HAROKOPION UNIVERSITY OF ATHENS

DEPARTMENT OF INFORMATICS & TELEMATICS

POST-GRADUATE PROGRAMME

TELECOMMUNICATION NETWORKS AND TELEMATIC SERVICES

MASTER THESIS

«A technical and economic study of G.fast for rural areas»

Eleftherios Kalerantes

Supervisor: Thomas Kamalakis

Assistant professor at Harokopeio university

Athens, September 2016

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Athens, September 2016

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ELEFTHERIOS KALERANTES

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Περίληψη

Σήμερα, στον τομέα των τηλεπικοινωνιών, οι πάροχοι αντιμετωπίζουν πολλές αυξανόμενες και κρίσιμες προκλήσεις, προκειμένου να παραμείνουν ανταγωνιστικοί στα πλαίσια της ελεύθερης αγοράς. Κύριος λόγος προς αυτή την κατεύθυνση, αποτελούν οι συνεχείς αυξήσεις στην ταχύτητα των δεδομένων που προσφέρεται σε σταθερά δίκτυα και η εμφάνιση νέων απαιτητικών σε εύρος ζώνης και πλούσιων σε περιεχόμενο υπηρεσιών. Έτσι, ένας μετασχηματισμός του δικτύου πρέπει να λάβει χώρα. Μέχρι τώρα, οι επιχειρήσεις έπρεπε να επιλέξουν μεταξύ του χαλκού, μέσω της τεχνολογίας VDSL, ή των οπτικών ινών, οδηγώντας με αυτόν τον τρόπο σε πλήρη ανάπτυξη οπτικών δικτύων.

Πλέον, μια νέα τεχνολογία χαλκού εμφανίστηκε, η G.fast, η οποία είναι μια πολλά υποσχόμενη τεχνολογία που προσελκύει αυξανόμενο ενδιαφέρον από τις επιχειρήσεις που επιθυμούν να παρέχουν ταχύτητες επιπέδου FTTH, χωρίς το κόστος που απαιτεί η οπτική ίνα. Η τεχνολογία G.fast υπόσχεται να προσφέρει ταχύτητα download και και upload εως και 1Gbps σε αποστάσεις μέχρι και 250 μέτρα, χρησιμοποιώντας την υπάρχουσα υποδομή χαλκού.

Ο σκοπός της παρούσης μεταπτυχιακής εργασίας είναι να παρέχει μια αναλυτική τεχνική επισκόπηση σχετικά με αυτή τη νέα τεχνολογία, καθώς και μελέτη της οικονομικής βιωσιμότητας σε σύγκριση με άλλες εναλλακτικές λύσεις. Αναφορικά με την τεχνική επισκόπηση, μια διεξοδική μελέτη θα πραγματοποιηθεί με την παροχή των τεχνικών προδιαγραφών αυτής της τεχνολογίας. Επίσης θα αναλυθούν τα δίκτυα επόμενης γενιάς (NGN) καθώς και θα περιγραφεί ο ρόλος του G.fast ως προς αυτά. Τέλος, θα μελετηθεί η οικονομική βιωσιμότητα της τεχνολογάις G.fast σε σύγκριση με εναλλακτικές τεχνολογίες, όσον αφορά CAPEX και OPEX, χρησιμοποιώντας ως υπόθεση την ενσωμάτωσή τους σε μια αγροτική περιοχή.

Abstract

Today, in the telecommunication field, operators are facing several increasing and crucial challenges in order to remain competitive within the open market. Main reason towards this, constitute the continuous increments either on the data rate offered in fixed networks, or the emergence of new bandwidth-intensive and content-rich services. So, a network transformation must take place. Until now, operators had to choose between copper, through VDSL technology, or fiber, leading this way to a full optical network deployment, in the access network.

Now, a new copper technology emerged, called G.fast, which is a promising technology that is attracting increasing interest from operators looking to provide FTTH-like speeds without the trouble and cost associated with fiber. G.fast promises to provide theoretical upstream and downstream capacity of up to 1Gbps at distances of up to 250m using existing copper phone line infrastructure.

This master thesis aim is to provide an analytical technical overview on this new technology as well as to study the economic viability compared to other alternatives solutions. As for the technical overview, a thorough study will be held providing the technical merits of G.fast technology, information on the Next Generation Networks and the missing link that G.fast provides to it. Regarding the economic viability, a deployment case study in a rural area will be assessed between G.fast and other alternative technologies in terms of CAPEX and OPEX.

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Chapter 1: Introduction

1.1 Introduction

Since their introduction in the early 1990s, wire-line broadband networks based on twisted copper pair, coaxial cable, and optical fiber medium have continuously evolved to keep pace with consumer demand for reliable high data rate connectivity. Today, more than ever, a growing number of Internet users as well as a plethora of new applications introduced, such as high definition television (HDTV) and multiplayer gaming, push providers toward a new groundbreaking network architecture design in order to fulfill this ever-increasing traffic demand. This domain is known as Next Generation Access networks, which studies the technical feasibility and economic viability of new access technologies and the deployment of them.

In this direction numerous deployment models have been introduced, also known as FTTx systems, in order to combine the tremendous bandwidth and reach of fiber systems to the compelling economics obtainable by exploiting existing copper infrastructure.

Nowadays, while a lot of institutional bodies were suggesting the migration from full copper infrastructure to full fiber in the access network, the G.fast technology appeared. It is a copper access technology able to provide up to 1Gbps per user by reducing the length of copper to 250m from the user premises.

In this diploma thesis, G.fast technology will be analyzed, while also an economic feasibility study will be held, where it will be compared to other FTTx systems and access technologies like VDSL and GPON. Main target is the in-depth understanding of the capabilities this new technology introduces in comparison to other technologies and also the economic viability of this new technological proposition.

1.2 Structure of thesis

This thesis is structured in chapters as follows.

Chapter 2 provides an overview of the structure of a network infrastructure by describing all the different components. Also a brief description on the access technologies and on the different mediums available is given, focusing mainly on copper technologies.

Chapter 3 addresses the Next Generation Networks established from ITU-T by studying the individual characteristics, while also the Next Generation Access networks and Next Generation Core networks, in which is deconstructed.

Chapter 4 provides a detailed analysis of FTTx systems, the variations of them, and all the different aspects and attributes, i.e. different topologies and modulation schemes. Moreover, it describes the direction of research for new technologies for data transmission and also provides a small analysis on the deployment of FTTx systems around the world and especially Europe.

Chapter 5 analyzes the different aspects of G.fast technology, while tries to induct us to the entire key points of differentiation from existing xDSL technologies. Special reference, is given towards the reverse power feeding concept, which constitutes a new breakthrough in the equipment power feeding domain, and to the new and optimized mechanisms in order to eliminate the crosstalk phenomenon. Finally, it presents a topological comparative study between various access technologies and G.fast deployment potentials.

Chapter 6 introduces us to the concept of some important techno-economic models and to the techno-economic analysis evaluation methodology. Furthermore introduces us to the open access framework, which is very important for the future of the telecommunications market. Finally in this chapter the main aspects of a SWOT analysis concept are outlined, since forms an essential tool for proper business planning of a network migration towards new technologies.

Chapter 7 provides a case study of techno-economic assessment of G.fast compared to other access technologies. This is accomplished by a description of a set of assumptions concerning the area, the different network topologies applicable, a SWOT analysis for the case study and the cost methodology. Finally it presents the results of each technology and a comparison of them.

Finally, chapter 8 gives an overview on the conclusions of G.fast technology as also it provides a glimpse on the future of broadband access networks and the key role of G.fast in this direction.

Chapter 2: Access technologies overview

2.1 Today's network segments

In order to study the different access technologies that are available today, initially a generalized network architecture concept, a high level of which is illustrated in figure 1, is going to be described by analyzing the different segments, i.e. customer premises, access and aggregation, and elements, which can be found in the reference location points.

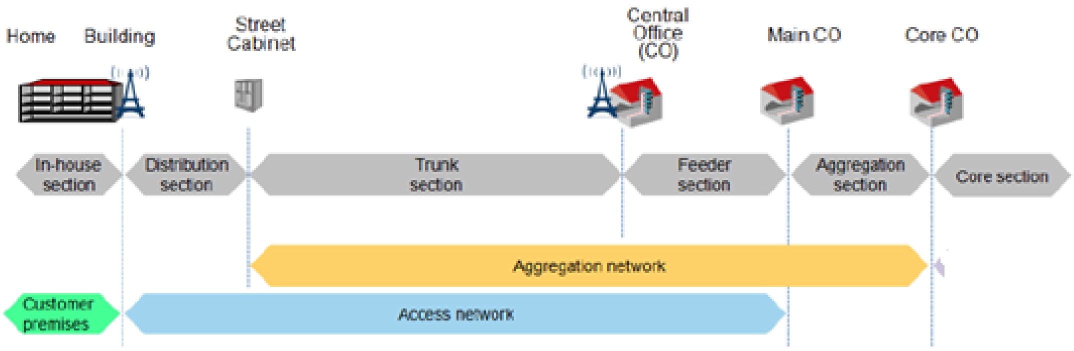

Figure 1: Generalized illustration of network architecture

As it is seen from the image above, the reference location points can be summarized in the following:

- The home or buildings represent the location of the customer premises, where typically fixed network provider offers connectivity.

- The street cabinet is the network point located in the outside network plan, where some network aggregation is typically done. Street cabinets are not mandatory to the network deployment and always depend on various reasons, like the network topology used, the town planning etc..

- The Central Office (CO) is a network provider building where traditional copper cables are terminated at the Main Distribution Frame (MDF). It aggregates passive infrastructure routes (e.g. copper or fiber routes) of multiple street cabinets. The CO is also the building where the first telephone switch of the Public Switched Telephone Network (PSTN) was located in the past. Today, the CO often hosts xDSL or optical access systems equipment (e.g. DSLAM, OLT).

- The main CO is a network provider building of the aggregation network section that typically aggregates passive infrastructure routes (e.g. fiber cable routes) of multiple COs (a main CO can be also a CO). The main CO, typically, hosts aggregation network system technologies, e.g. Ethernet switches, ATM switches, WDM de-/multiplexer, etc.

- The core CO is a network provider building that ends the aggregation network and connects it to the core network (a core CO can be also a main CO). The core network interconnects other aggregation networks and provides connectivity to other networks, such as Internet.

It must be noted that not all of the location points are present to providers' networks and that it depends on various reasons like network design, town and urban planni, financial data etc. Furthermore a network, as is shown in the bottom of the image above, can be divided in different segments. In particular:

2.1.1 Customer premises network

Customer premises network is the network segment which includes home and buildings reference locations and relates to the elements used by the subscriber for the service provision. The types of these elements used in customer premises depend on the different provided services, i.e. data, video services etc. So in common structural scenario a subscriber will have 2 or 3 elements at home:

i. Residential Gateway (RGW) is the device that acts as the data gateway within the home or business allowing subscribers to have an internet connection for all the users' devices in the network. It terminates the network for xDSL or CATV networks, provides control to access to the network (e.g. Point-to-Point Protocol (PPP) credentials), supports telephony service, supports high speed internet service, supports intra-LAN connectivity and supports different kinds of physical interfaces (e.g., Ethernet, Foreign eXchange Subscriber (FXS), Wi-Fi, Universal Serial Bus (USB) etc.)

ii. Optical Network Termination (ONT) for FTTH: It is a device that terminates the endpoint of an optical access line. The ONT adapts the fiber access system to subscriber service interfaces.

iii. Set Top Box (STB) is a device, usually linked to the TV service that allows customers to display TV contents over the fixed network.

All in all the main functions performed by these devices are related to offer certain services to subscribers. However, they also perform functions that allow provider to manage and monitor them.

2.1.2 Access network

Historically, the copper access network is the network segment between the customer premises and the Central Office (CO) as shown in figure 1. The traditional copper access network consists of i) a drop segment, i.e. between the customer premises and a termination box, ii) a distribution segment, i.e. between a termination box premises and the street cabinet and iii) a feeder segment, i.e. between the street cabinet and the CO. The street cabinet hosts a distribution frame which splits a high capacity copper cable in several smaller cables to address groups of households. The street cabinet is a purely passive location, without any power supply.

Some representative elements found in the access segments are listed below:

- Digital Subscriber Line Access Multiplexer (DSLAM): located within one of the provider's offices, allows providing data and now voice access to RGWs using xDSL technologies.
- Optical Line Terminal (OLT): it is the device that allows converting from the optical domain on broadband optical access side (end-users) to optical (or electrical) domain on provider network side. As with DSLAM devices, a single OLT can aggregate thousands of digital lines.

