16]:

- 16,7 M subscribers for broadband Internet access (mainly ADSL technology, next to a limited number of FTTH and Cable subscribers)
- 8,7 M subscribers from France Telecom and 8 M other subscribers, including 5,7 M using local loop unbundling (LLU) of which 4,3 M use full LLU (i.e. where the operator takes over the line in its entirety, rather than for broadband only).

We distinguish two areas in France (see Figure 3-11):

- Areas managed essentially by France Telecom (zone in grey)
- Areas where one competitor has at least an unbundled zone (zone in blue)

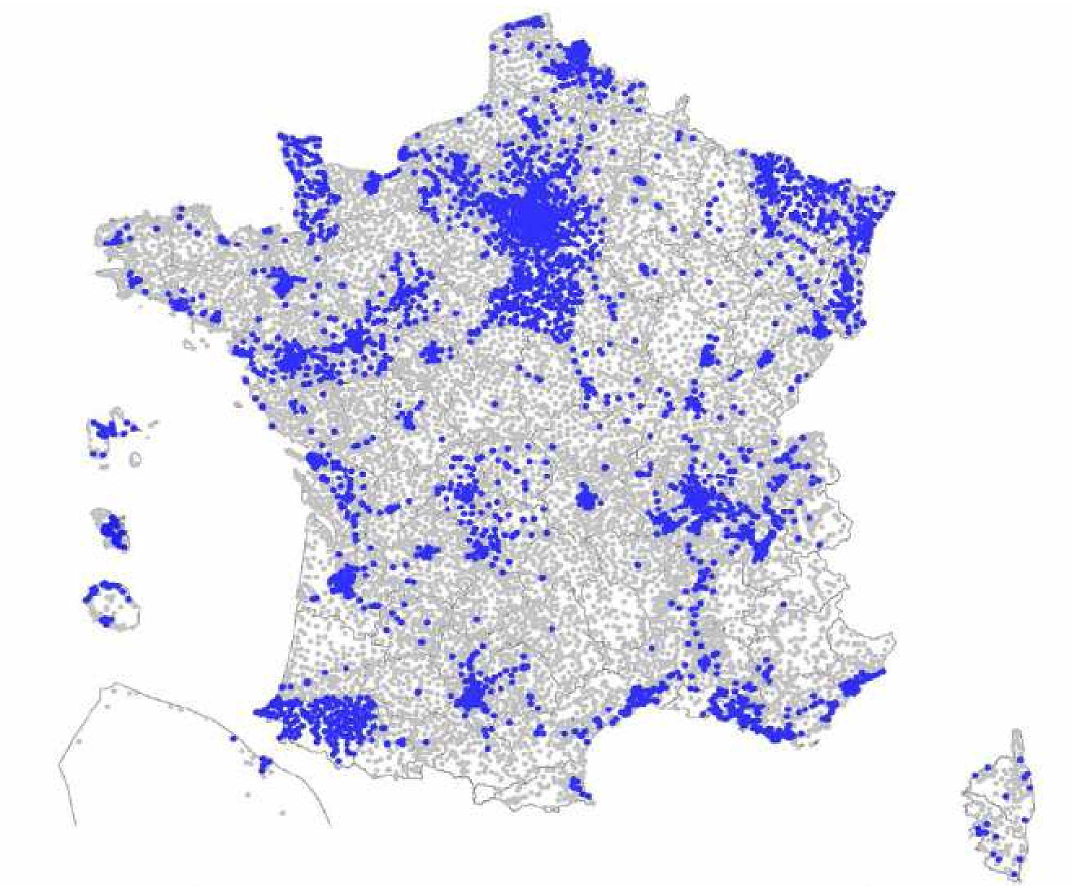

Figure 3-11: Picture of the broadband Internet penetration in France

Most broadband Internet connections in France are provided by ADSL (i.e. ADSL and ADSL2+), and the French ADSL market is shared between different service providers. The network consists of 13727 NRAs (Nœud de Raccordement Abonné, i.e. Central Offices where the DSLAM is located) and 35,471 M lines connected [17].

As mentioned in ALPHA Deliverables D1.1 and D1.2, there is a diversity of predictable high bit rate applications leading to the need for a multi-service network offering high bit rates [18],[19]. Furthermore, these high bit rates should be offered at low cost for everybody (notion of fairness). The problem of ADSL is its limitation in bit rate (< 25 Mbps) and its incapability to offer the same bit rate to different subscribers located at different distances from the CO. As mentioned in ALPHA Deliverable D2.1, FTTH is positioned as a potential technology to meet the above requirements.

The increasing importance of broadband Internet access is illustrated in Figure 3-12. For the fixed lines, the revenues in France are split into three categories: Low bit rate access revenues, high bit rate or broadband access revenues and other revenues. Figure 3-12 shows the evolution of these revenues between 2007 and 2008:

- The low bit rate access revenues include the contract and communication in the public switched telephone network (PSTN), and the low bit rate Internet access.
- The high bit rate or broadband access revenues include the contracts and the communications over IP, plus broadband Internet (ADSL).
- The other revenues include the public Telephony, the (prepaid) cards, and other revenues linked to an Access to the Internet.

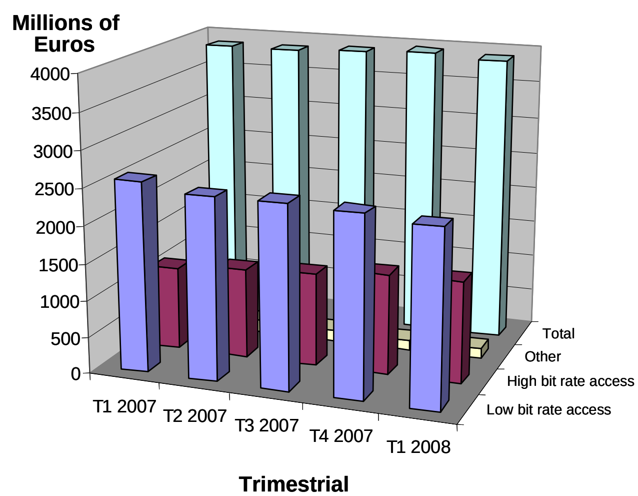

Figure 3-12: Evolution of the revenues between 2007 and 2008 in France

We observe that the global market is quite stable. But we observe also that the revenues for high bit rate or broadband Internet are constantly increasing (22,5% of increase in one year) whereas the revenues of the low bit rate access are decreasing (decrease of 8,3%). We can conclude that broadband access has an increasing demand in France.

3.3.1.2 Chosen FTTH architectures & technologies in France

Both PON and point-to-point architectures are available in France. The incumbent operator France Telecom has adopted GPON for its FTTH rollout, while the competitive carrier Free uses a home run fibre infrastructure for its rollout in Paris. A third important FTTx player in France is Neuf Cegetel, which mainly offers Fibre to the Building (FTTB) by a point-to-point architecture. In addition, there are also a lot of local network initiatives which are a kind of catalysts to push higher bit rates.

3.3.1.3 Cost study for an FTTH rollout in France

When analysing more in detail the deployment of the FTTH technology we can observe that in France the deployment is not as fast as wished. In this paragraph we will analyse the different costs for deploying an FTTH network.

The ARCEP («Autorité de Regulation des Commnications et des Postes») gives an example of costs for a FTTH technology in a city of 20 000 inhabitants/km², for an operator interconnecting 25% of the subscribers [20]. The given cost figures are shared into six categories: the civil works & buildings, the optical cables, the installation in the building, the interconnection, the active elements of the network (containing the OLT) and the active elements at the subscriber side (the gateway). The two highest costs are: the civil works and the internal cabling. Note that more than half of the total costs comes from the civil works.

One conclusion is that the cost of the active elements is negligible in front of the civil works, and that many technologies can find their place in the FTTH deployment. The civil works are a brake for the fast deployment, but also the required regulation imposes some new constraints. The need for new regulatory rules, however, is not the only brake to a rapid deployment of the FTTH technology. When we have a look to the cost of the FTTH deployment for different population density zones the conclusion is not in the favour of a rapid deployment.

Cost studies have been made for different population densities and are shown in Figure 3-13:

- Case 1 (Paris): High dense building, with a population of 20 000 inhabitants/km², 20 flats per building on average, and a capacity of 7500 lines.
- Case 2 (Lyon): Urban case, with 5000 inhabitants/km², 6 flats per building, and a maximum capacity of 15000 lines.
- Case 3 (average city): A house context with 2500 inhabitants/km² and an average capacity of 2500 lines.

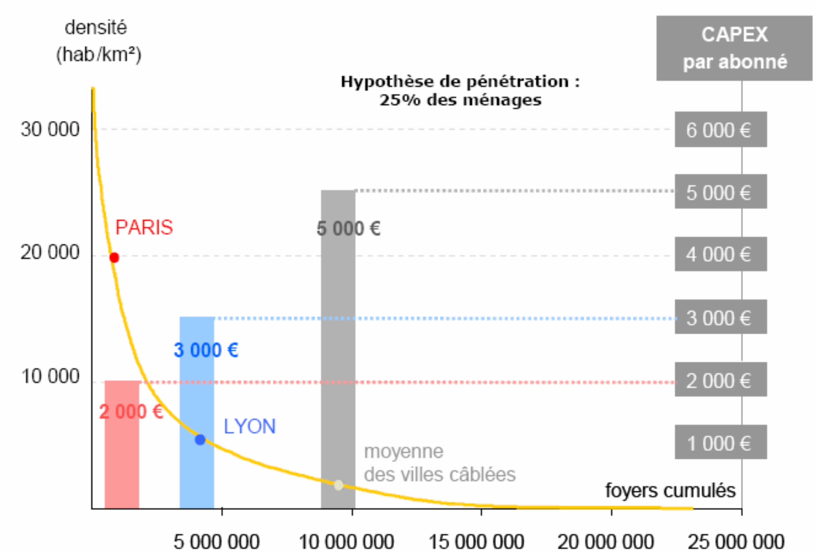

Figure 3-13: Cost studies for different French cases [20]

The first analysis showed that the civil works are impacting strongly the overall cost, which means that the rural zone will be severely penalised. From Figure 3-13, we can conclude that the cost of the civil works is becoming more and more important when the population is less and less dense. For the rural case, the civil costs are close to 80% of the total cost per subscriber.

3.3.1.4 Main tendencies observed

For offering the FTTH technology, the operator needs to invest a minimum of 1500 € per subscriber. To relate this number to the current ADSL network, take into consideration that each 10 € of OpEx, used for an ADSL line, offers a capacity of investment of 1500 € (over 30 years, at 7% of interest).

Taking into account the penetration ratio, the maximum possible investment per subscriber can be even lower than 1000 €. An FTTH deployment remains possible, but limited. Note also that France is not only Paris. The sharing of the population in France shows that there are 30610 small cities in the rural part, representing 25% of the total population of France. These figures indicate that a specific business plan must be found to deploy the FTTH technology everywhere in France.

Since in France the average for the different city sizes is close to a building of 4 floors the configuration is not favourable to the rapid deployment of the FTTH technology. Figure 3-14 shows the deployment foreseen in the next years in France, essentially focusing on the big cities.

Figure 3-14: Map of France showing the probable penetration ratio in the next decade

FTTH will be deployed, but it will take a long time due to the specifics of the country. The operators have started their deployment and the competition is present. The operators are targeting the most economical zones for the moment, but there is a risk of unfairness with respect to the rural case.