The main functions performed by these devices are to offer and manage access of several subscribers and to enable the transport of those communications towards the aggregation network.

In the case of optical technologies, they allow extending the reach of access links, meaning that it is possible to bypass some historic copper COs. The main CO is a CO that is elected to terminate the optical access network: it hosts the OLT for GPON technology. The feeder segment of the access network transports transparently the traffic from the historic CO up to the main CO. It can be done, for example, with high capacity fiber cables thanks to Wavelength Division Multiplexing (WDM) systems.

The optical access network is extended compared to the copper access network, because It comprises a distribution, a feeder and a drop segment.

2.1.3 Aggregation network

By definition, the aggregation network is independent of the underlying access network technologies. The aggregation network purpose is to transport traffic to the core CO from different elements based on the different access technologies utilized, for example for copper access network, aggregation transport traffic from the CO, for the optical access network, from the main CO etc.

Several different technologies may be considered for building the aggregation network, like Ethernet, Multiprotocol Label Switching (MPLS) and Optical Transport Network (OTN). The aggregation network typically is a hub-and-spoke network that is built on a point-to-point and/or a ring physical topology.

Different access technologies and different fixed services (residential, business) ideally use the same aggregation network. In practice, the provider may support different aggregation network technologies (e.g., ATM for first broadband deployments) corresponding to different generations of equipment. The provider may also support a dedicated aggregation network for business customers.

Some of the main elements located in the fixed aggregation network are:

- Aggregation Switch: this network element aggregates the traffic of multiple access network domains and forwards it typically on layer-2 using ATM or Ethernet. Depending on the needs the provider has, there may be more than one level of this type of device.

- Broadband Remote Access Server (BRAS): it is the element that behaves as the gateway for fixed access services. Additionally, it enforces the IP Quality of Service (QoS) and management policies in the network.

The aggregation network is typically the first network segment allowing for route diverse protection.

2.1.4 Core network

The core network interconnects all core nodes together. It also connects:

- The core nodes to the provider's data centers, which host the service platforms (e.g., portal, IPTV service logic, and IMS), the management platforms (e.g., network managers, billing, and customer care), and some control platforms (e.g. DNS and AAA).
- The core nodes and the provider's data centers to other Service Providers and other Network Providers through peering points.

The core network is commonly a meshed network based on IP/MPLS and OTN technologies.

One of the main elements located in the core of a fixed network is the Label Edge Router (LER). This network element is located at the border of a labeled network that allows marking certain traffic types in order to treat them with different priority levels (such as e.g. MPLS).

The elements located in the core of a fixed network take care of the following functions managing user voice calls, routing user data traffic to the Internet, TV content distribution, user management, policy and charging, lawful interception and network monitoring and management.

Overall the elements in the network segments can be summarized below:

Customer Premises Network	Access Network	Aggregation Network	Core Network
Fixed			
RGW STB CPE	DSLAM OLT Remote DSLAM	Ethernet switch Lv1 Ethernet switch Lv2 BRAS	LER

Figure 2: Elements of network segments

Apart from the different segments that constitute the network design, another important aspect, which must be analyzed, is the technology as well as the physical media used to achieve connectivity.

2.2 Physical mediums and technologies

2.2.1 Copper technologies

Herein the transmission medium is a twisted-pair cable, where the two wires are twisted together into a helix to reduce interference (figure 4). There are a various of technologies used for transmitting data through copper and each was developed by the need for higher data rate, and each grow by a decade may demarcate a new generation of broadband services. The generations of broadband evolution are:

2.2.1.1 First Generation Broadband: Voice band modems and ISDN

The first generation technologies provided bit rates well below 1 Mbps. These techniques included voice band modems (up to 56 kbps) and ISDN. ISDN enabled 2 digital telephony channels (at 64 kbps) and one additional data channel (at 16 kbps). The reach of ISDN is such that it is able to deliver its maximum bit rate of 144 kbps to almost all the customers connected to a CO.

2.2.1.2 Second Generation Broadband: HDSL, SDSL and ADSL variant

The overall idea was to utilize and leverage the old, already existing, telephony infrastructure to provide customers broadband services, such as internet access.

The DSL techniques that deliver 2GBB services are best divided in symmetric and asymmetric services. All second generation DSL techniques were designed and optimized for deployment from the central office, i.e. with a loop length range of typically 0 to 6 km1

Symmetric DSL (SDSL/SHDSL)

For the business market, the focus has traditionally been on delivering symmetric services. In particular, there has been a need for technologies to deliver 2 Mbps internet leased lines and voice connectivity service, for example call center etc.

Asymmetric DSL (ADSLx)

For the consumer market, the focus has been on delivering more downstream bandwidth than upstream. There is a wide range of asymmetric DSL (ADSL) technologies that were developed and are summarized in figure 3.

In case of ADSL2+, 24 Mbps (DS) and 1 Mbps (US) is delivered to the majority of the market2. In addition, there exist various ‘flavors’ of ADSL2 and ADSL2+ with somewhat different properties. These flavors are defined in Annexes of the ITU standard, and are therefore often referred to by their Annex name. For instance, there exist “Annex A” and “Annex B” variants, intended to be combined with respectively POTS or ISDN telephony services in the baseband.

Modem	Data rate*	Application	Recommendation
ITU-T V.90	56 kbit/s	Data and Internet access	ITU-T V.90
ISDN BRI	144 kbit/s	2B (2 x 64 kbit/s) + D (16 kbit/s)	ITU-T I.432.x series
HDSL	2,048 kbit/s	1.5 – 2.0 Mbit/s symmetrical service on two-three pairs	ITU-T G.991.1
SHDSL	768 kbit/s	HDSL on a single pair	ITU-T G.991.2
ADSL	6 Mbit/s / 640 kbit/s	Access to Internet and multimedia databases, video distribution	ITU-T G.992.1
ADSL2	8 Mbit/s / 800 kbit/s		ITU-T G.992.3
ADSL2+	24 Mbit/s / 1Mbit/s		ITU-T G.992.5
VDSL	52 Mbit/s / 2.3 Mbit/s	Internet Access + HDTV	ITU-T G.993.1
VDSL2	100 Mbit/s		ITU-T G.993.2
VDSL2 vectoring		Internet Access + HDTV over longer loops with more users	ITU-T G.993.5

Figure 3: Copper technologies

Initially, copper was chosen to transport analogue voice signals with a maximum frequency of 3.4 kHz. DSL carries digital broadband signals on the Public Switched Telephone Network (PSTN) using higher frequencies than those used for voice traffic. In particular, DSL technologies exceed this maximum frequency by several orders of magnitude; for example ADSL2+ supports frequencies up to 2.2 MHz.

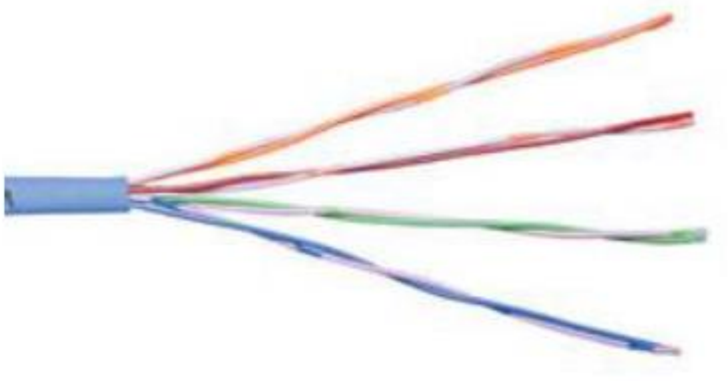

Figure 4: A twisted pair cable

In general terms, all DSL techniques can be described as in figure 5. In the telephony grid, each customer is connected in a star-like network to a DSL Access Multiplexer (DSLAM). In the earlier standards like ADSL, the DSLAM is located in the Central Office (CO), where the local telephone switch is also located. Then, optical fiber connects the CO to the Internet. The voice and data signals are physically separated both in the DSLAM and in the Customer Premises Equipment (CPE), but both signals are sent in a Frequency-Division Multiplexing

(FDM) transmission over the twisted-pair copper lines in the telephony loop to deliver Internet access.

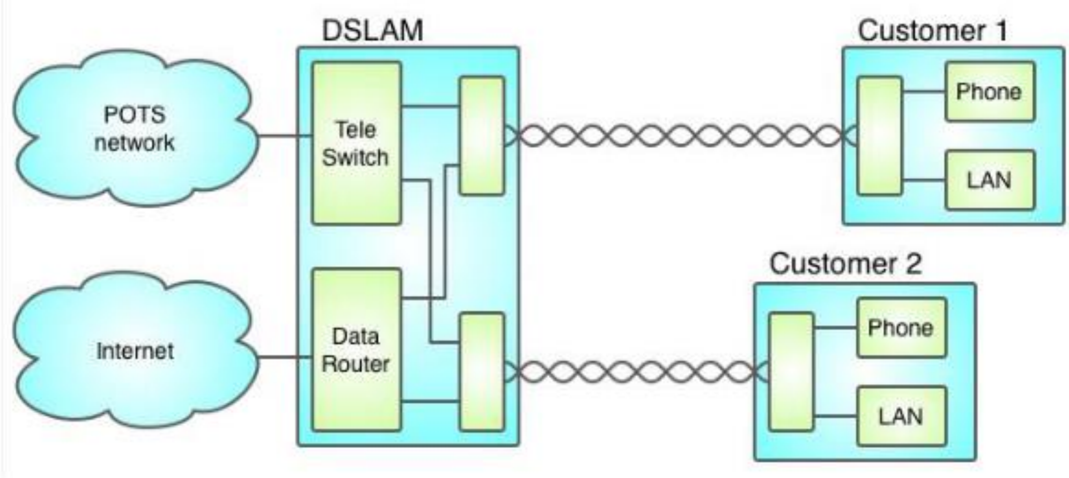

Figure 5: A general DSL connection

DSL exhibits various inhibiting factors in order to achieve higher bit rates.

Firstly, the high frequencies, which are required for higher bit rates, are strongly attenuated by the twisted-pair cable. This places severe restrictions on the achievable length and speed, meaning that higher bit rates are only possible over short lengths of copper cable. So, home located some distance away from the CO will not be able to access the higher speeds (figure 6).

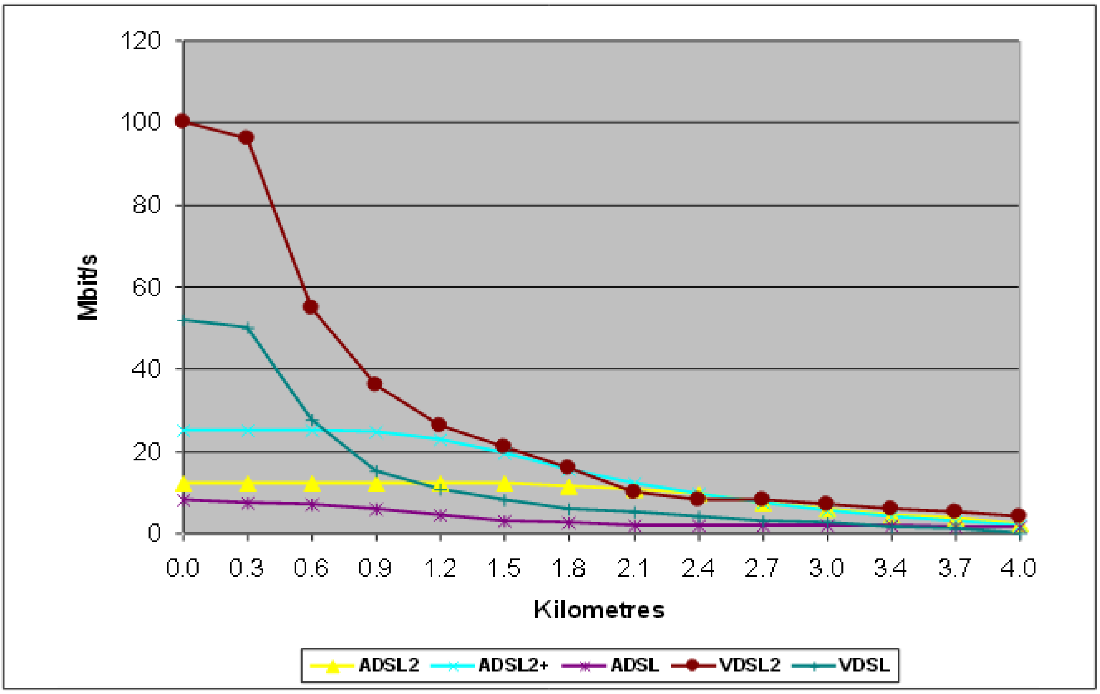

Figure 6: Attenuation of data rate according to copper length

2.2.1.3 Third Generation Broadband: Very high bit rate DSL (VDSL)

To deliver many tens up to one hundred of Megabits per second, VDSL (and later VDSL2) were developed. These techniques are intended and optimized for cabinet deployment, and thus for loop lengths up to roughly 500 m. It is also possible to deploy VDSL2 directly from COs, but it will only benefit the customers that live nearby the CO. For VDSL2, various profiles exist that differ in the frequencies being used (e.g. up to 8.5 MHz, 12 MHz, 17.664 MHz and 30 MHz)3. The more physical bandwidth used, the higher the maximum bit rates at short loop lengths. Typical numbers for the maximum possible bit rate at short loop lengths are more than 100 Mbps in downstream and 30 Mbps in upstream. However, due to the use of high frequencies, VDSL is strongly limited by crosstalk. Therefore, more realistic short loop (~100 m) bit rates for real-world VDSL2 are 50 Mbps downstream and 10 Mbps upstream, about half the maximum bit rate without cross talk noise. On longer loops, the performance goes down further and noise cancellation methods are mandatory for service provision.

In any case, as with 2GBB technologies, the performance is limited by the quality of the physical plant. Old cables damaged by age, fatigue, corrosion, or even poor handling and installation practice, can reduce the line performance. Even the presence of lighter gauge wires (which can range from 0.4 mm to 0.9 mm) or the mix of different wire diameters reduces capability and impairs services.

Finally, performance is affected by the number of subscribers served within a distribution area, as well as the coexistence of different services in the same cable. The remedies are noise cancellation and efficient spectrum selection techniques. These techniques and the use of channel (pair) bonding can guarantee proper service deliverance, of course depending always on the distance. This is going to be further analyzed in the next chapters.

- **Crosstalk elimination - Vectoring**

In VDSL2, crosstalk is a primary limitation and its effect dominates loops shorter than 1 km. The most relevant type of crosstalk in VDSL2 and ADSL2+ is FEXT (Far End CrossTalk), consisting of the interference of one line’s signal over the signal that travels in the neighbor pairs along the cable propagating in the same direction.

Vectoring minimizes the effect of the crosstalk in both transmission directions, downstream and upstream, by means of interference cancellation. Vectoring in VDSL2 systems is defined in the ITU-T Recommendation G.993.5 [1].

Vectoring is optimal for cables shorter than 1 km and without crosstalk coming from non-vectored systems (without unbundling). Literature states that for poorly isolated cables and little twisting, some improvement can still be achieved for loops between 1 and 1.4 km.

If noise other than this interference is very high, the positive effects of vectoring are highly diminished. Moreover, if a cable has multiple binders, vectoring gain will be higher when applied to the whole cable since coupling from different binders, although slightly, affects the victim pair. In any case vectoring will be studied thoroughly in the next chapters.

- **Bandwidth boosters for xDSL**

Bonding is the simultaneous use of multiple DSL pairs to improve total throughput. In bonding, the data channel of multiple DSL pairs is actually bonded, not anything at the physical layer.

The throughput of a set of *n* bonded DSL pairs is approximately the sum of the rates of the individual DSL pairs. Therefore, *n* twisted pairs should achieve *n* times the rate of any individual pair alone. The overall rate may differ from this slightly, since a small amount of extra framing information must be transmitted so that the bits received at the far end can be reassembled in the correct order, even though the delays on the individual pairs may be slightly different.

ITU Recommendations G998.1 [2] and G998.2 [3] provide details for bonding arbitrary types of DSL pairs at either the Asynchronous Transfer Mode (ATM) or the Ethernet layers.

Bonding has several challenges to overcome. It obviously requires at least two twisted pairs running to the respective home, which is not always the case. Moreover, bonding introduces complexity in management due to the need of tracking two or more pairs when provisioning the DSL service. Further, bonding has no inner mechanisms to recover bonded transmission whenever one of the pairs resynchronizes, thus the whole system needs to be reinitialized manually to achieve bonding rates again.

- **G.INP: DSL layer retransmission**

A technique that has been added relatively recently to xDSL is DSL-layer retransmission [4]. G.INP is a newer alternative to FEC (Forward Error Correction) and interleaving to provide a lower overhead (FEC loses about 12% whereas G.INP only corrects errors when they actually occur) so there is little overhead [5].

The purpose of retransmission is to combat the effects of impulse noise that is present in the twisted-pair copper access network. Impulse noise can cause the loss of data packets, and it affects in particular delay sensitive services and high-quality streaming services in which there is not enough time to have the application request a resend of a lost packet. Before the availability of retransmission at the DSL layer, it was necessary to use a robust error correction protocol that requires a substantial overhead, thus reducing of the maximum throughput of the line.

The operation of it lies in the physical layer. The transmitting modem keeps a copy of transmitted data in a retransmission buffer. If the receiver detects corruption (by way of a checksum) a retransmission is requested. If the transmitter responds in time, the data is repaired. The round-tip time of a retransmission should be <4ms. If the transmitter doesn't retransmit in time, the corrupt data is forwarded for higher level protocols to sort out.

2.2.1.4 Fourth Generation Broadband: G.fast

The latest generation of xDSL technology is called G.fast, and is intended to deliver many hundreds of Mbps to customers. This technology is optimized for bridging the last meters or the local loop to the customer, and is therefore intended to be deployed from a point close to the end-user. This technology is going to be examined thoroughly on chapter 5.

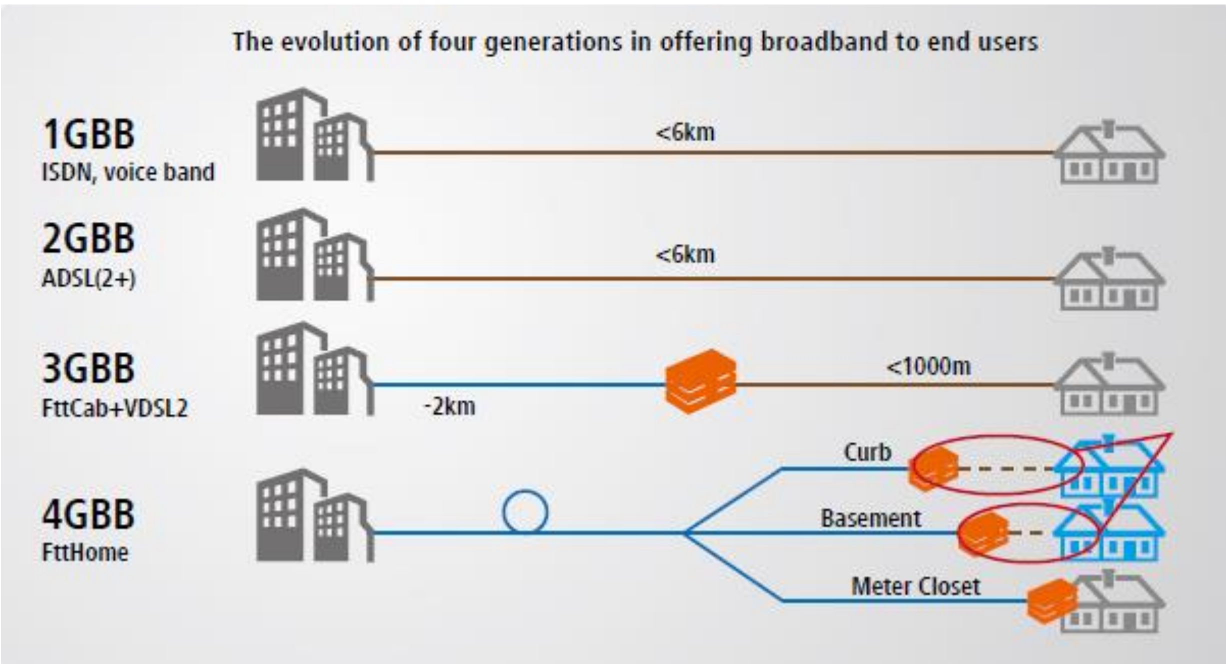

Figure 7: Development of broadband access

2.2.2 Cable technologies

Cable networks were originally established as unidirectional networks to deliver television into customers' home (Cable TV - CATV), as a high-quality alternative to terrestrial television broadcasting that was often subject to interference. The networks were later upgraded to provide two way communication, creating next generation cable TV networks, which are typically Hybrid Fiber Coaxial (HFC) networks, and thus telephony and broadband Internet access were integrated into the cable television infrastructure similarly to xDSL, which uses the existing telephone network.

Indeed, the old cable networks were fully coaxial cable based, but modern cable networks are based on an architecture, where optical fiber is penetrated to the access segment of the network and specifically to the cabinet. Namely, optical fiber is installed to nodes in the street, and coaxial cable connects those nodes to individual customers' home. Furthermore the network has tree-and-branch or star architecture and distributes signals via optical fiber from the provider's central premises to optical nodes, and via coaxial cables from the optical nodes to the subscriber's premises.

Typically, the coaxial cable is a shared medium (figure 8). Where in telephone networks each subscriber is connected by his own twisted copper pair, in a cable TV network a group of subscribers shares the same coaxial cable. So for CATV networks the service level and sustainable bit rate will depend on the number of concurrently active subscribers on the segment of coaxial cable. For example, a single optical node in a big city can serve up to several thousand homes, connected over the same optical fiber. As a result, providers needing to upgrade the cable plant to cope with bandwidth growth are segmenting the network into smaller sharing groups by various methods, i.e. dividing the fiber nodes into two or into smaller nodes, connecting individual fibers to each fiber node etc.

Coaxial cable was always intended to carry high frequency signals. The coaxial portion of the network also includes electronic amplifiers to boost the signal relative to the noise, and so the maximum frequency supported by the cable is determined by the distance between amplifiers.

Figure 8: Coaxial cable

Data transmission over cable networks uses the Data Over Cable Service Interface Specification (DOCSIS), which has been standardized by ITU-T. The current generation, DOCSIS 3.0, was ratified as ITU-T Recommendation J.222 [6].

DOCSIS 3.0 makes it possible for cable providers to increase cable modem capacity relative to earlier technologies by bonding multiple channels together; however it should be noted that these are radio frequency (RF) channels on the coaxial cable spectrum rather than physical cables. DOCSIS 3.0 has no limit on the number of channels that can be aggregated, as long as they fit into the available RF spectrum.

Limits arise from the capabilities of the Cable Modem Termination System (CMTS), usually installed at the provider headend, and the CPE. The cable provider must also decide on the most appropriate (and profitable) split between television and broadband services. An example of cable network is shown in figure 9.

To improve the download and upload speed over cable networks, several suppliers are preparing the next generation of standards, DOCSIS 3.1. The goal is to achieve 10 Gbps for the download bitrate, as well as more than 1 Gbps for the upload (This is shared capacity used by all home on the same coaxial cable segment) [7].

DOCSIS 3.1 will increase the available cable spectrum and aims to use it more efficiently, while providing for error correction Low Density Parity Check (LDPC) instead of Reed-Solomon code.

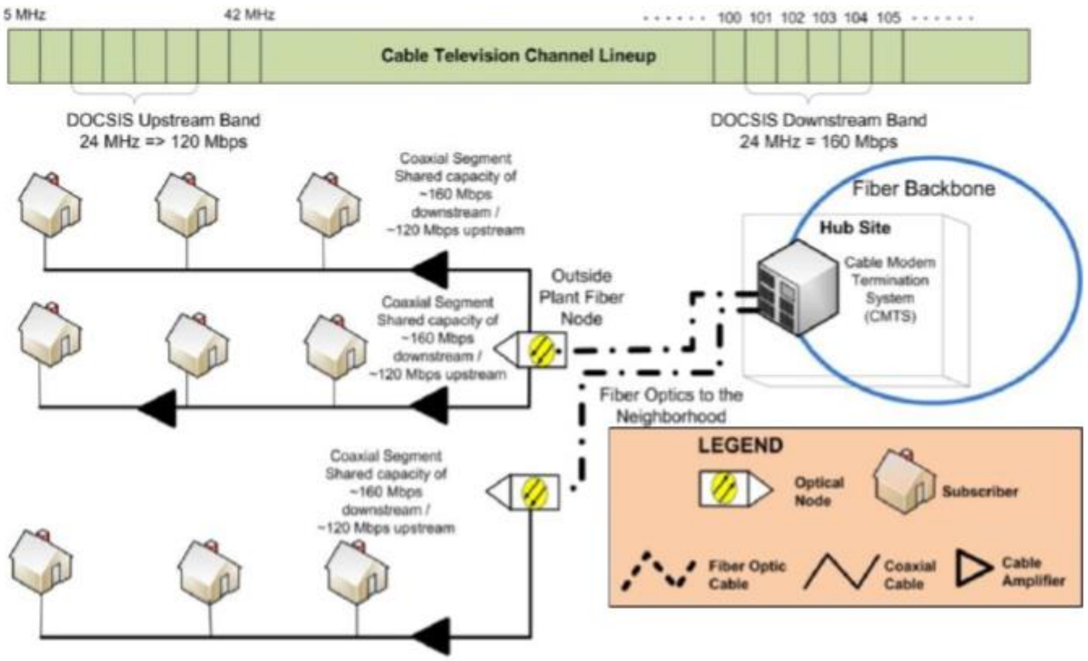

Figure 9: DOCSIS 3.0 Hybrid Coaxial cable architecture

2.2.3 Optical fiber technologies

An optical fiber is a cylindrical dielectric waveguide made of low-loss materials such as silica glass. It has a central core in which the light is guided, embedded in an outer cladding of slightly lower refractive index (figure 10). Light rays incident on the core-cladding boundary at angles greater than the critical angle, undergo total internal reflection and are guided through the core without refraction. Rays of greater inclination to the fiber axis lose part of their power into the cladding at each reflection and are not guided.