Furthermore, the ultra high bit rate in the buildings imposes a modification of the rules for the co-owners, a modification of the rules in the building, a modification of rules in the Posts and Electronic Telecommunications (modification of the local loop, access to the infrastructures of the incumbent operator France Telecom in the local loop, access to the infrastructures in the networks interconnected). So, there is a need to create new regulatory rules, which takes some time.

The circle C.R.E.D.O. («Cercle de Réflexion et d'Etude pour le Développement de l'Optique») gives some necessary keys to the project plan, the conception and the realisation of the FTTH technology in a new context [16]:

- Rules of engineering and dimensioning adapted to France.
- Choices of an infrastructure adapted to the needs and coherent with a competitive market.
- Rules for a rapid deployment and revenues adapted to a massive deployment.

3.3.2 Swedish case

3.3.2.1 Broadband market in Sweden

Broadband penetration

Sweden has a strong tradition within ICT and broadband. The first FTTH installations were rolled out in the late 90's, and in 1999 almost 50% of Swedish broadband households had FTTH, which was world leading by then. Sweden is now surpassed by Korea and Japan that have a much higher FTTH penetration. Concerning broadband as a whole, Sweden is no. 8 in broadband penetration per 100 citizens worldwide [21]. Broadband is here defined as "always connected" with no requirements on bandwidth.

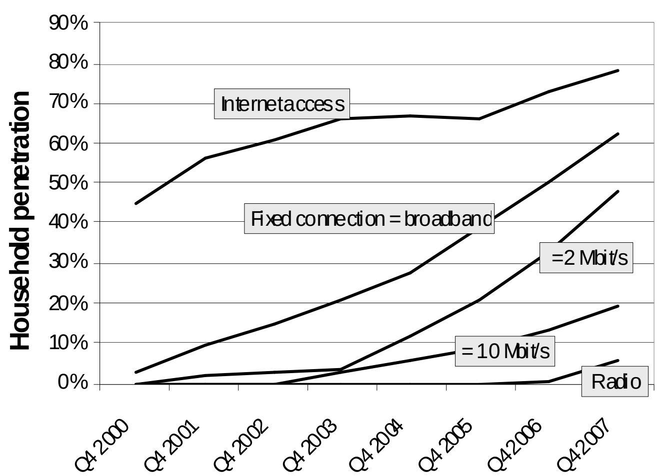

Figure 3-15: Internet and broadband penetration in Sweden, per household [22]

Sweden's broadband and Internet penetration per household since year 2000 is shown in Figure 3-15 [22]. Observe that the Internet penetration is getting slightly saturated while broadband shows no such signs. The Internet penetration by Q4 2007 was 78% and slowly growing while the total broadband penetration was 62%. This should be compared to Korea that with 94% (2006) has the highest broadband penetration by far per household worldwide [21] and still slowly growing. Note that 48% of broadband subscribers have at least a 2 Mbps connection (downstream) and that 19% of the subscribers have a connection of 10 Mbps or more.

Access technologies in Sweden

The dominating access technology in Sweden is digital subscriber line (DSL), primarily ADSL and ADSL2+, with a share of 61% of the total broadband subscribers [22]. This is followed by Cable with 22% and local area network (LAN) with 18% (almost exclusively fibre-to-the-home/building, FTTH), see Figure 3-16 which even shows the development since 2000. See also [23] for more information. There is furthermore a small but rapidly growing share of fixed wireless access, primarily through 3G but also a few WiMAX deployments. The tendency is that all access technologies are growing, however at the moment DSL is growing faster than the others in numbers while FTTH is growing faster in percent.

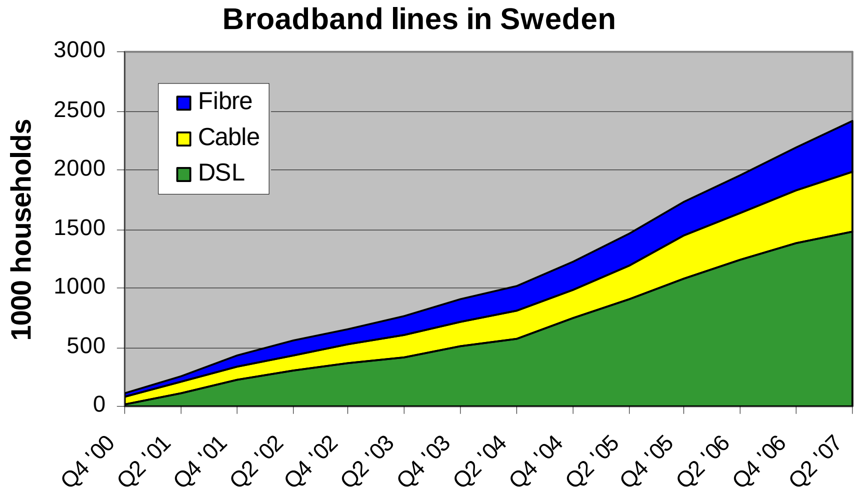

Figure 3-16: The share of deployed broadband connections for different access technologies in Sweden from 2000 - 2007

3.3.2.2 Chosen FTTH architectures & technologies in Sweden

The dominating FTTH technology is AON, a.k.a. active Ethernet or point-to-point Ethernet. AON is "born" with 100 Mbps symmetrical connections, but subscribers often pay for (and receive) a smaller bandwidth (typically 10 Mbps). PON is only rarely deployed, but is likely to grow.

The majority of Sweden's more than 150 municipality networks and a large fraction of the housing companies are using the so-called "open access network" model where the roles of the service provider and the network owner are separated, and where the service providers should get access to the network and thereby the end customers on "fair and non-discriminatory conditions". This should be compared to the traditional vertically integrated business model where the service provider and the network operator are the same (the case for virtually all incumbent operators).

<u>*The open access network*</u>

An integral part of the Swedish information technology (IT) politics has been to separate the roles of a network operator and a service provider for networks receiving public subsidies. There are two main reasons for that: Public subsidiaries for national infrastructure build-out require open networks in order to avoid conflict with EU legislation; and it is envisioned that such open networks will benefit the end user, the industry and eventually the society:

- The end-user can freely select the service from a given service provider that offers the most attractive conditions, and he can combine different services from different providers.
- The service provider gets a chance to reach many users without having to own or operate infrastructure or active equipment.
- Competition will stimulate growth and enable public services to be more easily offered to the end-users which in turn will benefit the whole society.

A network is called an open network if:

- The ***network operator*** and the ***service providers*** are separated.
- The relationship between an ***end-user*** and a ***service provider*** depends on mutual agreements.
- The ***network operator*** is not involved in that relationship beyond the connectivity service.
- All ***end-users*** can choose a service from all ***service providers*** over the common infrastructure operated by the ***network operator***.

Open networks are also called operator or service neutral, multi-operator network etc. Most municipality networks in Sweden are built as open networks, however with slightly different business models and different degrees of openness. Also many new residential area networks are built as open networks. An open network puts more stringent requirements on interfaces and standards and/or practices – both from a technically and a business model point of view – because the different functions are separated between different organizations. The open network model is generating interest abroad and has inspired other installations primarily in Europe.

Functions when operating municipality networks

The main functional layers in operating a network are seen in Table 3-3. The table exemplifies different implementations of municipality networks (muni nets) in Sweden. In an open network a neutral part is appointed the role as communication operator (CO) by the infrastructure owner - typically a municipality or an estate owner. The role of the CO is to open the network to several service providers and TV suppliers in order to assure competition and with the intention to reduce prices and shorten the subscription period. Typically the CO owns the active equipment in the network – this includes routers, switches and transmission equipment.

Table 3-3: The functional layers in operating a municipality network (muni net). Typical implementations of an open network and vertical integration are shown.

	Open network	Vertical integration	
Operation of service	Several ISPs and SPs	Vertical operator	
Owner of active equipment and operation of connectivity	Communication operator, CO	Vertical operator	
Owner of passive infrastructure	Municipality/ estate owner	Municipality/ estate owner	Vertical operator

In a vertically integrated network the different functions are managed by one organisation, the vertical operator (an incumbent operator is a typical example of a vertical operator). However, also here the owner of the passive infrastructure could be a municipality or an estate owner. Observe that there are hybrids between open networks and vertical integration, and even within open networks as depicted in Table 3-3. For instance – and not indicated in the table – in some cases the owner of the active equipment and the connectivity operator can be separated because the municipality or estate owner owns the active equipment. Also, for large networks there may be an extra layer between the service provider and the CO. This is the service broker that selects, makes agreements and maintains the relations with the service providers. Otherwise, the service broker role is part of the communication operator's responsibility. For muni nets the municipality often acts as communication operator, but the different roles may belong to different organisational units.
A communication operator will typically get a contract of 3-7 years from the municipality or estate owner for operating their networks, and typically the CO will remove old network and transmission equipment and install its own.

Relationships and monetary flows in muni nets

The relationships between end-users, service providers, the communication operator and the infrastructure owner of an open network together with the physical connectivity are shown in Figure 3-17. The service providers (ISPs, TV-suppliers etc) pay the CO to get access to the network or rather the end-users. The end-users pay the service providers for the service, and the CO is *not* involved in this transaction (apart from providing the connectivity). The CO has been appointed by the owner of the passive infrastructure and pays for the rights of operating the network. In the case the infrastructure owner is an estate company, the end-user may live in an apartment owned by the estate company (as shown in the lower left corner of Figure 3-17). Compare that with a vertically integrated network where the service provider and network operator and in some cases also the infrastructure owner are identical. The left figure also gives an idea of the business model in an open network.

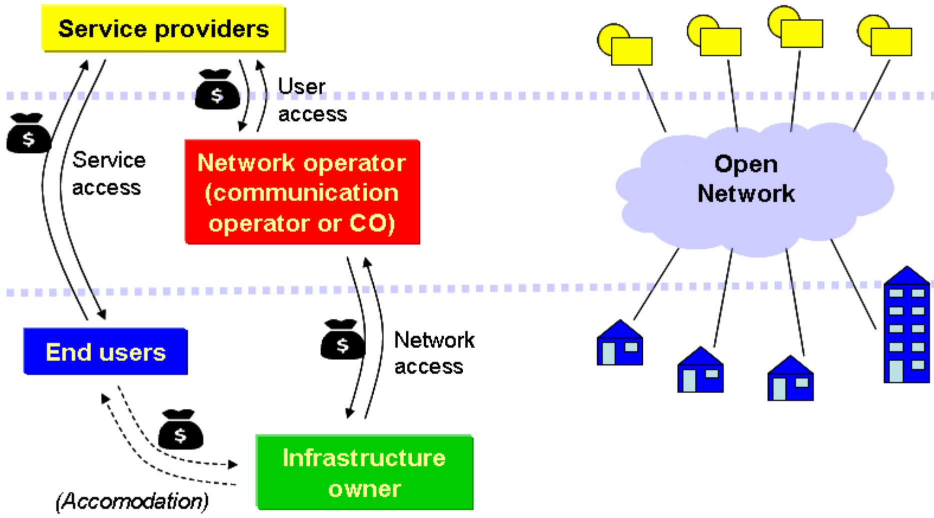

Figure 3-17: The relationships between the different parties of an open network (left) and the physical connectivity of an open network (right)

3.3.2.3 Cost study for an FTTH rollout in Sweden

We had no access to cost data for Swedish open networks.