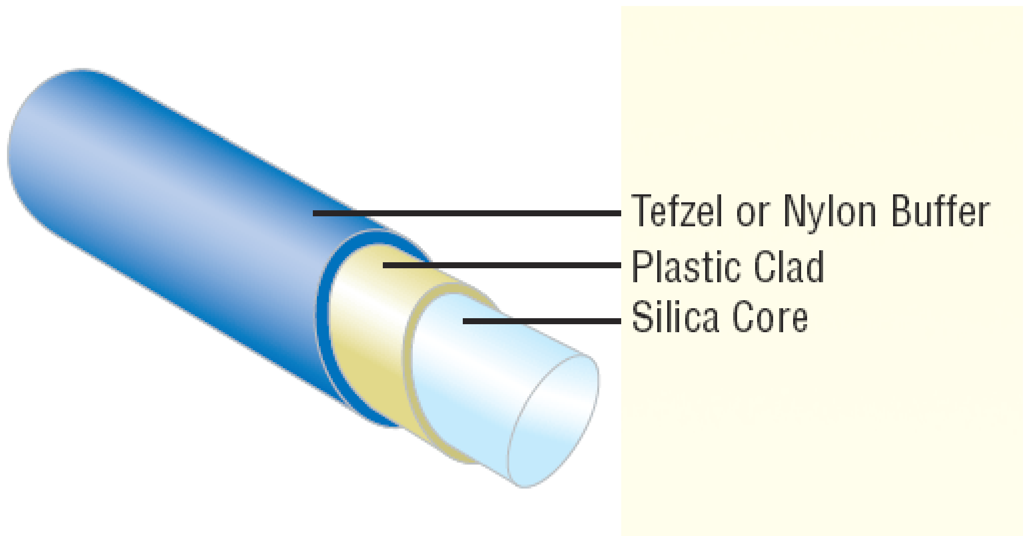

Figure 10: Optical fiber

Optical fiber has incredibly low loss coupled with extremely high capacity, making it a unique transmission medium. From the point of view of the access network The Shannon Limit can effectively be ignored. Distance is not an inherent limitation as optical signals can travel 70–80 km before they need to be amplified. Instead the limitations on bit rate arise from the pace of development of transmission equipment [8].

In contrast to copper and coaxial cables, optical fiber is considered future proof and the systems that integrate it have many advantages over their metallic-based communication systems counterparts. More specifically:

- Long-distance signal transmission: The low attenuation and superior signal integrity found in optical systems allow much longer intervals of signal transmission than metallic-based systems. While single-line voice-grade copper systems longer than a couple of kilometers require in-line signal for satisfactory performance, it is not unusual for optical systems to go over 100 kilometers (km) with no active or passive processing
- Large bandwidth, light weight, and small diameter: Today's applications require an ever-increasing amount of bandwidth. Consequently, it is important to consider the space constraints of many end users. It is common practice to install new cabling within existing duct systems or conduit. The relatively small diameter and light weight of optical cable make such installations easy and practical, saving valuable conduit space in these environments.
- Nonconductivity: Another advantage of optical fibers is their dielectric nature. Since optical fiber has no metallic components, it can be installed in areas with electromagnetic interference (EMI), including radio frequency interference (RFI). Areas with high EMI include utility lines, power-carrying lines, and railroad tracks. All-dielectric cables are also ideal for areas of high lightning-strike incidence.

So, since optical fiber exhibits so many advantages over copper and coaxial cables it is reasonable for the statutory bodies to use it as a key element on the research for new and emerging network infrastructures, which integrate it, fully or partially, into the access segment of the network design.

Chapter 3: Next Generation Networks

3.1 Next Generation Networks

Today, in the telecommunication field, operators are facing several increasing and crucial challenges in order to remain competitive within the open market. From one hand, are the continuous increments either on the data rate offered in fixed networks. In particular, several reports are referring to the increased bandwidth demand based on the emergence of the new services, with some of them to report that by 2016, in some cases, they could surpass 250Mb/s for residential use in fixed networks. Furthermore, the rise of business backhaul applications in whole can lead to a bottleneck in today's gigabit-class backhaul deployments.

On the other hand, crucial challenge constitutes the increased levels of heterogeneity, from types of services to physical interfaces. Specifically, operators must support a plethora of services with different requirements in terms of Quality of Service (QoS), while, concurrently, their transport networks are composed of different transmission technologies in aspects such as coding and modulation formats. These lead firstly, in the occurrence of different networks designed to provide different types of services, and secondly in the high degree of complexity of coding, monitoring and management of the equipment of the network. In short, key issue of highly heterogeneous networks is how to efficiently control and manage network resources while fulfilling user demands and complying with QoS requirements.

So, research community in order to provide a solution for all the aforementioned challenges came up with the Next Generation Network (NGN) framework, which was established by ITU-T and provides the specifications for new era's networks. NGN definition, as formulated by ITU-T, is following below.

"NGN is a packet-based network, able to provide telecommunication services and able to make use of multiple broadband, QoS-enabled transport technologies and in which service-related functions are independent from underlying transport related technologies. It enables unfettered access for users to networks and to competing service providers and/or services of their choice (figure 11). It supports generalized mobility which will allow consistent and ubiquitous provision of services to users." [9]

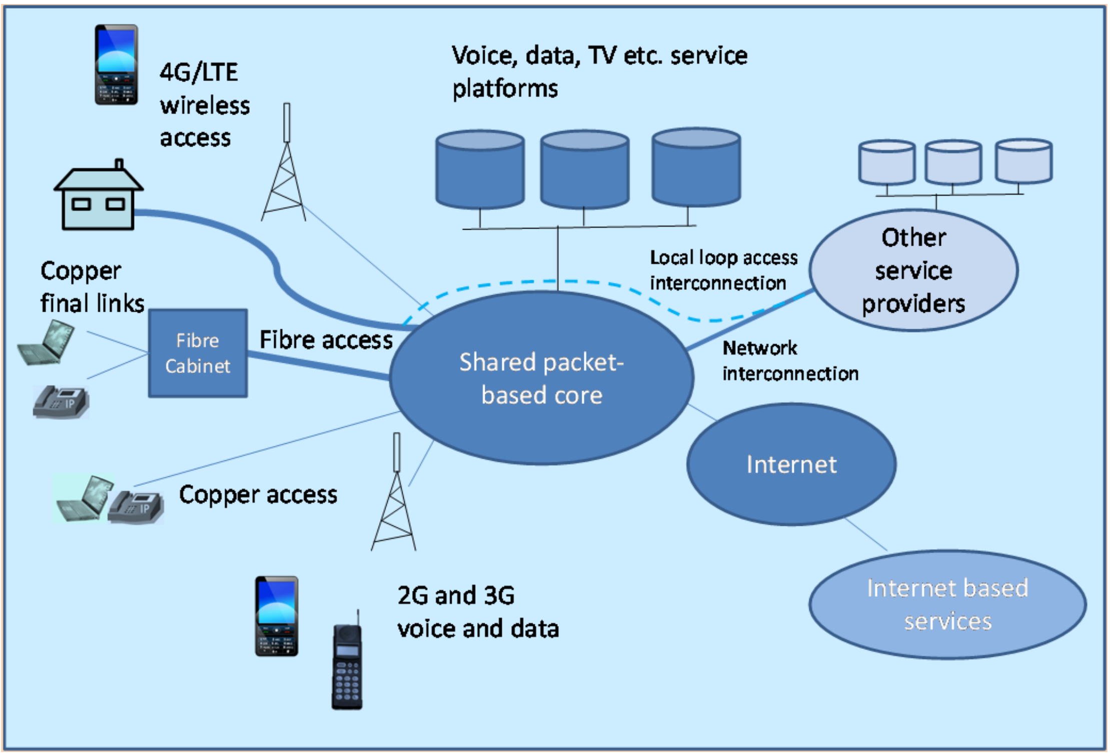

Figure 11: NGN framework

Moreover the fundamental aspects of NGN are:

- Packet based transfer
- Separation of control functions among bearer capabilities, call/session, and application/service
- Decoupling of service provision from transport, and provision of open interfaces
- Support for a wide range of services, applications and mechanisms based on service buildings blocks (including real time/streaming/non-real time services and multi-media)
- Broadband capabilities with end-to-end QoS and equivalent conveyance of all services with the same QoS
- Interworking with legacy networks via open interfaces
- Generalized mobility
- Unfettered access by users to different service providers
- Unified service characteristics for the same service as perceived by the user
- Converged services between Fixed and Mobile networks
- Support of multiple last mile technologies
- Compliant with all Regulatory requirements, for example concerning emergency communications and security/privacy, etc.

In order for NGN to be more comprehensible, below will be expanded some of the key aspects described above and they will be compared to the traditional way that telecom networks have been structured (also known as legacy networks).

- The use of packet based technology as the transport method. Although IP (Internet Protocol) is the main packet based protocol used to transport services, NGNs are physically separate to the Internet, and are managed independently. NGNs commonly supply broadband services that link a customer to the Internet, which is one of many NGN based services.
- Legacy networks typically have service providing systems within the network. Therefore voice switches are located within a transmission network that links them together. Each service (voice calls or leased lines etc.) has its own transmission network and its own dedicated systems. In contrast, NGNs have the same shared IP based platform to convey the services (figure 12). The packets may be differentiated by QoS factors (such as the priority over other packets) but are carried over a shared core network.
- Most legacy networks have specific access links for each service: separate copper wires for every voice and data service. NGN access allows multiple higher speed services to be carried over a single access link-typically fiber or fiber/copper combinations. This enables broadband access at speeds of 100Mbit/s or even more. In contrast copper wires, as used in legacy fixed networks, are limited to a few Mbit/s.
- NGN based services can be delivered over different access technologies making them “agnostic” to the access technology. In principle IP based voice, IP TV or broadband Internet access can all be delivered over one access link which can be fiber, copper or wireless based. The services remain the same (albeit perhaps at different speeds), irrespective of how they are delivered.
- Services are primarily defined by the end user device and the service providing platform. The general purpose packet transport “simply” provides the linkage between the two.

On the other hand both legacy and NGNs have some common features:

- The transmission networks between cities and over international cables use high capacity fiber systems. The capacity on the links may be managed and used differently, but the underlying transport platforms are the same.
- The retail interfaces to customer–billing, customer help desks etc., need to be similar.
- The services seem by the customers are essentially the same. Some are new such as virtual private network leased lines, but most existed before, but at slower speed.

Customers buy the service, not the NGN, so the technology itself should not be a selling point.

- The business need to make profit is not altered, even if the cost base is different. Legacy network managers often struggled to define product margins and to set sensible prices. As costing the different products is harder with NGN, setting profit targets is at least as difficult. The business imperative need to control costs and manage profits, by product and by customer segment, remains common requirements.
- The access needs ducts, cabinets, poles etc. to carry fiber, just as they carried copper cables.

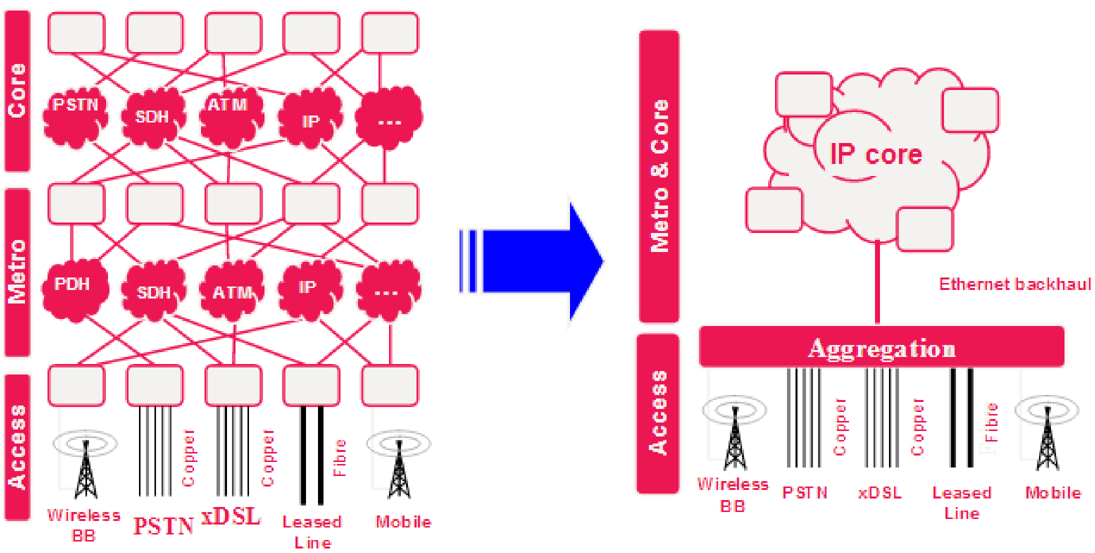

Figure 12: IP based platform

So, one of the most radical changes NGN brings, is the separation of services from transport, allowing them to be offered asunder and to evolve independently. This, also, constitutes key cornerstone of NGN characteristics.

The separation is represented by two distinct blocks or strata of functionality. The transport functions reside in the *transport stratum* and the service functions related to applications reside in the *service stratum [10]*.

Firstly, there is a set of *transport functions* that are solely concerned with conveyance of digital information, of any kind, between any two geographically separate points. A complex set of layer networks may be involved in the transport stratum, constituting layers 1 through 3 of the OSI 7-layer Basic Reference Model. The transport functions main purpose is to provide connectivity.

In particular, the transport stratum facilitates:

- user-to-user connectivity
- user-to-services platform connectivity
- services platform-to-services platform connectivity

In general, any and all types of network technologies may be deployed in the transport stratum, including connection-oriented circuit-switched (CO-CS), connection-oriented packet-switched (CO-PS) and connectionless packet-switched (CLPS) layer technologies according to [11] and [12]. For NGN it is considered that IP (Internet Protocol) [13] may be the preferred protocol used to provide NGN services as well as supporting legacy services.

The services platforms provide the user services, such as a telephone service, a Web service, etc. The service stratum may involve a complex set of geographically distributed services platforms, or in the simple case just the service functions in two end-user sites.

Additionally, there is a set of *application functions* related to the service to be invoked. In this stratum, services may be voice services (including telephone service), data services (including but not limited to Web-based services), video services (including but not limited to movies and TV programs), or some combination thereof (e.g., multimedia services such as video telephony and gaming). Figure 13 below provides the two stratums, service and transport, as well as example list of services that are expected to be operated over NGNs.

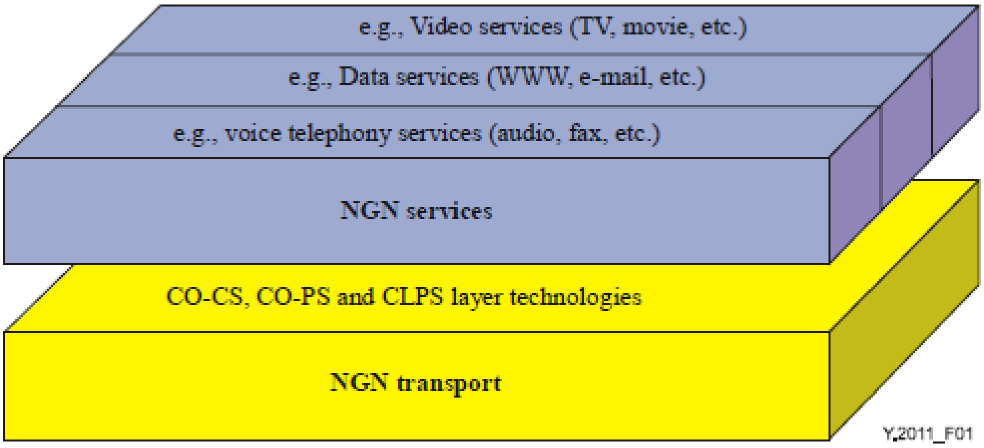

Figure 13: Service and Transport stratum

In general, each stratum will have its own set of roles, players and administrative domains. The roles involved in service(s) provision are independent from those involved in transport connectivity provision. Each stratum needs to be treated separately from a technical point of view. This is achieved by mandatory decoupling of the user (or data) functions of the two strata.

To sum up, based on the above discussions and considering the key cornerstone of NGN, which is separation of services and transport, the following concepts are defined:

- NGN service stratum: That part of the NGN which provides the user functions that transfer service-related data and the functions that control and manage service resources to enable user services and applications. User services may be implemented by a recursion of multiple service layers within the service stratum. The NGN service stratum is concerned with the application and its services to be operated between peer entities. For example, services may be related to voice, data or video applications, arranged separately or in some combination in the case of multimedia applications.
- NGN transport stratum: The part of the NGN which provides the user functions that transfer data and the functions that control and manage transport resources in order to carry such data between terminating entities. The data carried may itself be user, control and/or management information. Dynamic or static associations may be established to control and/or manage the information transfer between such entities. An NGN transport stratum is implemented by a recursion of multiple layer networks as described in [11] and [12].

It is clear that NGN framework refers to a conversion from the existing network infrastructures by changing and evolving towards the new features provided by the technological development. More specifically, NGN, also defined as broadband managed IP networks, can be divided into the Next Generation Core network (NGC), which evolve towards a converged IP infrastructure capable of carrying a multitude of services, such as voice, video and data, and the Next Generation Access network (NGA), i.e. the development of high-speed local loop networks that will guarantee the delivery of innovative services.

3.1.1 Next Generation Core network

The NGCs are defined on the basis of their underlying technological “components” that include– as mentioned in the ITU definition– packet-based networks, with the service layer separated by the transport layer, which transforms them into a platform of converged infrastructure for a range of previously distinct networks and related services. These features may have an impact on traditional business models and market structure, as well as on regulation:

- IP-based network: NGCs generally cover the migration from multiple legacy core networks to IP-based networks for the provision of all services. This means that all information is transmitted via packets. Packets can take different routes to the same destination, and therefore do not require the establishment of an end-to-end dedicated path as is the case for PSTN-based communications.

- Packet-based, multi-purpose: While traditionally separate networks are used to provide voice, data and video applications, each requiring separate access devices, with NGN different kinds of applications can be transformed into packets, labeled accordingly and delivered simultaneously over a number of different transport technologies, allowing a shift from single-purpose networks (one network, one service), to multi-purpose networks (one network, many services). Inter-working between the NGN and existing networks such as PSTN, ISDN, cable, and mobile networks can be provided by means of media gateways.

The migration process towards IP-NGN potentially entails several structural changes in the core network topology, such as the rearrangement of core network nodes and changes in the number of network hierarchy levels. As a result, an overall reduction in the number of points of interconnection will take place, especially with regard to interconnection points at the lowest level. This could negatively affect alternative operators whose previous interconnection investment may become stranded For example, BT today has some 1.200 COs at which competitors have installed DSLAM's, using Local Loop Unbundling (LLU) to provide broadband and bundled services [14]. In addition, BT has over 700 COs at which competitors can connect their voice services. The number and location of points at which competitors could connect their networks to BT's voice services is expected to reduce substantially to at most 108 Metro-node sites, and probably to a subset of these which could number as few as 29, while the number and location of COs at which LLU is likely to be possible are not expected to be affected by the roll-out of 21CN. [14]

3.1.2 Next Generation Access networks

NGAs are new or upgraded infrastructure that will allow substantial improvements in broadband speeds and QoS compared with current services.

The definition of next generation access networks is usually inseparable to investment in fiber in the local loop, i.e. fiber replacing copper in the access segment, able to deliver next generation access services–i.e. an array of innovative services, including those requiring high bandwidth (voice, high-speed data, TV and video).

However, while next generation access networks tend to refer to a specific technological deployment, there are other technologies which can compete in offering some of the services envisaged to be provided by NGNs. In this context, there are also other technologies which may not be able to fully compete with fiber's capabilities in terms of capacity or medium characteristics, but may be perfectly suitable either for users who do not have the need for high capacity access or for providers aiming at a stepwise and cost efficient migration towards full copper infrastructure. The different technologies available include existing upgraded copper networks, coaxial cable networks, power line communications, high speed wireless networks, or hybrid deployments of these technologies. Although full fiber deployment is often described as the ultimate of network infrastructures to deliver next generation access [15], there are likely to be a number of alternative and complementary options for deployment by incumbent telecommunications operators, and new entrants.

3.2 NGN drivers

NGN is an evolutionary process and it can be expected that operators will take different migratory paths, switching to NGN while gradually phasing out existing circuit networks, or building a fully-IP enabled network from the outset. The investment in developing NGN is motivated by several factors, as these are depicted in figure 14. Telecommunication operators have been faced with an increasing competitive pressure in the market to lower tariffs and offer innovative services. This has generated pressure to decrease the cost and complexity of managing multiple legacy networks, by disinvesting from non-core assets and reducing operational and capital expenses.

In this context, the migration from separate network infrastructures to next generation core networks is a logical evolution, allowing operators to open up the development of new offers of innovative content and interactive, integrated services, with the objective to retain the user base, attract new users, and increase Average Revenue Per User (ARPU). NGN is, therefore, considered essential for network operators in order to be "more than bit pipes" [9] and to strategically position themselves to compete in the increasingly converged world of services and content of an already saturating market, where voice is no longer the main source of revenue, and may become a simple commodity. The investment in next generation access networks will be necessary in order to support the new services enabled by the IP-based environment, and to provide increased quality.

Economic Drivers	Technological Drivers	Social Drivers
• Erosion of fixed line voice call revenues. • Competitive pressure from new entrants in high-margin sectors of the market (long-distance, international) and from vertically integrated operators (triple-play bundles). • Saturation of both Fixed and Mobile telephone services • Retain and expand users' base , lower customer churn • Ability to expand into new market segments • Possibility of "ladder of investment", i.e. a phased approach for investment, initially targeting more densely populated areas, and then gradually expanding in other areas	• Obsolescence of legacy networks, plus cost and complexity of managing multiple legacy networks. • Lower capital and operational expenses. Increased centralisation of routing, switching and transmission, lower transmission costs over optical networks. • IP-based networks enable the provision of cheaper VoIP services as a replacement for PSTN voice services. • IP-based networks enable the provision of a wider range of services, and allow bundling of services (triple and quadruple play). • Evolution and convergence of terminal equipment.	• Demand for innovative, high-bandwidth, services (HDTV, VoIP, etc). • Demand for more targeted or personalised content (on demand multimedia services, mobility)., • Demand for increased interactivity: possibility to interact actively with the service, growing interest for user-created content. • Demand for evolved and more flexible forms of communications, including instant messaging, video-conferencing, P2P, etc. • Business demand for integrated services, in particular in case of multi-national structures, which need to link different national branches, guaranteeing a flexible and secure access to centralised resources and intelligence.

Figure 14: NGN drivers

It is evident that one of the most powerful and important drivers for all the technological migrations network deployments is the provision of emerging and bandwidth-demanding services and applications.

Indeed, there is a wide range of services and applications offered, from the Service Providers (SPs) to the end users, which are assigned with different values in respect to QoS parameters. Applications like telephone, internet and IPTV are popular and constitute a well-known product solution called triple play. Henceforth SPs, with the advancements in the bandwidth and technology domain in general, are obligated to offer new and rich feature-wise services, in order to differentiate themselves in an increasingly saturating market. Moreover, SPs must be able to retain support for legacy services, such as TDM and POTS, through either emulation (complete replication of the service) or simulation (providing a service that is almost the same as the desired one), in an adequate level equivalent to today's standards.

The most important services as of right now are: VoD, IPTV, High Speed Internet (HSI), VoIP and they form the basis for a wide range of applications like web space, online backup, gaming, home surveillance, immersive TV, free viewpoint TV, web3D etc. Figure 15 shows that entertainment services and applications, especially interactive ones, drive the necessity to increase the available bandwidth at the so called final-drop, while they constitute an attraction for residential market.