3.3.2.4 Main tendencies observed

The broadband penetration in Sweden is high (62% and growing with no signs of saturation by the end of 2007), the country is almost in top considering ICT maturity, and the national ambitions are very high. Almost 20% of the broadband connections are FTTH, and 25% of the broadband subscriptions are of 10 Mbps or above – primarily due to FTTH but also from ADSL2+. Virtually all new homes are connected with a fibre, and FTTH is the fixed bandwidth technology that is growing fastest in percent. Most of the new fibre installations are done in “open networks” where the roles of the infrastructure owner, the network operator and the service provider ideally should be separated. Such open networks are very popular in municipality networks and public and private housing companies. The by far most common FTTH technology is point-to-point Ethernet with symmetrical bandwidths of 100 Mbps.

3.3.3 Danish case

3.3.3.1 Broadband market in Denmark

Broadband penetration

In Denmark less than 1% of the population is unable to get broadband access (according to the OECD definition of broadband – if broadband is defined as 2 Mbps the number is 7%). By the middle of 2008 18% of the population in Denmark was able to have fibre based broadband access. This was twice as many as 2 years earlier [24].

As shown in Figure 3-18, it is remarkable that FTTH mainly is provided outside the major cities. In the major cities there is a strong competition from a number of xDSL providers offering 10-20 Mbps for 25 €/month.

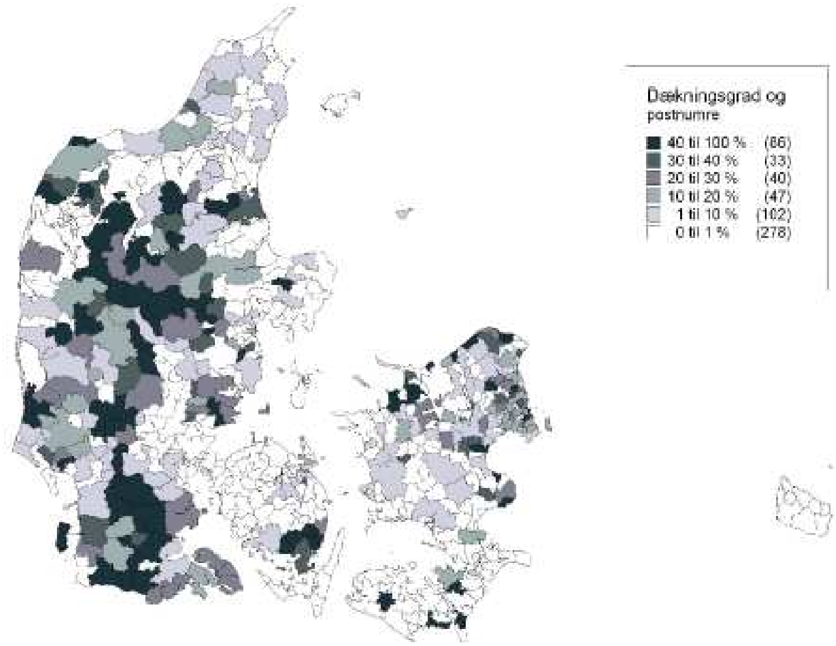

Figure 3-18: Coverage in different parts of Denmark

In Denmark it is primarily the electrical power companies that provides FTTH [25],[26]. The incumbent Danish telecom operator (TDC) is also deploying FTTH whenever they install new copper cables, but they are still not offering FTTH as a service to the customers.

3.3.3.2 Chosen FTTH architectures & technologies in Denmark

In Denmark the different power companies are running 15 different FTTH operators with individual strategies on architecture and technologies. Some of the operators are just providing an IP service open to content providers while other is providing a complete bundle of any kind of triple-play services (sometimes even mobile telephone service).

Initially almost all the FTTH companies decided to base the network on an active star architecture (AON) which was well suited for rural areas that were the initial focus areas, as these areas were characterised by a long distance between customer and local telephone exchange – and as such cannot get high xDSL capacity.

However, recently some of these FTTH operators have changed their strategy towards PON based networks. This change in strategy has mainly been taken by operators with a large uptake and operators aiming at FTTH in large cities. The argumentation is not directly based on cost, but more related to space problem.

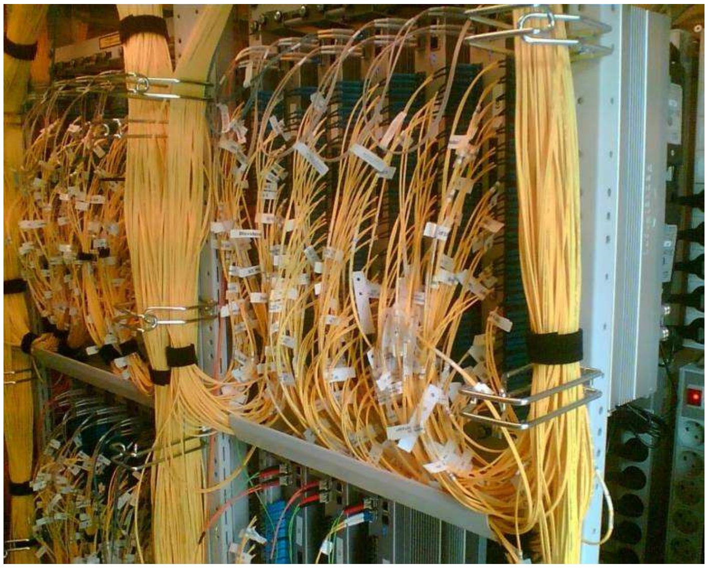

Figure 3-19: Fibre patch panel

As the FTTH operators have there background in power supply companies the FTTH equipment is not placed in the same kind of network locations as commonly used by telecom operators (central office, local exchange, street cabinet, curb well etc.), but rather in transformer building etc.

The physical elements that need to store the fibre patch panels (Figure 3-19) have often shown to be too small and the alternatives has either been to set-up new kinds of street cabinets or rethink the architecture and technology.

3.3.3.3 Cost study for an FTTH rollout in Denmark

No specific cost studies are available, but TDC (the incumbent telco) has recently announced that they see no working business model for FTTH, but are open to provide services on other FTTH operators.

3.3.3.4 Main tendencies observed

The broadband and fibre penetration in Denmark is quite high. The Danish FTTH case is comparable to the Swedish case with a lot of active optical networks installed, however in Denmark the FTTH deployments are rather driven by power companies and in Sweden by municipalities.

3.3.4 Poland: East European case

3.3.4.1 Broadband market in Poland

The Internet access market in Poland is shared between several service providers. The major companies are: Telekomunikacja Polska s.a., Netia s.a.,Telefonia Dialog s.a. GTS Energis Sp. z o.o., Vectra s.a., Aster City Cable Sp. z o.o., UPC Sp. z o.o., Multimedia Polska S.A., Tele2 Polska Sp. z o.o. Table 3-4 shows the distribution of Internet access in Poland, regarding the type of access. The presented numbers correspond to the number of subscribers in million.

Table 3-4: Internet access market in Poland [27]

Access technology	2005	2006	2007
xDSL	1,25	1,86	2,35
CATV	0,52	0,75	0,89

Wireless (WiFi)	0,05	0,07	0,22
UMTS	-	-	0,21
EDGE	-	-	5

Due to increasing needs for broadband access, (passive) optical access networks seem to be the natural target to satisfy customers' needs and requirements to provide high bandwidth services.

3.3.4.2 Chosen FTTH architectures & technologies in Poland

Considering deployment of FTTH networks, one of first choices an operator has to consider is the type of FTTH architecture and technology. Telekomunikacja Polska as national operator has decided to implement a point-to-multipoint architecture using GPON class B+ technology. Several smaller operators like Telefonia Dialog s.a. also implements GPON.

In contrast to bigger operators, local operators, especially CATV ones, e.g. Multimedia Polska, Aster City Cable (covering city of Warsaw) decided to implement FTTH networks in point-to-point architecture.

It is worth to mention the local government initiations to support deployment of FTTH networks in cooperation with the European Union.

3.3.4.3 Cost study for an FTTH rollout in Poland

The results in this section are based on an FTTH trial performed by TP. The trial network (GPON, 1:32 split ratio) covers one MDU building which has got 256 home passed. In-Building cabling infrastructure is performed by a traditional solution with fusion splices. A cross-connecting box with splitter is located in the basement of a building. Cabling infrastructure consists of single mode fibre G.652 in vertical and horizontal part. Each floor box supports up to 3 floors. Figure 3-20 presents the CapEx structure, with a percentage share of particular infrastructure factors.

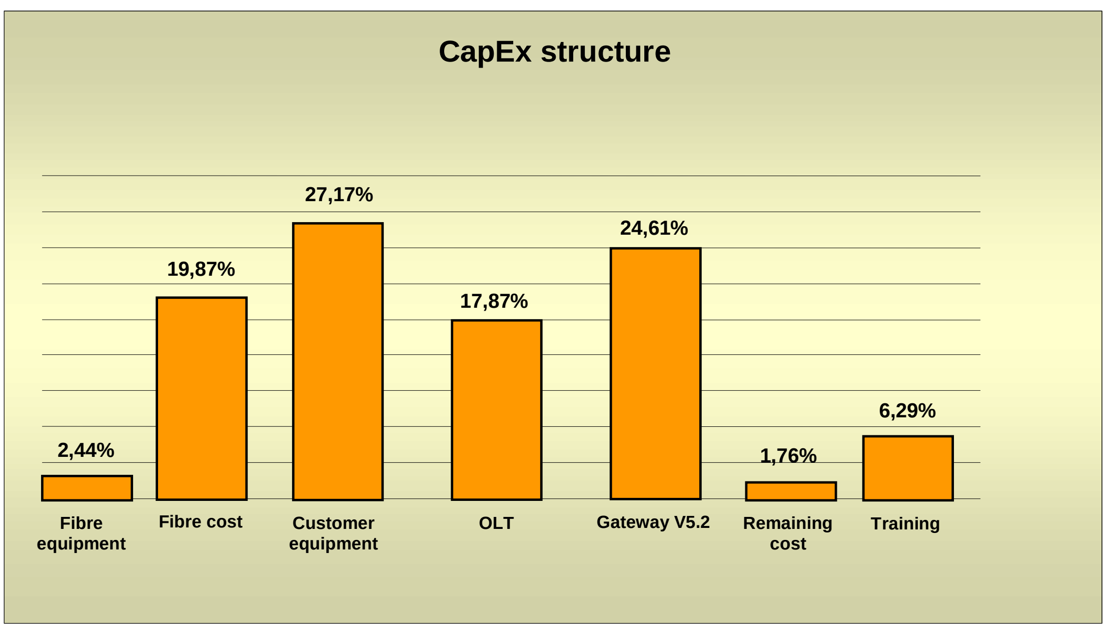

Figure 3-20: CapEx share profile of infrastructure components from TP trial

Some key elements of the CapEx structure are:

- Passive optical elements - fibre equipments (distribution boxes, etc), fibre costs (indoor, outdoor cables), splitter, etc
- Customer equipment (ONT, LiveBox)
- OLT, Gateway
- Labour

Other factors influencing the network profitability are the provided services. Telekomunikacja Polska tests following services:

- high speed Internet (e.g. Neostrada 50/10 Mbps)
- IPTV (soon multiroom HD), VoD
- VoIP, POTS

Another step to optimize network cost is assumed shape of cost per subscriber. Figure 3-21 shows the decreasing character of the cost per subscriber (in arbitrary units, a.u.) with an incrementing number of subscribers.