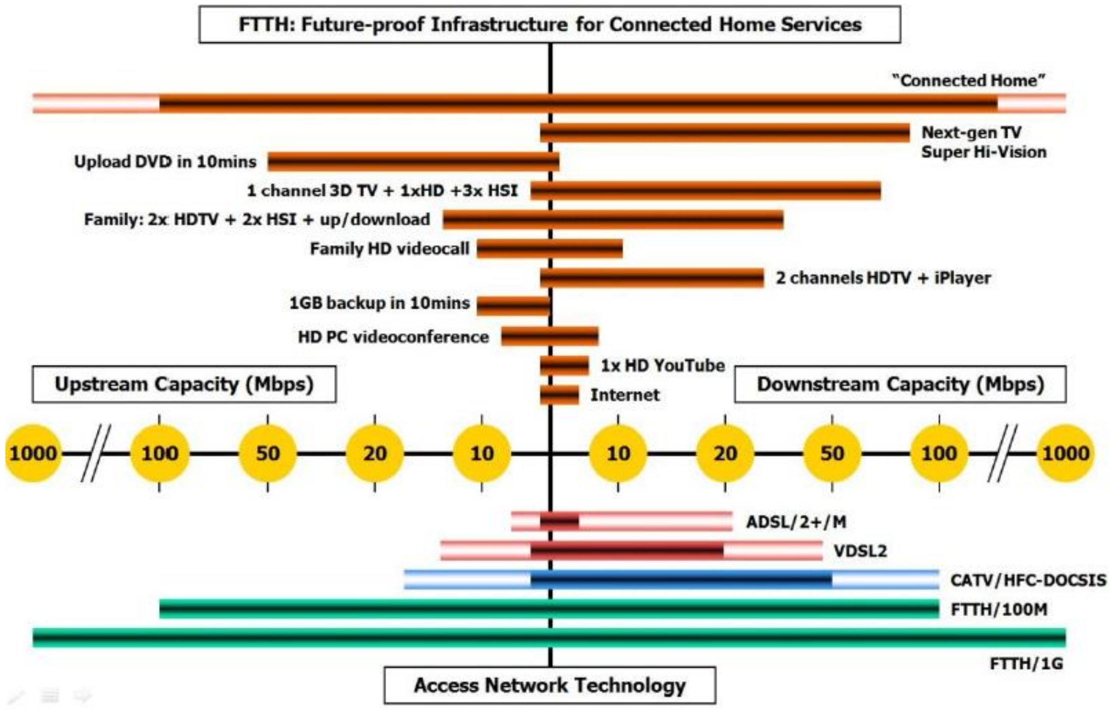

Figure 15: Demanding home services

This wide variety of services offers SPs the opportunity to bundle applications to different basic packages aiming in this way at specific market segments, while creating increased revenue potential. Thus SPs must be in position to fulfill the different service requirements, arising from the end-user needs and expectations, as well as from the nature of the data, for smooth, unobstructed and continuous delivery of services. The former, deals with the demands and the expectations of the end user regarding the provided application or service, and it is closely associated to Quality of Experience (QoE) or the overall acceptability of an application or service, as it is perceived subjectively by the end-user [16].

These mainly depend on user's previous experience with similar telecommunication services and on the price he is willing to pay.

Chapter 4: FTTx networks

4.1 FTTx networks

In the research field of NGA, which was described in previous chapter, there are a lot architectures proposed known as FTTx networks or Fiber to the x, wherein x denotes the place where fiber is terminated. Basically, FTTx is a generic term used for any network architecture that uses an optical fiber infrastructure to deliver high speed voice and data signals in a variety of applications. Some examples of such networks are Fiber to the Home (FTTH), Fiber to the Curb (FTTC) and Fiber to the Building (FTTB).

Optical distribution within an FTTx network and mainly in FTTB and FTTH, can face a number of competing technologies including Direct fiber, Shared fiber, Active Optical Networks (AON's) and Passive Optical Networks (PON's). Direct fiber is possibly the simplest form of optical distribution. In this architecture, each fiber leaving the Point of Presence (PoP) goes to only one customer. This type of network provides the customer with excellent bandwidth as they have their own dedicated fiber. Shared fiber is the most common architecture used across FTTx applications. In this type of network the fiber leaving the PoP is shared by a number of customers. It is not until the fiber gets relatively close to the customers that it is spliced into individual customer specific fibers.

The difference between the Active Optical Network and the Passive Optical Network is quite simple. The AON relies on some form of electrically powered equipment to distribute a signal, such as a switch, router or multiplexer. Each signal leaving the PoP is dedicated to one customer and the powered equipment acts as a buffer to prevent any signals colliding. The PON is a point-to-multipoint, fiber to the premises network where unpowered optical splitters are used to enable a single optical fiber to serve multiple premises. A PON configuration can help reduce the amount of fiber and PoP equipment required compared to the point to point nature of an AON.

With the criterion described above, some major FTTx networks are analyzed below:

- Fiber-To-The-Curb or cabinet (FTTC)
- Fiber-To-The-distribution-point (FTTdp)
- Fiber-To-The-Building or basement (FTTB)
- Fiber-To-The-Home (FTTH)

FTTC

In this architectural proposal the equipment, switch or DSL access multiplexer (DSLAM), is installed in outdoor cabinets, originally used for copper sub loop aggregation, and therefore a single fiber or a pair of fibers extends from this point back to the CO, while the end user continues to use existing copper infrastructure to obtain services. The outdoor cabinet's equipment carries the aggregated traffic via Gigabit Ethernet, xPON or 10 Gigabit Ethernet connections. Many service operators deploy this architecture as it is less intensive in terms of investment compared to solutions like FTTH/B, by avoiding the installation of fibers in the last mile. Deploying FTTC is a step that many operators embrace in order to achieve required bandwidth increments, utilizing VDSL2, with or without vectoring, which can provide significantly higher rates than ADSL2+. For the majority of operators this is regarded as an interim step towards FTTB/H deployment.

FTTdp

This solution has been proposed recently and connects the CO with the Distribution Point (DP) via fiber and, from there, connects the end user via the existing copper infrastructure. The DP can be a manhole, a drop box on the pole or a mini-cabinet and it is in smaller distance, normally less than 250m, than the FTTC's equipment installation location.

The technical and financial feasibility for the selection of the DP as the adaptation point between fiber and copper access technologies depends on some crucial factors. Firstly, it depends on the existing architecture of the copper network and on whether using DP offers any advantages compared to using the outdoor cabinet. Specifically, one has to distinguish between Urban and Rural areas.

In Urban areas a dense network of outdoor cabinets exists and the average copped sub-loop length to the end user in most cases does not exceed 300m. Therefore, it would be pointless for someone to not choose as distribution point the outdoor cabinet, as no significant advances in data rates are expected.

In Rural areas though, the situation is rather opposite with sub-loop extending up to 1km in some cases. In those cases the distribution point is a considerable alternative as the data rate differences would be substantial.

Another significant factor that determines the feasibility of FTTdp is the regulatory environment and more specifically whether the DP is included in the options for sub-loop unbundling.

FTTB

FTTB refers to the network architecture where the fiber reaches the boundary of the building, such as the basement of an apartment block or a business space, where the optical termination box is installed. The connection with the equipment in the CO can be achieved through dedicated fiber or through an optical splitter, which uses shared fiber in the feeder section. From the optical termination box each individual connection with the end-user is achieved by non-optical medium, such as coaxial cable, twisted pair etc., and thereby the maximum bandwidth that an individual can reach is limited by the physical condition of the medium as well as by the bandwidth allocation, which depends on the total number of users, especially in the shared fiber model.

The end user receives services via existing copper technologies such as VDSL (with or without vectoring) and the upcoming G.fast. The concept of routing fiber directly into the home from the CO or through the use of optical splitters brings us to the FTTH scenario.

FTTH

In FTTH copper ceases to exist and the access path consists only from fiber cables, which are used to connect end users to CO, either via dedicated fiber or initially to a passive optical splitter via dedicated fiber and then though shared fiber in the feeder section to the equipment in the CO.

Below is depicted a high level network design for each of the FTX networks analyzed above.

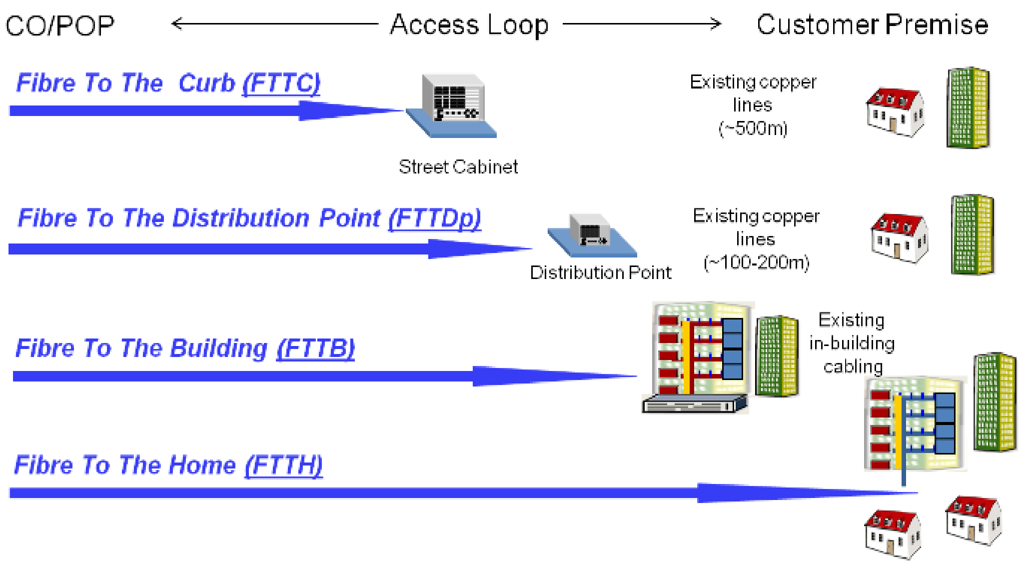

Figure 16: FTTx network architectures

Apart from the aforementioned, other architectures that fall within the FTTx term are Fiber To The last amplifier (FTTla), where fiber extends to the last amplifier and from there coaxial cables are used to connect end users, and Fiber To The Antenna (FTTA) where fiber extends from the base station to the antenna and it is mostly deployed by Mobile Network Operators (MNOs).

Other crucial aspects of the FTTx networks for a network provider or operator, apart from the architecture, are the topology, regarding the way that fibers and equipment will be integrated, the technology for data transmission, and the modulation scheme.

In order to specify the interworking of passive and active infrastructure, it is important to make a clear distinction between the topologies used for the deployment of the fibers (the passive infrastructure) and the technologies used to transport data over the fibers (the active equipment).

The two most widely used topologies are point-to-multipoint, which is often combined with a passive optical network (PON) technology, and point-to-point, which typically uses Ethernet transmission technologies figure 17.

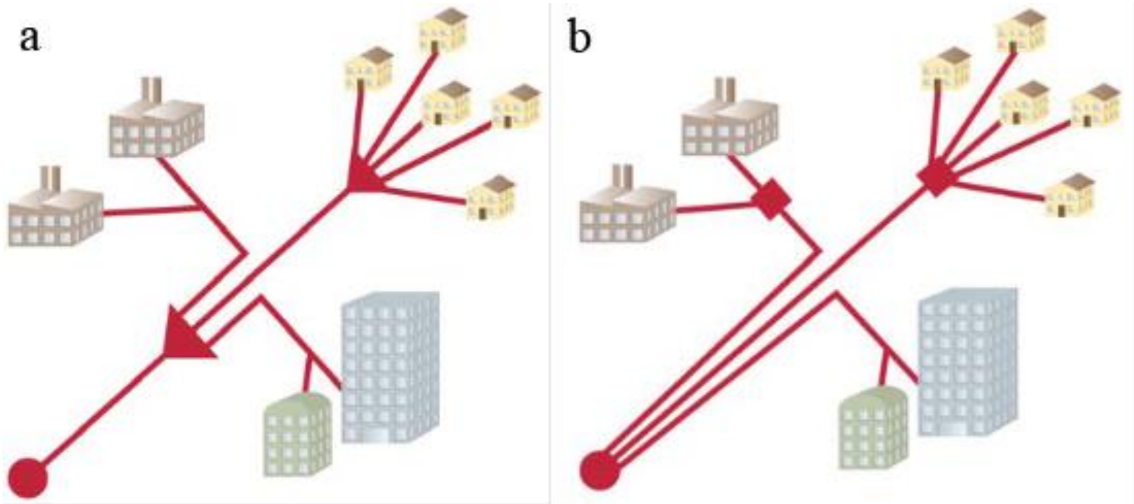

Figure 17: a) Passive optical network b) Active Ethernet network

Point-to-point topologies provide dedicated fibers between the CO and the subscriber, wherein each subscriber has a direct connection with a dedicated fiber. The route from the central office (CO) to the subscriber will probably consist of several sections of fibers joined with splices or connectors, but provides a continuous optical path from the Access Node to the home. Most existing point-to-point FTTH deployments use Ethernet, which can be mixed with other transmission schemes for business applications (e.g. Fiber Channel, SDH/SONET).