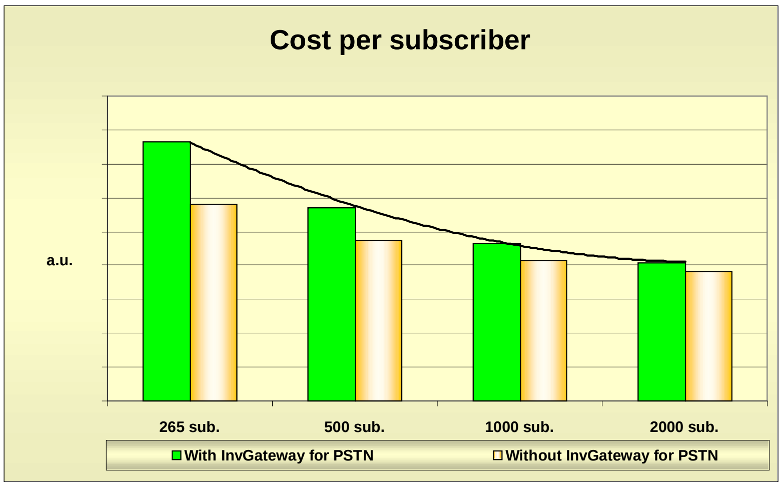

Figure 3-21: Assumed decrease of cost per subscriber, using arbitrary units (a.u.)

3.3.4.4 Main tendencies observed

For polish perspective (TP perspective) passive optical access networks seems to be the natural target to satisfy customers needs and requirements to provide high bandwidth services. But nowadays differences in cost of copper solution and FTTH solution are relatively high. Key component contributing to this difference is the cost of customer equipment (ONT, LiveBox). This cost item does not depend on the number of households. Thus some marketing policy statements have to be taken:

- FTTH seems to be the suitable technology for green-field, with high level of potential customer numbers in big agglomerations. It seems to be relatively easy to achieve within FTTH projects with address locations for which CapEx per household tends to the level of 1000 €.
- In order to make Very High Broadband „service” come true at mass scale, a mid market and low end customers must be addressed. Moreover, the implementation scenario for brown-field must be considered.

Moreover, other points that can have influence on network revenue profile could be:

- The areas of network deployment - Poland like other European countries planning mass deploying of optical access considers agglomerations of big cities like Warsaw, Krakow and others, as presented in Table 3-5. Such locations assure stronger potential growth of broadband market, stronger PR/advertisements effects, etc. Moreover other goals can be achieved like: broadband access delivery to white zones, partnership for development of information society-cooperation with local authorities and lasting relationship with them for future business. These aspects lead to a better economical profile of a network.

Table 3-5: Potential areas of FTTH implementation in Poland

	Potential areas of FTTH (GPON) implementation	
✓	Broadband everywhere	EU funds + local authorities to drive broadband penetration and cover white zones.
✓	Developers (new buildings)	Attractive greenfield market as easier for FTTH implementation. Strong competition from cable service providers.
✓	Agglomerations	The biggest agglom.: Warsaw, Krakow, etc.
?	Other large cities (excluding agglom.)	Other cities - 31 cities above 100k citizens in Poland.
?	Others	Small towns and villages.

✓- interest for FTTH: study first
? - potentially in the scope of interest for FTTH: study later

- The development of broadband access services - deployment of new optical access networks could be considered as indirect relationship with incremental customer demands on broadband access (broadband services). As stated above, operators need to face customer requirements for broadband services. Connecting this fact with Figure 3-22, showing a developed profile of place of Internet access, one can notice the potential place for passive optical networks as assuring sufficient bandwidth and "placing" services at the customer's home.

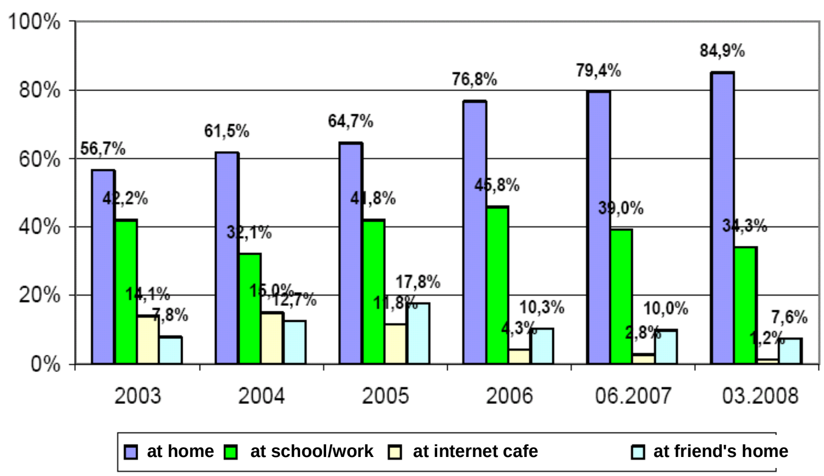

Figure 3-22: Place of Internet access [27]

4 Active Optical Networks: access-distribution network convergence

4.1 Description of the AON architecture

Topologies

AON can be built either as a home run (with direct fibres between the CO and the end users) or as a star architecture (Figure 4-1, left). The latter means "home run" from somewhere in the network closer to the end user, and thereby the CO becomes distributed. That is, it does not make sense to talk about a geographically specific place that contains the CO. A "pure" home run is almost never deployed in the field, but it is possible that such deployments exist. In an active star (shaped as a tree) some of the equipment and also bandwidth is shared between the users through standard Ethernet statistical multiplexing. That is, all users cannot have a 100 Mbps throughput at exactly the same time.

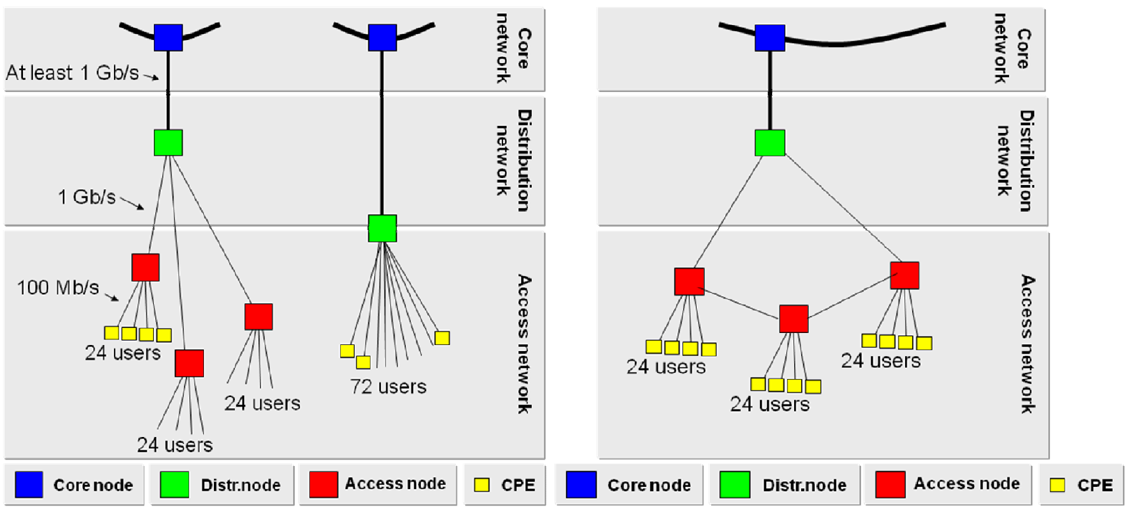

Figure 4-1: Active star vs. homerun (left), active star with access nodes in a ring (right)

The easiest solutions to compare with PON are pure tree/star structures like those in Figure 4-1, left. However, many AON active star installations include rings between the access nodes which give redundancy on the transmission lines (Figure 4-1, right). Larger networks have also dual switches/routers further out in the network which gives node redundancy as well. This is where we think that AON may become more favourable than PON from an economical point of view. Furthermore, in a larger network, the distribution nodes can be arranged in a mesh, which provides an even more efficient network. This is especially the case if there are large amounts of local traffic (local traffic = traffic between users in the same access network). These are the normal advantages of meshed networks.

Figure 4-2 shows a typical (but very schematic) municipality network. It has a dual connection to the core network (blue nodes) for redundancy. The access nodes (red) have redundant connections to the metro/metro-access network (the distribution network or green nodes), and the access nodes themselves are organised in rings, also for redundancy. Note that SDH is depicted in the core network since it still by far is the dominating core transmission technology, but it could as well be carrier Ethernet or optical transport network (OTN).

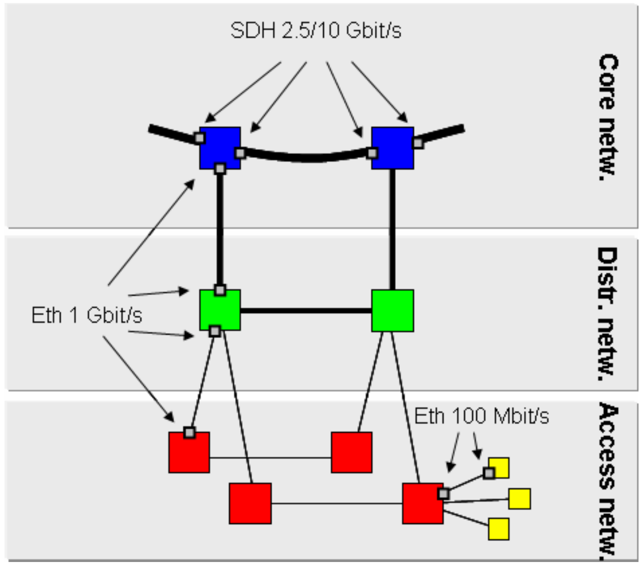

Figure 4-2: Schematic view of a typical AON-based municipality network.

Compared to PON it is hard to see where the access network ends and turns into the metro or metro-access network. And indeed, the intention is to take a much wider perspective of the access network and include the metro/metro-access parts as well in a techno-economic analysis.

<u>*Equipment*</u>

AON can be built either with layer 2 (L2) equipment (Ethernet switches, which most providers do such as Cisco, Ericsson, 3Com, Extreme, Alcatel-Lucent, etc) or layer 3 (L3) equipment (“slimmed” IP-routers which PacketFront does). In case it is L2 equipment, some of L3 functionality is needed in order to prevent end users on the same switch to communicate directly which each other. If this is possible, it is also possible to “take over” the neighbours identity and thereby get access to this user’s communication. This L3 functionality is to a large extent standardised, but as far as we know, there is no interoperability between the L2-vendors with respect to this. For a start we assume it is not needed to distinguish between L2 and L3 as the functionality is almost the same. L3 is slightly more expensive than L2 but with slightly higher functionality.

Most AON access switches have 24 or 32 ports, all with fast Ethernet towards the end users and Gigabit Ethernet (GbE) towards other access nodes or distribution nodes. This leads to the need of one 1 GbE SFP-transceiver in the access node on the link towards the neighbouring nodes in the distribution network. If redundancy is required or if there is a number of access nodes in a ring structure, two SFPs towards the neighbouring nodes are needed for each access node. A ring could typically comprise 4-6 nodes. The main limitation is how many users should share the total bandwidth in the ring – that is, the number of nodes is not a technical constraint. 10 Gbps between distribution nodes exists today, and even 10 Gbps between access nodes is viable. There are today a few commercial deployments with GbE to end users [28], but when the prices on GbE ports come close to Fast Ethernet (100 Mbps) ports, the former will probably become the standard solution. This would eventually lead to the need of 100 Gigabit Ethernet (100GbE) in the access distribution network, which is currently a topic for applied research and standardization [29].

There is no RF-overlay on a separate wavelength as in many PON solutions (that is, TV is IPTV), but in some cases there is a separate, parallel, passive network distributing TV over RF which is terminated in the end user gateway and distributed in the home over the domestic coax network.

4.2 Preliminary techno-economic analysis for AON

Discovered difficulties to compare AON and PON

A detailed cost comparison between the reference GPON (as mentioned in section 3.1.2) and AON is not a trivial task because of several factors.

- AON and PON apparently attract different kinds of customers. Often the largest operators choose PON and the smaller operators choose AON, but it is not always so. Also, EPON is biggest in Asia, GPON biggest in North America, and both GPON and AON are popular in Europe. Within Europe there are wide differences. For instance, Sweden is completely dominated by AON whereas most other countries have a preference for PON or at least a mix between PON and AON. Whatever causes these different preferences, it indicates that different business models and perhaps different political environments play a role.
- It is relatively clear to define what part of the network is the PON. The end points are at the central office and at the end user. Therefore a CapEx analysis is relatively easily done. An AON is more integrated in the metro or metro-access network and can in principle be an integral part of this. The "central office functionality" is in principle available at any access node, and therefore it is not always meaningful to use the term "central office" for AON – or perhaps rather, the central office is decentralised in the AON case.
- OpEx is a parameter that is hard to capture but which is often used when discussing PON vs. AON. For one type of operators and for a given network it is possible to make such a comparison. However, different operators can have widely different business models which make a general comparison impossible. Also the capacity upgrade scenarios are fundamentally different for AON and PON which cannot be readily translated into OpEx contributions.

A study activity in ALPHA is to define a framework for a more comprehensive comparison between PON and AON for different scenarios (types of operators and characteristics of networks), to point at the critical OpEx factors and identify under which circumstances they can be compared, and to take a wider perspective of the network when doing the comparison between the two optical access technologies. This general reference framework is under development within the project.

Advantages of an AON

Some general advantages of an AON compared to a PON that should be taken into account during future techno-economic evaluations are:

- An AON infrastructure is better suited to implement redundancy in the access network.
- An AON infrastructure is also better in a competitive market because this architecture is more flexible to upgrade the service level.
- AON can in principle be built with off-the-shelf Ethernet equipment. Due to dedicated point-to-point connections, the requirements on the optical budget are much less stringent and the end-user bit-rate equals to the line bit-rate (not shared with the other users).

5 WDM-based PONs: enabling dynamic capacity allocation

5.1 Description of WDM-based PON architectures

5.1.1 Pure WDM PONs

In contrast to TDM-PONs (like GPON), a pure Wavelength Division Multiplexing (WDM) PON delivers a pair of wavelengths per customer – one upstream and one downstream. A WDM PON architecture provides no time sharing of the downstream and upstream bandwidth, which allows users to have a high-bandwidth symmetrical and secure connection. Moreover, WDM PONs can be deployed in several types of architectures, e.g. CPON (Composite PON), LARNET (Local Access Router Network), RITENET (Remote Interrogation of Terminal Network), etc. [30]. Figure 5-1 compares the principals of a pure TDM PON and a pure WDM PON.

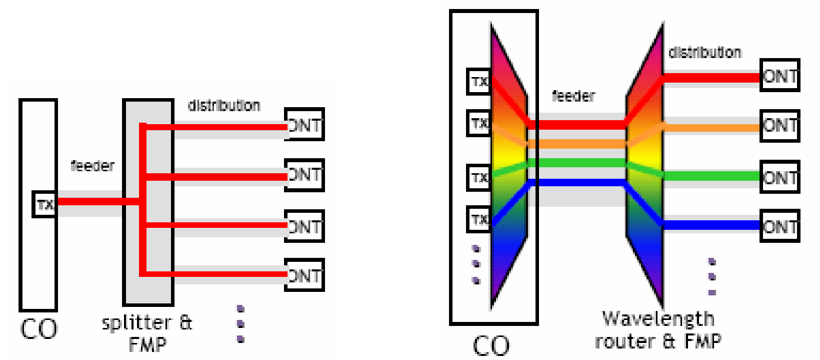

Figure 5-1: Pure TDM PON vs. pure WDM PON comparison

Although there is a perception that WDM PON is "tomorrow's technology" some national operators has started to deploy WDM PON, e.g. Korean Telecom has deployed more than 150 000 subscriber lines using WDM PON platform.

In section 5.2.2, GPON will be compared with a pure WDM PON. This comparison will be used to analyse the pertinence of managing a wavelength instead of the time domain. To achieve sufficient dynamic bandwidth allocation (DBA) capability of the pure WDM PONs and the PONs mentioned below, Reconfigurable Optical Add/Drop Multiplexers (ROADMs) may be required in the CO and remote nodes. ROADMs are capable of offering a number of unique features including dynamic reconfigurability, great connectivity, forecast tolerance, bit-rate/protocol transparency, and efficient assignment of connections between sources and destinations without the need of O-E-O conversion. In addition, the fast electrically controlled wavelength routing flexibility provided reduces network operation cost, and the circumvention of the unnecessary O-E-O conversion at network nodes mitigates equipment cost, overcomes the transmission capacity bottleneck set by electrical signal processing, and relieves the burden on the electrical grooming switching at ingress and egress points of networks. Note that, for given dynamic networks, an optimum ROADM design not only maximizes the network flexibility and connectivity but also reduces device fabrication cost.

5.1.2 WDM/TDM PONs, enabling dynamic bandwidth allocation

Next to the pure WDM PON from the previous section, there exist different options to add a WDM dimension in TDM PON networks. In this section, two flexible WDM-based network architectures enabling DBA are described. The dynamic allocation of network resources provides congestion-free access to users with traffic demands fluctuating in time and in place, and increases flexibility in terms of network management. The two considered architectures are shown in Figure 5-2 and a short description of them together with the objectives of the related techno-economic studies are summarized below:

- *Architecture 1:* WDM/TDM PON using broadcast-and-select (B&S) at the user side
    - *Description:* In the downstream, all wavelength channels are broadcast from the local exchange to all the users, without any selectivity in the network itself. The selection is done at the user side. This approach is well suited for broadcasting services, but due to power and security reasons, it is less efficient for services which are intended for only one or a few users. In the upstream, a wavelength is chosen taking into account the load constraints of the network. To avoid disturbing the services already connected, a wavelength with a low load will be selected. This technique limits then the service interruption while offering at any time the available bandwidth of the network.
    - *Techno-economic study:* The objective is to compare the WDM/TDM PON with one set of TDM PONs to reach the same connectivity and number of users. A 10G GPON will be considered as TDM PON. N × 10G GPONs and the WDM 10G GPON will then be compared to identify the techno-economic advantages of introducing the WDM dimension on the top of the 10G GPON (see section 5.2.3). Note that the aggregation network, concentrating all the traffic at the central office, is also included in the study, since the WDM dimension on top of TDM PON will create one network for the access and the aggregation part.
- *Architecture 2:* WDM/TDM PON using a centralized tuneable λ-router
    - *Description*: The network is a flexible WDM access network using fast optical gates. This architecture is more flexible to implement the dynamic capacity allocated network. In the downstream, the wavelength channels are routed by a remote-node in the middle of the network, controlled by the network operator, to only those users which should get it. Thus, no signal power is unnecessarily wasted, and a safeguard against privacy is possible. In the upstream, network traffic monitoring is not needed because the wavelength channel is already allocated by the remote-node according to the traffic situation or the call request from ONUs. Therefore, the same wavelength as the downstream wavelength channel is chosen by a wavelength-following tuneable source or it is possible to design the upstream link wavelength-agnostic and source-free by using a reflective type transmitter such as RSOA, REAM.
    - *Techno-economic study:* The objective is to analyse the techno-economic advantages of the architecture providing more flexibility in the network, through a performance analysis. At this moment, the available data is too limited to perform a full techno-economic analysis, but we can assume that the extra flexibility introduced in the network will increase both CapEx and OpEx, compared with the B&S variant. The increased performance and the extra costs then have to be balanced again each other. A full techno-economic analysis of this architecture will be performed in the next phase of the project.

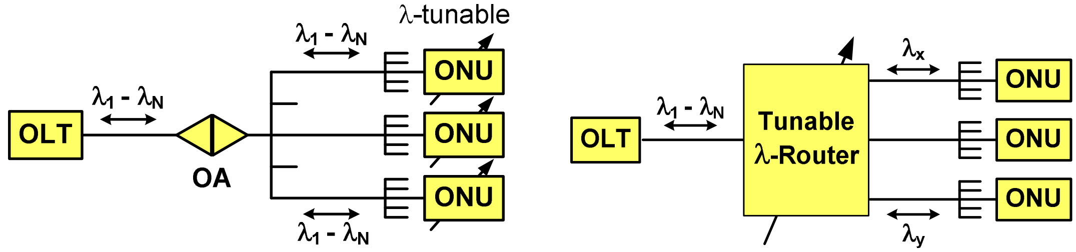

Figure 5-2: Basic options for dynamic capacity allocated network: broadcast and select at user-side (left), and network capacity allocation in the middle of network (right)

5.1.2.1 WDM-GPON based on broadcast-and-select (B&S) architectures

Description of the network:

The WDM GPON B&S architecture, as described in deliverable D2.1 of the ALPHA project, is a possible evolution of the 10G GPON to aggregate more subscribers onto one unique network.

The new dimension explored on the top of a GPON network concept is the WDM dimension. Each subscriber is time shared with other subscribers with the advantage of having access to a WDM dimension. Since the adoption of colourless interfaces can open new perspectives in terms of volume of production at the component level, we will focus our analysis on tuneable sources and suppose to have at the same time: colourless terminals AND a flexibility in the network to optimise the bandwidth utilisation by introducing some load balancing techniques.

Figure 5-3 shows then the network proposed (WDM 10G GPON) whereas Figure 5-4 represents an equivalent network without the wavelength sharing (N × 10G GPON).