- Point-to-multipoint topologies provide a single "feeder" fiber from the central office to a branching point and from there one individual, dedicated fiber is deployed to the subscriber. A passive optical network technology such as Gigabit PON (GPON), which is today's frontrunner in Europe and Ethernet PON (EPON) being the most popular in Asia, uses passive optical splitters at the branching point(s) and the data are encoded so that users only receive the one intended for them, due to the use of time-sharing protocols to control the access of multiple subscribers to the shared feeder fiber [17]. Specifically, PON equipment comprises of an Optical Line Terminal (OLT) in the CO. One fiber runs to the passive optical splitter and a fan-out connects a maximum of 64 end-users with each having an optical network unit (ONU) at the point where the fiber terminates (figure 18).

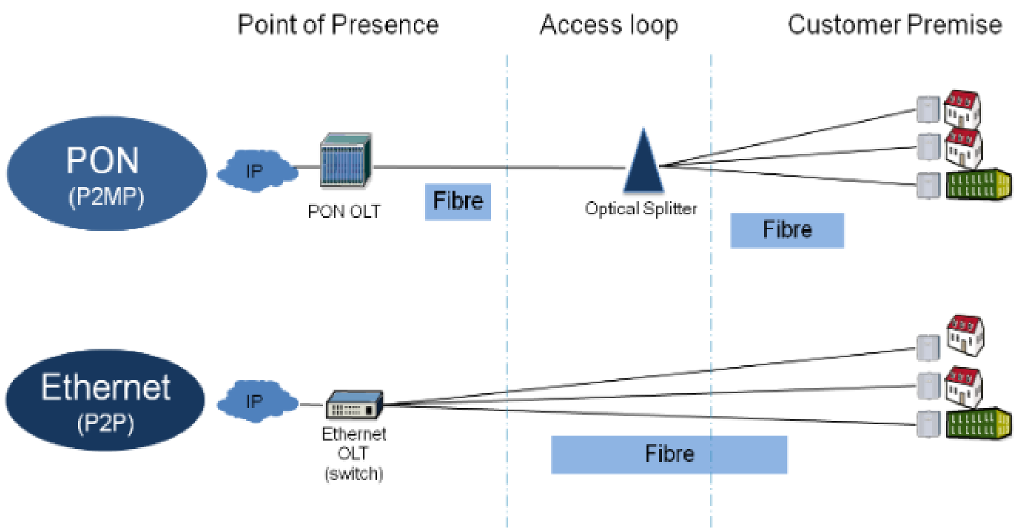

Figure 18: GPON and Active Ethernet 1

To further emphasize on the technologies used for data transmission in the access segment, IEEE and FSAN, in cooperation with ITU-T, conceptualized the solutions proposed for both PON and AON.

IEEE, through EFM working group, proposed solutions that integrate Ethernet in the access segment for ptp and ptmp connections.

- For ptp connections IEEE produced three standards for single fiber mode
  - Fast Ethernet, whose specification called 100Base-XX,
  - Gigabit Ethernet, whose specification called 1000Base-XX
  - 10 Gigabit Ethernet, whose specification called 10GBase-XX
- For ptmp IEEE introduced Ethernet PON (EPON) which initially offered symmetrical 1Gb/s and in 2009 ratified a new standard, 10G-EPON, offering symmetrical 10Gb/s bit rate. As of right now IEEE investigates the requirements for the next generation of EPON (NG-EPON) in order to provide rates higher than 10G-EPON. On the other hand, FSAN/

ITU-T standardized PON solutions like APON, BPON, GPON and 10G-PON, these are several generations of PON technologies to date (figure 19). Right now, asymmetric 10G-PON with 10Gb/s downstream and 2.5Gb/s upstream and symmetric 10G PON with 10Gb/s downstream and upstream are commercially available. The next goal for FSAN/ITU-T is to provide NG-PON2 specifications, with 40Gb/s downstream and 10Gb/s upstream based on TWDM-PON (TDM/WDM-PON) hybrid system.

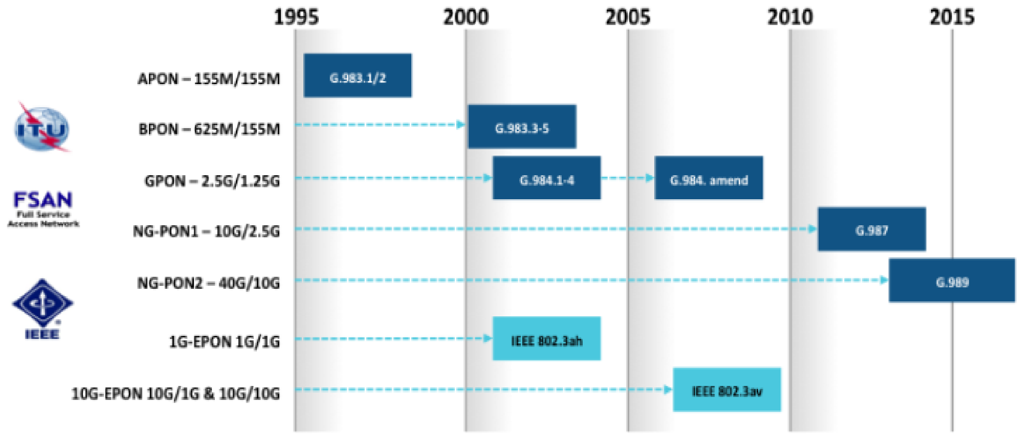

Figure 19: PON evolution

Finally, besides the distinction based on the network's topology and equipment's technology incorporated, another one can be made according to the modulation scheme used, which is currently based on Time Division Multiplexing (TDM).

FSAN, between 40Gb/s TDM PON, WDM PON, TWDM and OFDM PON, chose TWDM for NG-PON2 deployment scheme, as said before, which is a hybrid system that piles up four 10G-PON in only one fiber and achieves an aggregate capacity of 40Gb/s, whilst retains cost convenience since it doesn't require changes in the outside plant. This choice is considered less risky and less expensive than other approaches because it reuses existing components and technologies [18].

On the other hand 40Gb/s TDM PON supports very efficient bandwidth sharing between users, but presents high costs and uncertainty associated with some challenges, such as resolving the problem of chromatic dispersion for very high line rates [18].

Moreover, WDM allows the transmission of several different wavelengths over the same fiber and concurrently promises to combine the two access topologies: a PON network with logical ptp connectivity (one wavelength per user). While the technologies behind WDM are commercially available, they are excessively costly and so WDM doesn't constitute a viable solution as of right now.

Finally, OFDM is a technique where a high-speed data stream is divided into multiple parallel lower speed streams and is modulated to different frequency subcarriers.

Up until today OFDM has not been proposed by any vendor, but there is an extensive research focus on deploying OFDM not only on the access networks but also for long-haul transmissions as it provides promising results [19].

4.2 FTTx deployments

As stated before fiber is the leading access solution, since it provides the ability to accommodate new and emerging services and, unlike copper, is considered future proof. So, many countries around the world focus on deployment strategies for integrating the aforementioned architectures in the access network. Regarding FTTH/B deployment, Asia is leader in total subscribers with China particularly in the 1st place, Japan in 2nd and South Korea in 3rd, following U.S.A and Russia in 4th and 5th place respectively, whereas in FTTC VDSL deployment, Europe is the leading force overall with an increasing interest from the majority of European countries as is more cost efficient than FTTH/B, and also consists an interim step towards them. On the other hand FTTdp is relatively new technology and begun to be commercially as of 2016, but a lot of operators are already showing interest, due to the high bandwidth rates offered while retaining copper in the access segment [20].

The deployment of the different FTTx architectures by region is depicted in figure 20, where Asia again provides the highest FTTH/B rates. For North America the greater proportion of FTTx technology used is FTTla, due to existing cable TV network. On the other hand, for Middle East and Africa (MENA) FTTH/B constitutes the only deployment architecture, wherein FTTH represents the 99% and FTTB 1% of total. Moreover, United Arab Emirates (UAE) is in the first place in the Global FTTH ranking of countries with the highest household penetration, where there is a big percentage of FTTH/B deployments against other architectures, which are based on copper or Hybrid fiber-coaxial (HFC) [21].

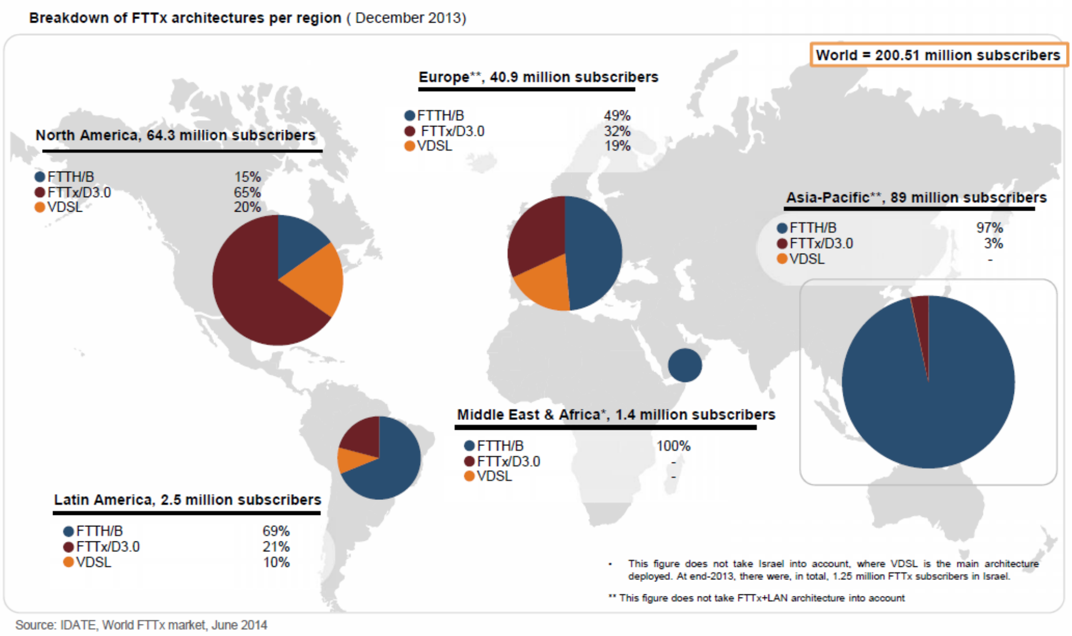

Figure 20: World FTTx market, June 2014

Finally Europe has an overall percentage of FTTH/B deployments that accounts for one fifth of global FTTx connections, with Lithuania being the leading force in fiber penetration followed by Norway, Latvia, Sweden and Russia (figure 21). For Greece, currently, there is low FTTx deployment, with the exception of a small number of limited in scope FTTH pilot projects across the country and the FTTC – VDSL deployment plan by incumbent operator OTE.