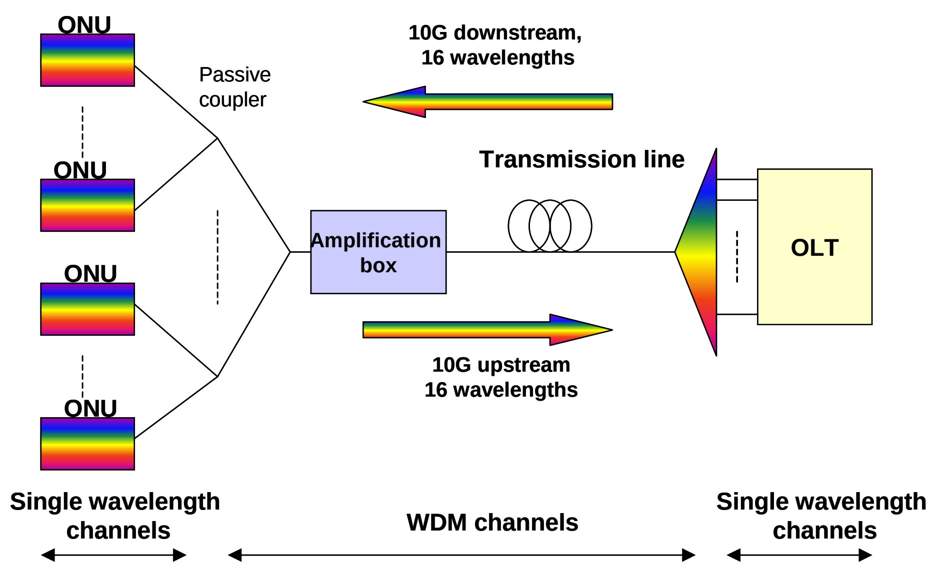

Figure 5-3: WDM 10G GPON with dynamic capacity allocation

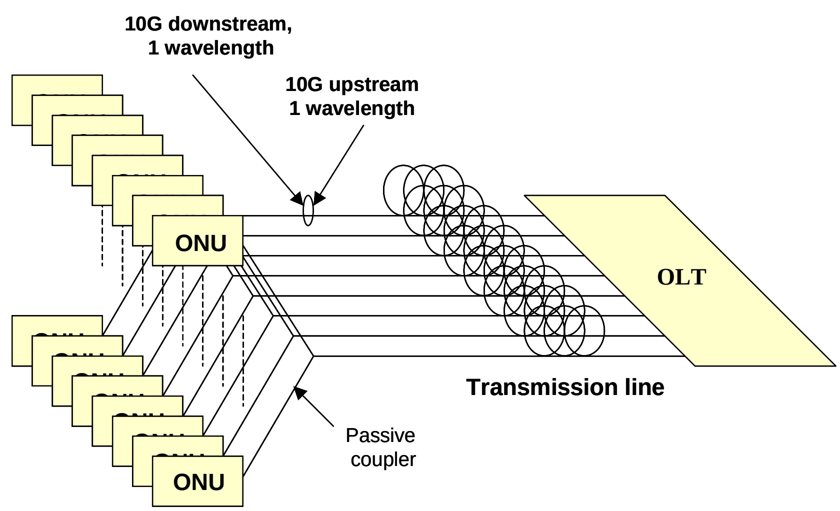

Figure 5-4: Equivalent architecture based on N × 10G GPONs with no dynamic wavelength allocation

Advantages and drawbacks of the approach:

Table 5-1 gives some advantages and drawbacks of the solution illustrated in Figure 5-3 with respect to the architecture of Figure 5-4. For the comparison we assume that both architectures can provide the same capacity.

Table 5-1: Advantages and drawbacks of WDM 10G GPON vs. N × 10G GPON solutions

	WDM 10G GPON Advantages	**WDM 10G GPON Drawback**	**N × 10G GPON Advantages**	**N × 10G GPON Drawbacks**
Fibre	Only one fibre for the transport			Several fibres for the transport
ONU terminals	Tuneability allows load balancing	Tuneable sources are more expensive than fixed sources. Need for tuneable filters	Natural evolution of the current GPON version No need for a colourless version	
OLT terminals	Same as for N × 10G GPON		Same as for WDM 10G GPON	
Couplers	Full flexibility, compliant with a colourless concept	Extra losses requiring an EDFA	Full flexibility The limited splitting does not impose an optical amplification	
EDFA	Burst mode EDFA available on the market place	Need to have a burst mode EDFA	No need for an EDFA	
Load optimization	Load balancing possible with tuneable sources			No possibility of load balancing
Quality of service	Low probability of service interruption			Probability of having a service interruption

Taking into account Table 5-1, the comparison between the two models requires a CapEx analysis, a performance analysis and an OpEx estimation. A CapEx analysis is done in section 5.2.3, together with an indication of the importance for a performance and OpEx evaluation.

Note that the B&S approach is well suited for broadcasting services. However, it is less efficient for services which are intended for only one or a few users; much signal power is wasted by distribution to users who did not subscribe it. In addition, there is a privacy issue, as the operator should prevent users to have access to information which is not intended for them, and thus should have secure access to the wavelength selection at the user-side.

5.2 Techno-economic analysis for WDM-based PONs

5.2.1 Required technology for WDM-based PONs

Deployment of WDM PONs require introduction of new types of elements being either standalone components or part of transmission systems. At this point it is important to mention that we will further consider WDM PON based on dense grid spacing.

The relatively small number of available CWDM channels (a maximum of 5 downstream and upstream pairs) within the wavelength ranges of the O, S or L bands makes CWDM unattractive for WDM PON deployments. In contrast to CWDM, a relatively large number of channels can be packed into the allocated bands using DWDM. But this density comes with increased cost associated with tight manufacturing tolerances of lasers, as well as with stabilizing the laser within the narrower channel width. To reduce costs, wide channel spacing can be employed (400 or 200 GHz). However, even though the 200 GHz channel spacing reduces the optics cost, the current cost of such optics is still substantially higher than for GPON optics [31].

Hereunder we list the key WDM PON components that will be required for future systems.

<u>*Light sources for WDM PON:*</u> The main obstacle to WDM PON is the cost since the transmitters need to emit at a specified wavelength. This is especially critical for the subscriber units (ONTs) since the cost directly affects each subscriber line. Recently, tuneable lasers, wavelength settable lasers, spectral slicing sources, injection seeded optical sources were proposed as low cost WDM PON light sources [6],[32].

Tuneable lasers: Rather than stock and manage different wavelengths of a laser, it would be preferable to have just two tuneable laser types; one type for downstream and one type for upstream.

We can tune the laser by means of change the temperature. However, this tuning procedure is difficult for the Distributed Feedback (DFB) lasers (for changing the output wavelength beyond 2-3 times 200 GHz channels). In turn Distributed Bragg Reflector (DBR) lasers offer a wider range of tuning than DFB lasers by separating the grating from the gain region and adding a so-called phase section. The adjustable phase section enables smooth tuning and ensures optimized output power by finely adjusting the cavity modes to the selected DBR reflection wavelength. While simple three-section DBR lasers are tuneable over about 12 nm, many creative solutions have been designed to increase the tuning range by adding another grating section. Tuning through current injection in DBRs is much faster than thermal tuning but the multiplicity of currents needed make DBRs harder to control than DFBs. Because of cavity length it is impossible to directly modulate DBR lasers (with the data) by using the injection current as for DFB lasers. An additional modulator is needed, which reduces the output power from the module and adds to the cost. An alternative approach to wavelength tuning is to move the variable cavity that allows tuning of the wavelength outside the active device completely, but such variable external cavity lasers (ECLs) have traditionally been bulkier and better suited for test and measurement systems rather than for communications systems. These lasers can be tuned over an 80 nm wavelength range. They remain too expensive for residential access network [6],[31].

Application: This type of light source can be applied to CPON (Composite PON) or LARNET (Local Access Router Network) as WDM source in OLT.

Wavelength settable lasers: In WDM PON we can use also a so-called wavelength settable laser. In the simplest form, we can use an arrayed DFB laser. The desired wavelength can be generated by powering the appropriate DFB in the array, allowing one to “set-and-forget” at the time of provisioning. However, such a solution is not cost effective for access networks, due to all the extra laser chips in the package that are never used, as well as to the decreased yield and increased complexity of manufacturing a lasers array as compared to a single laser module.

Such a “set-and-forget” approach is, however, highly desirable because it removes the need for tight operational control of the current in the phase region as required in a DBR laser. Another approach to “set-and-forget” is to attach an external cavity, e.g. in the form of a Fibre Bragg Grating (FBG), to the laser at the time of provisioning. This allows the deployment of only a single laser type but many types of FBGs would have to be stocked, which again becomes operationally prohibitive. And, as in the case of DBR lasers and ECLs, the increased cavity length prevents direct modulation at Gbps rates, requiring the addition of an external modulator, which lowers power and adds cost. In summary, while no commercially viable solution is currently available, “set-and-forget” ways of imposing a grating onto the laser and activating it electrically from within the laser module at the time of provisioning, are currently being researched [6],[31].

Application: This type of light source can be applied to CPON or LARNET as WDM source in OLT.

Spectral slicing sources: The ability of AWGs to route the different wavelengths to specific output ports suggests an additional use as wavelength selectors from a broad spectrum light source (spectral slicing). The broadband light source e.g. Light Emitting Diode (LED) can be modulated with data and this signal is sliced by the multiplexing AWG and coloured (the colour is determined by the port number on the multiplexing AWG). In the receiving side, the signal is routed to the correct ONU by the demultiplexer, with each individual colour being directed to a different AWG port. Unfortunately, the coupling loss between a broadband light source and a fibre is usually much higher than that of a laser coupled to a fibre. The slicing process induces a loss of around 15 to 17 dB, depending on the WDM channel spacing and the source spectrum. Thus, the otherwise beneficial replacement of power splitters by AWGs in the WDM PON architecture is counterbalanced. The slicing scheme reduces the cost of the light sources. But, there are some key limitations: First, it is difficult to modulate LEDs at high speeds; by means of LED the data rate beyond 1 Gbps is very difficult to reach. Second, the output power of LEDs is also quite temperature dependent; LEDs do need cooling to provide reasonably steady power [6],[31].

Application: This type of light source can be applied to LARNET architecture as light source in ONU.

Injection seeded optical sources: Injection seeding works as follows: in addition to the usual downstream data signal, the ONTs receive an additional unmodulated optical seed signal at the wavelength designated for upstream transmission. These seed signals are either generated by an array of appropriate DWDM lasers at the OLT or are generated from an ASE source by slicing its broadband spectrum with an AWG. The ONTs receive this seed light, modulate their data onto it, amplify it and reflect it upstream towards the OLT. Many optical solutions have been proposed for the ONT side, but the two most common are: Reflective Semiconductor Optical Amplifier (RSOA) or Wavelength Locking of Fabry-Perot (FP) lasers. Remotely seeded optical technologies suffer from the fact that the network layout and dimensions are now dictated not only by the power budget for the normal data transmission channels, but also by the power budget for the optical seed signals provided from the OLT through the network down to the ONTs. In order to suppress the self-initiated lasing of the Fabry-Perot lasers at the ONTs, a rather high optical seed power (c.a. 0 dBm) has to be provided at the ONT. With RSOAs, the power required is somewhat lower, but the deployment and design flexibility (rate, split, reach) of these networks is reduced compared to TDM PONs having standalone lasers at the ONTs [33].

Application: This type of light source can be applied to RITENET (remote interrogation of terminal network) architecture as light sources in OLT and ONU.

Receiver module: A receiver module consists of a photodetector and its accompanying electronics for signal recovery. Common photodetectors are positive-intrinsic-negative (PIN) and avalanche photodiode (APD), which find different applications according to the required sensitivity. Electronic parts, usually composed of preamplifier, main amplifier, and clock and data recovery circuits, depend on the protocol used on each wavelength. Since each wavelength can work separately in a WDM PON, each receiver can be configured differently [6].

Wavelength multiplexer and demultiplexer: The AWG based selective filter insertion loss of about 4-5 dB (regardless of the number of channels) is far less than that of the optical splitter, which has an excess loss of 0.5-1.5 dB in addition to the (large) 1:N splitting loss. But, in spite of all such good properties, the AWG's center wavelength shift of about 0.01 nm/°C makes it difficult to be used in the Remote Node of a WDM PON. Recently, thermal packages of AWG have been reported, which are made by having a compensating material. There is another common scheme for multiplexing and demultiplexing wavelengths, called thin-film filters or multilayer interference filters. By positioning cascaded filters in the optical path, wavelengths can be demultiplexed, and vice versa. Each filter is designed to transmit a unique wavelength while reflecting others. Recently, a new type of wavelength router, called a bulk grating, has been suggested for use in a DWDM system. This bulk grating is based on a bulk-type diffraction grating and is reported to have less insertion loss of sub-3 dB and to go to narrower channel spacing and larger channel counts compared to AWG (to 160 channels with 25 GHz channel spacing). But there remains a dispute on which is the better solution between AWG and bulk grating. The AWG has an apparent advantage of integration with other devices in thin structure since it is implemented on a silica-based planar lightwave circuit (PLC), while the bulk grating has a potential for temperature insensitivity and narrow channel spacing [6],[31].

5.2.2 GPON versus pure WDM PON

Figure 5-5 shows a comparison of the estimated CapEx cost per subscriber in the near term, and in the future, for the GPON and pure WDM PON (as described in section 5.1.1), which are the two main PON types being commercially considered for future access techniques [31].

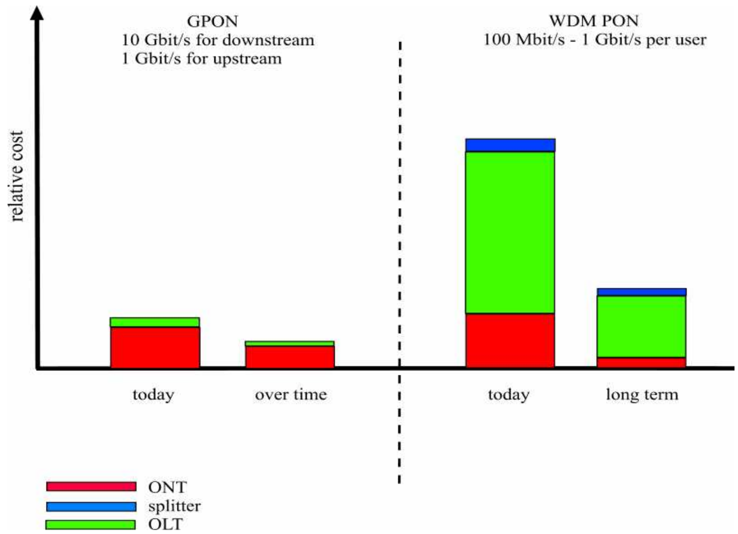

Figure 5-5: Comparison of the estimated cost per subscriber in the near term, and in the future, for the GPON and WDM PON; 1:32 split

Long term refers to an approximate time horizon of 2015 to 2020, when additional research has reduced the cost and complexity of the requisite WDM components, allowing existing commercial volume components to be leveraged. Cost of the power splitter in comparison to the other components is neglected.

In turn Table 5-2 shows a comparison between some WDM PON and GPON techniques [31]. The WDM PON networks are split into the following four groups: classical WDM PON, Wavelength tuneable/settable WDM PON, Injection-seeding WDM PON. Note that the main cost component is the WDM light sources part.

Table 5-2: Short comparison between some WDM PON and GPON

	Technology maturity	**Optics CapEx costs**	**Optics OpEx costs**
2.5 Gbps GPON	High	low cost	low cost
Classical WDM PON (2x32 DFB transmitters)	High	high cost	high cost
Wavelength tuneable/settable WDM PON	High	high cost	Low/medium cost
Injection-seeding WDM PON	low/medium	high or medium	Low/medium cost

Although natural roadmap for PON deployments leads to WDM PON systems which may be the long term preferred solution for fibre access networks one must be aware that the economic aspect will be the decisive one. Key enablers for WDM PON are evolution of cost effective optical integration and a well planned migration from the GPON networks. It means that the most preferable solutions will be the ones that promote using current optical infrastructure of GPON deployments. It is expected that a cost effective solution at the ONT and a proper choice of the wavelength grid will drive the success of WDM PON.

5.2.3 WDM 10G GPON versus N × 10G GPON

In the following study we compare a network capable to interconnect 256 subscribers.

CapEx analysis

For the CapEx evaluation, we adopt a relative analysis to compare and identify the different aspects that impact the CapEx.

In the architecture of Figure 5-3, the extra cost comes from:

- A bidirectional EDFA before or after the passive coupler to compensate for the losses.
- Tuneable sources and receivers at the subscriber side by applying a coefficient with respect to a fixed transponder.
- An optical demultiplexer located in the OLT to separate the channels before detection.

In the architecture of Figure 5-4, the extra cost comes from:

- The extra number of fibres required in the transmission span.

The diagram in Figure 5-6 shows the positioning of both solutions. We can see that the cost per subscriber when taking into account the CapEx is in favour of the WDM 10G GPON, and the difference is increased if we integrate in the calculations a cost reduction of the components.

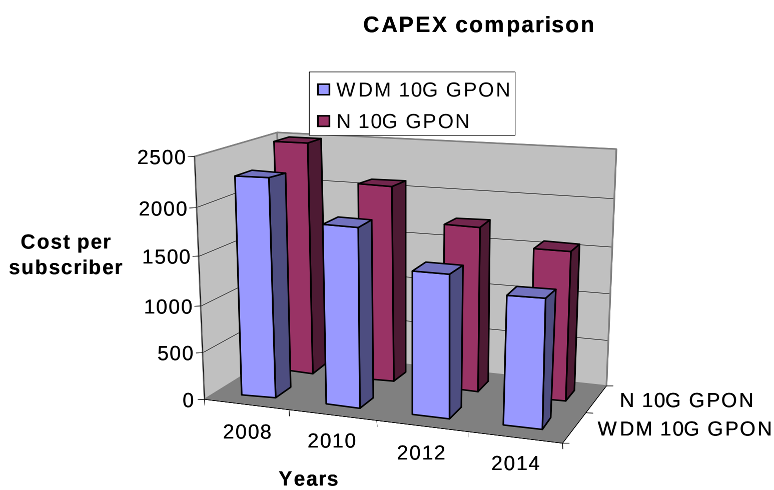

Figure 5-6: Evolution of the cost per subscriber, taking into account the CapEx for the WDM 10G GPON and for the 8 10G GPON solution

Other calculations show that there is a need for a minimum number of subscribers required to have some benefits. Typically the limit is close to half of the total capacity. For a 256 subscriber capacity, the minimum is then close to 128 subscribers.

Importance of an OpEx and performance analysis

In addition to the above CapEx analysis, there is a need to reinforce the study with an OpEx evaluation and with the predictable improved performance of the network due to the dynamic capacity allocation offered.

In the architecture of Figure 5-3, the extra OpEx cost comes from:

- The maintenance of the EDFA.
- Its additional power consumption.

In the architecture of Figure 5-4, the extra cost comes from:

- The maintenance of the extra number of fibres required in the transmission span.

Finally to compare fairly both architectures, we must take into account the additional average load that can be offered, in the first case due to a better bandwidth allocation.

The OpEx and performance aspects will be studied in the next step of the ALPHA project.

6 Radio over Fibre technology over PON: fixed-wireless convergence

The main goal of this RoF section is to indicate the extra costs associated with implementing Radio over Fibre (RoF) over a PON architecture. An indication will be given about the order of magnitude of the cost difference between such an integrated solution, in comparison with two separate networks.

6.1 Description of the RoF over PON architecture

Figure 6-1 shows the architecture resulting from a joint investigation performed by FTRD and ATFI. Such architecture is based on a typical 1:64 PON tree where a RoF based Distributed Antenna System (DAS) system (also called Fibre-DAS or F-DAS) is superposed with dedicated wavelengths. The Base Transceiver Station (BTS) or a BTS Hotel is at the level of the OLT and a multiplexer is used to put the signal on the PON. The remote antenna unit (RAU) is at the same level of the ONUs and optical demultiplexer is used to extract the wavelengths reserved for RoF.

According to the schematic block of Figure 6-1, one C-Band wavelength is used for the downlink (wavelength #1) and collects the signal coming out of several BTSs. In the uplink, one C-Band wavelength is used for each RAU connected to the PON. Thus, (N+1) wavelengths are necessary for N RAUs. Then multiple RoF RXs are needed in the Central Office and each RoF RX is processing just one wavelength after having filtered it.

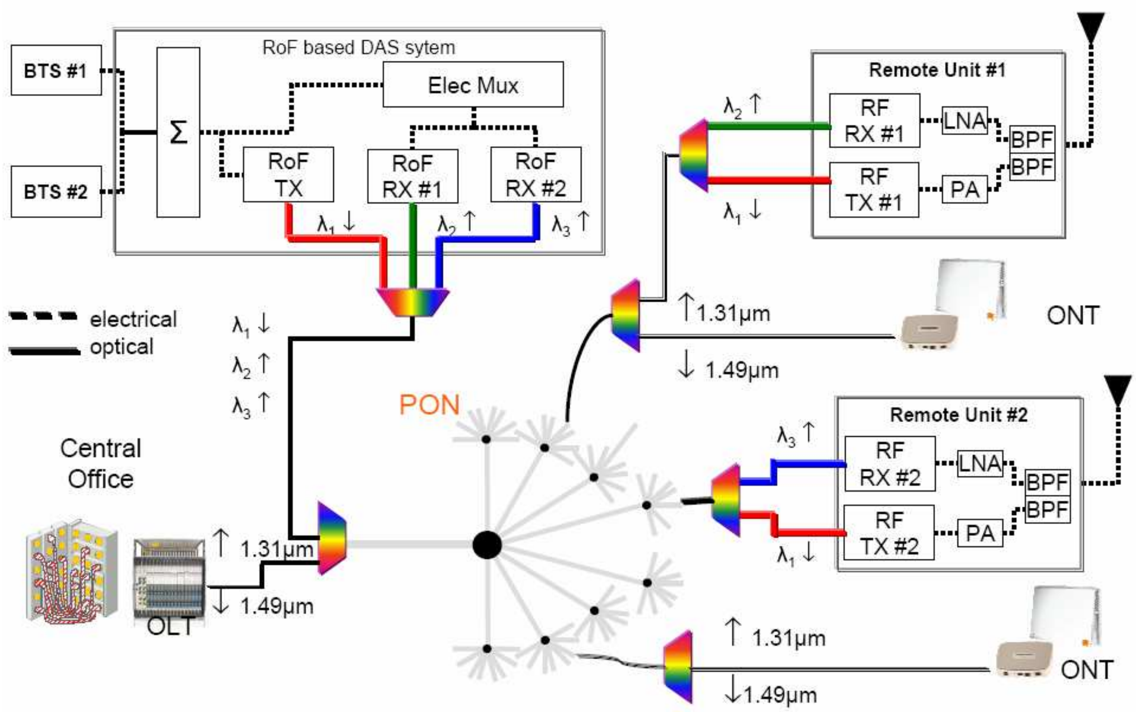

Figure 6-1: Starting point of merging a current commercial RoF based DAS into a PON with as little changes as possible

For a practical real case scenario (also denoted as the ALPHA scenario), we consider what is needed for a single wireless operator to provide mobile coverage for the current available mobile applications (i.e. GSM, DCS (GSM-1800) and UMTS) in an outdoor scenario. This, for instance, requires a high power RAU, in the range of 30W of RF power.

6.2 Techno-economic analysis of the proposed RoF over PON architecture

In this section, we compare the additional cost for the RoF system when using it over the PON architecture, in comparison with the case where a dedicated fibre infrastructure is used. Besides, we also mention what is the difference with a traditional wireless network, without using RoF.

The main constraint in using the PON network for feeding the RAUs is the required optical budget, which requires a more sensitive RoF transceiver (TRX). Besides, there is an extra cost for the required optical MUX / DEMUX in the proposed ALPHA F-DAS (Figure 6-2). The analysis shows that the cost difference between both systems for RoF equipment is close to 10%.

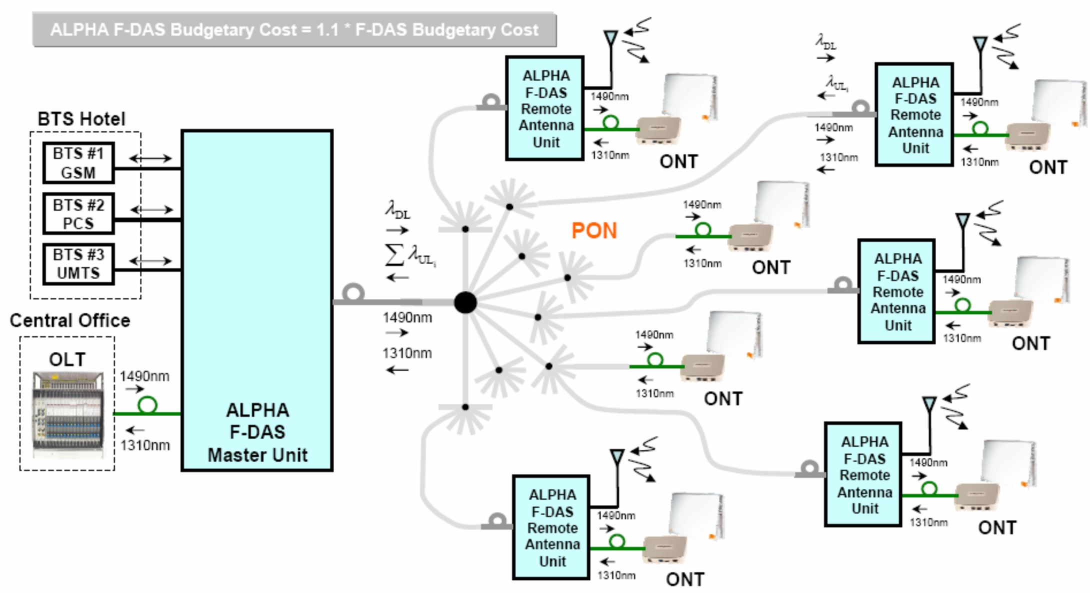

Figure 6-2: RoF over PON, for the ALPHA F-DAS deployment

When using a conventional F-DAS system and rolling out a dedicated fibre infrastructure (Figure 6-3), the cost will be much higher than the mentioned 10% for the proposed ALPHA F-DAS.

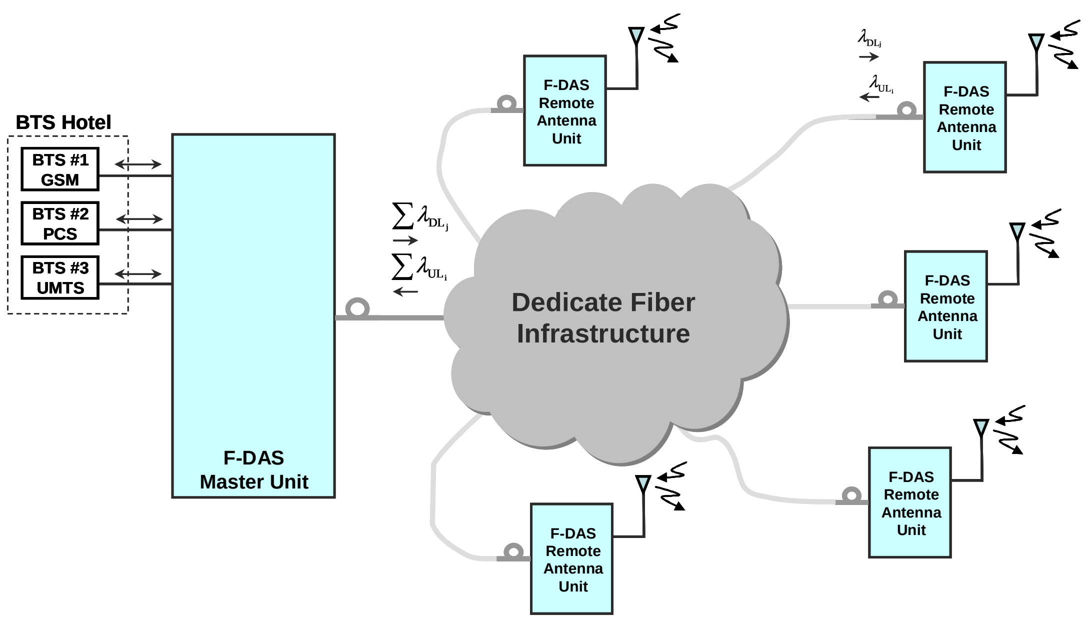

Figure 6-3: RoF over dedicated fibre infrastructure, for the conventional F-DAS deployment

Another possibility is to rollout a traditional mobile network (without using RoF) which is connected to a PON (Figure 6-4). Now, all centralized equipment from the F-DAS Master Unit is distributed in the network. For the moment, we could not obtain detailed cost information for such a system, but the additional cost to deploy a three-band wireless system will be much higher than the 10%.

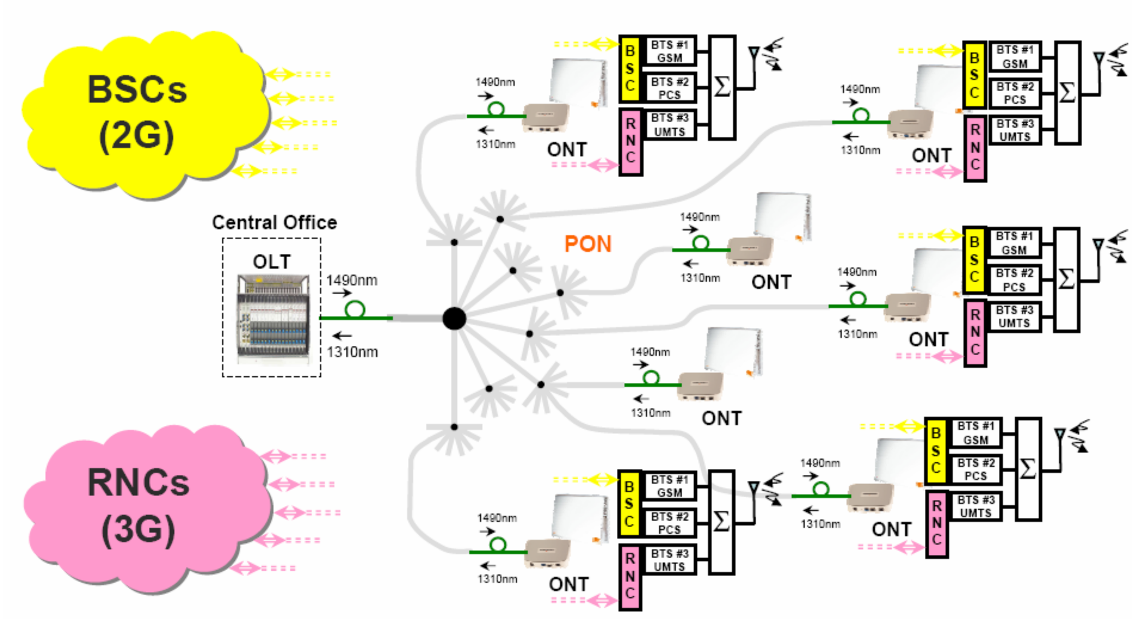

Figure 6-4: Traditional PON and mobile network deployment

Conclusion

This section presents a real case scenario for implementing a three-band wireless system, by using a RoF solution over PON, denoted as ALPHA F-DAS. In comparison with both a conventional F-DAS (using a dedicated fibre infrastructure to distribute the RoF signals) and a traditional mobile network deployment (based on a PON infrastructure to connect the BTSs), the proposed ALPHA F-DAS has a clearly proven techno-economic advantage even in a small scenario such as a single wireless operator in an outdoor environment. The intrinsic transparency of the RoF technology can be additionally exploited in a multiple wireless operator scenario. Indeed the same ALPHA F-DAS infrastructure could be shared with a very limited additional cost affect enabling a multi-operator wireless signal distribution.

7 General conclusions

In this deliverable, we have described an approach adopted for a techno-economic analysis of different FTTH options. For some technologies (WDM/TDM PON and RoF over PON), we already performed some quantitative analyses, for AON we made the techno-economic study as a qualitative analysis. However, more detailed and extensive techno-economic studies will be performed further in the ALPHA project.

This deliverable first gives an extensive overview of the state-of-the-art, consisting of two main parts:

- Examples of existing techno-economic studies for FTTH, that we map on the architectures proposed in ALPHA to deduce some general trends.
- Status on the introduction of FTTH in different European countries, with three typical cases: France, Sweden/Denmark and Poland.

The main conclusions from the state-of-the-art study can be summarized as follows:

- The costs for an FTTH rollout are dominated by the civil works (digging), so that the cost of the technical solutions represents only a fraction of the overall cost (typically 50%, in an urban zone).
- A PON typically has some cost advantages compared with AON, but what is often not mentioned is that an AON will have a higher service level and more opportunities for delivering redundancy and allowing competition.
- Introducing a WDM dimension in a PON seems favourable for next generation PONs. This is only a very recent trend, as five years ago WDM PON was only briefly mentioned but considered as unfeasible, while this perception is really changed over the last years.
- Traditional (incumbent) operators typically adopt a PON-based solution (cf. FT in France and TP in Poland), while alternative operators, power utility companies, housing companies and municipalities often prefer an AON-based solution, as seen in Sweden and Denmark.

Three sections are then devoted to the three ALPHA architectures: AON, WDM/TDM PON and RoF over PON. Preliminary results in terms of techno-economics for the different architectures either quantitatively (for WDM 10G GPON and RoF over PON) or qualitatively (for AON) have been achieved.

- *WDM 10G GPON*: first results comparing a set of 10G GPON and a WDM 10G GPON clearly show cost advantages for the WDM 10G GPON solution. Two alternatives are considered to enable dynamic capacity allocation: a broadcast & select architecture (indicated as the above WDM 10G GPON) and an architecture with centralized wavelength router.
- *RoF over PON*: the cost of upgrading the RoF equipment for using it over PON instead of a dedicated infrastructure has been estimated to be in a range of ten percent of the overall costs of a “classical” RoF implementation. The upgrade allows totally avoiding the dedicated RoF fibre infrastructure and eliminating all the costs associated with it.
- *AON*: different advantages are qualitatively considered, like the addition of redundancy, better support for local traffic, allowing an open access network model.

It has been in particular discovered that the deployed AON and PON solutions differ in the functionalities at the central office and the local exchange, in particular they have different street cabinet size and/or power supply possibilities. The two solutions do not map directly and cannot be compared in a straightforward manner. Initial work is being performed to generalise the network architecture in an attempt to make an adequate comparison. Besides, a general techno-economic model is being built that will be able to analyse different architectures and topologies.

This deliverable has in general given the base to draw some preliminary conclusions and identified the scope of the next studies of the project.