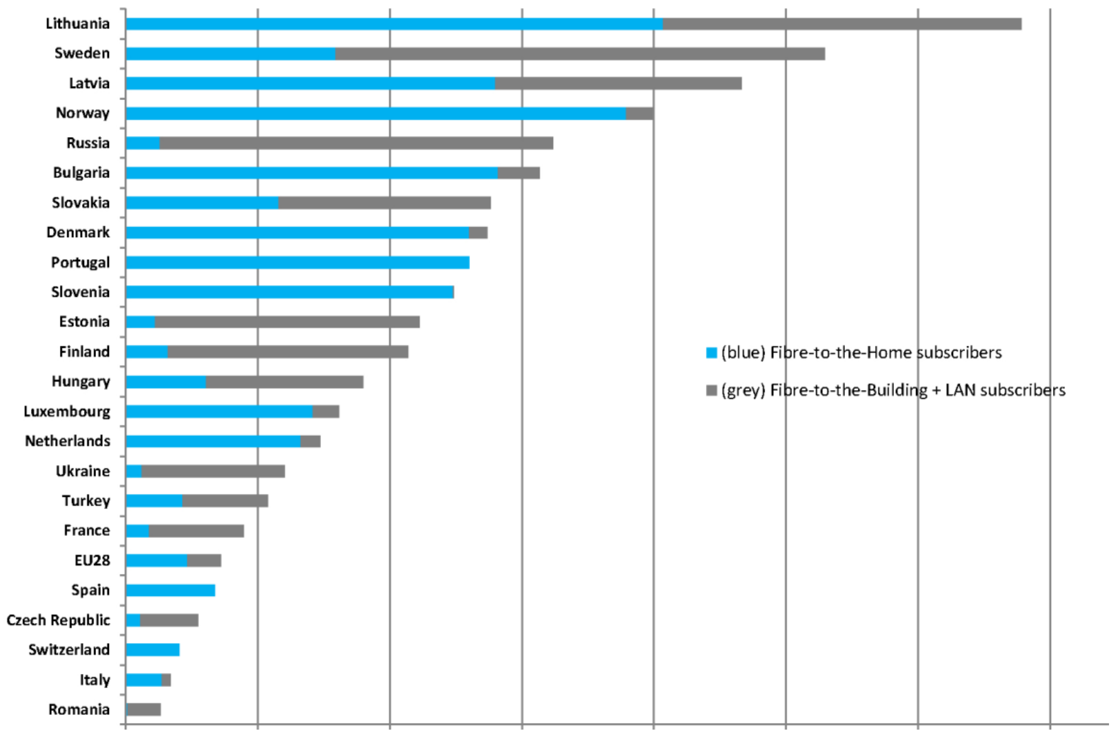

Figure 21: European household penetration

Particularly interesting is the fiber deployment strategy that each European country follows in order to meet the Digital Agenda of Europe (DAE) 2020 [22], which indicates a minimum of 30Mbps access rate for all by 2020. This strategy depends on the different existing infrastructure of each country, the different architecture deployed and the regulatory status for NGA in each country.

Initially the majority of countries headed towards direct integration of FTTH/B regardless the existing infrastructure, but some of them changed this plan to a gradual process towards it, selecting a gradually approach and starting with of more cost efficient technologies like VDSL2+, VDSL2+vectoring, G.fast etc., which prolong the lifespan of existing copper networks. Additionally, apart from copper network, many countries, like Spain, already have cable infrastructure offering services, such as cable TV. For them it was a logical outcome to shift to FTTla technology, instead of FTTH/B.

Chapter 5: G.FAST

5.1 Introduction

In the previous chapters it was made clear that the demand for higher data rates is continuously increasing, making this way the upgrades in the network architecture domain essential. Applications like Cloud Computing, Video Streaming, Big Data and the Internet of Things drive these demands.

Strong competition of cable network operators increases the pressure on copper network operators and vice versa to deliver high speed services. But a pure fiber network will cause very high costs to be built today at a large scale. During the transition from copper-based access networks to pure fiber networks, the fiber network is gradually extended towards end users, leading to a copper fiber hybrid network. This idea is gaining ground among providers and vendors due to ability to offer bigger bandwidth, while reducing overall expenses.

In this context, the fourth generation of broadband or 4GBB consortium was able to develop a new DSL protocol known as G.fast. The name G.fast is an acronym for *fast access to subscriber terminals,* while the letter *G* stands for the ITU-T G series of recommendations, specifically G.9700 and G.9701, whose goal is to develop and describe methods to transmit data at fiber speed over short copper wires, probably to multiple subscribers sharing a cable binder, with low power consumption.

A dense fiber network, where the fiber ends very close to the subscribers and the remaining gap is closed using short length copper wires, requires introducing a new network node, the distribution point (DP). At this point, the fiber is connected to a small number of copper pairs using an active device called DP unit, DPU, (figure 22). DPU includes typically a DSL Access Multiplexer (DSLAM) that can support up to 24 users and an Optical Network Terminator (ONT), which connects the DPU to the CO where the OLT is located. The network architecture that exploits the benefits of G.fast is the FTTdp, which provides a new and attractive solution compared to the others FTTx systems, studied in previous chapter [23].

Notably, G.fast aims to provide ultra-high speeds over copper twisted pairs, up to 1 Gbps. The planned loop lengths for G.fast are from 50 to 250 meters (figure 22), although BT, through extensive field trials, aims at G.fast to be able deliver service nearly 300+ meters from the end user premises [24].

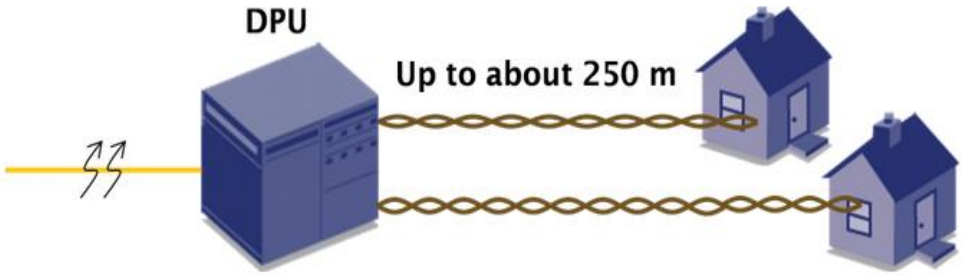

Figure 22: G.fast high level topology

5.2 G.fast Technology

G.fast is based on the latest VDSL technology including crosstalk cancelation and retransmission. Main changes are done for Physical Media Dependent (PMD) layer of the system. The physical layer design is based on the idea of the DP as described above. The medium access is done with Time Division Duplexing (TDD) rather than Frequency Division Duplexing (FDD), which reduce analog complexity and analog front-end power consumption, that is used by the other DSL technologies. With TDD, the system transmits only downstream signals for a fraction of time, and transmits only upstream signals for the remaining time. TDD allows the speed asymmetry to be varied at will, among all the lines emanating from the same DPU. This allows some areas to be served with business-class symmetric service, while other areas can be served with asymmetric service that best addresses consumer needs.

Finally, G.fast technology uses the 106 MHz frequency band in the initial stage and 212 MHz in the future. The wider the frequency band, the higher bandwidth G.fast can achieve (figure 23). However, higher frequencies also mean shorter transmission distances, higher costs, and greater power consumption. The frequency band that is ultimately used is a compromise between performance and costs.

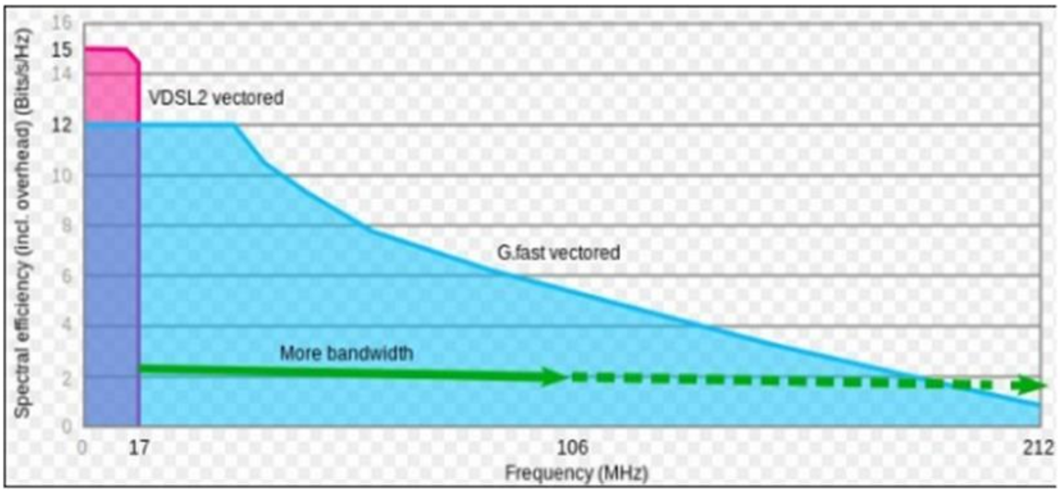

Figure 23: G.fast and VSDL spectrum

Based on the figure 23 it is clear that G.fast as a technology uses significantly more spectrum than VDSL, achieving this way higher data rates, but with the tradeoff of enhanced crosstalk, which will be analyzed below

5.3 Reverse Power Feeding

Another significant change is that DPU is placed in DP, raising the question about the power supply of the DPU, as the distribution point may be in different position from the existing cabinets. Towards this direction, research community and especially Broadband Forum with WT-318 and ETSI with TM6, proposed Reverse Power Feeding (RPF), where power is sent from the customer premises to DPU. RPF reduces installation cost by removing the need to connect the DPU locally to the power grid, as well as the need to monitor its power consumption with a smart meter.

Overall, the benefits of RPF are:

- Flexibility
- AC source proximity or location safe for AC not necessary
- Alternative to batteries at the DPU
- No need to wait for the electrical company to install
- Cost advantage in low port count DPUs
- Standardized by ETSI
- Interoperability, Safe

Reverse powering needs to provide approximately 10 Watts, which is sufficient because the G.fast transceivers are very close to the subscribers and require little transmitter power, while is also estimated that it will exploits different source classes for short range (60V DC) and long range (120V DC). Reverse powering, and low-power modes planned for G.fast, are expected to lower its deployment costs by eliminating the need for costly network powering and battery back-up of remote DPUs.

The use of reverse powering means that the DPU may lose power if all the CPE connected to it are turned off and no longer provide reverse power feed. The solution is to employ a Persistent Management Agent (PMA) located either in a continuously-powered part of the network, or preferably virtualized in the cloud. The PMA will store diagnostics data from the DPU, so these are available after the DPU is powered down. The PMA can also accept configuration changes and apply them after the DPU regains power.

5.4 G.fast crosstalk

To achieve high data rates on low quality cables, crosstalk cancelation, as it has been introduced in VDSL2 Vectoring is of increasing importance [1]. Due to the increasing crosstalk strength at high frequencies used in G.fast, advanced crosstalk cancelation methods must be evaluated. Especially, at these frequencies, it is not uncommon to see crosstalk on a G.fast line that is similar in strength to the actual signal. One challenge is to create a compensating signal that eliminates crosstalk without exceeding the Power Spectral Density (PSD) mask. More advanced algorithms are required to compensate for these high crosstalk levels.

Whenever multiple subscribers are part of the same cable binder, some portion of the signal from one line disturbs the signals of other lines through the electromagnetic coupling between them. With increasing frequency, the crosstalk coupling between the lines becomes stronger until the crosstalk couplings and the direct connection have the same strength at very high frequencies. Crosstalk is based on the Electromagnetic Interference (EMI).

In order to become more comprehensible, figure 24 provides a plot of the impact of crosstalk in G.fast. This plot exhibits several signal-to-noise (SNR) ratio curves of one G.fast line in a cable binder of 16 lines. When all other lines are switched off, no crosstalk is present and the SNR curve of the green line is achieved. But when all lines are active, crosstalk is present and the SNR reduces dramatically to the red line.

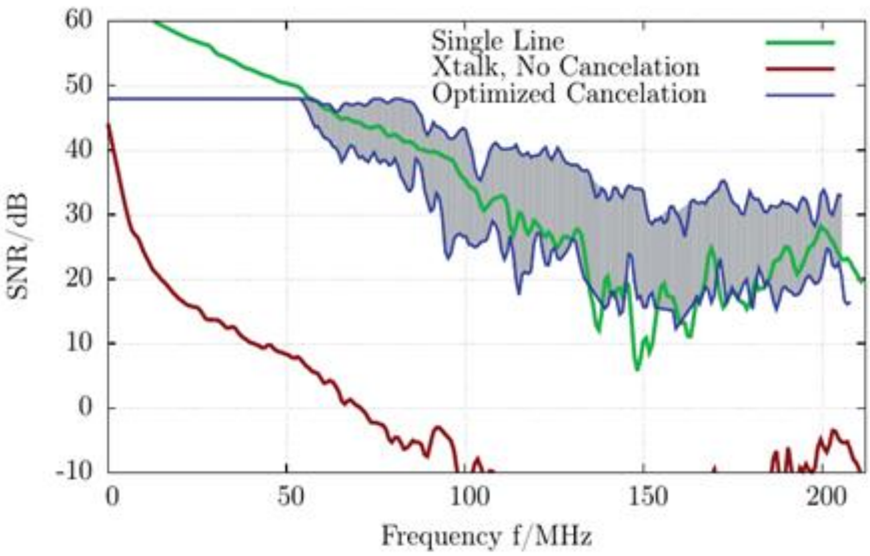

Figure 24: Crosstalk in G.fast 1

Crosstalk cancelation aims to compensate with the negative effect of crosstalk, while all lines are still active.

For crosstalk we distinguish two types; near-end crosstalk (NEXT) and far-end crosstalk (FEXT). The situation of a binder with G.fast lines only is shown in figure 25 (a). In this case, only FEXT is present, where the G.fast receivers get signals from the corresponding far-end transmitter, but are disturbed by far-end signals from other lines. NEXT does not exist in pure FTTdp scenarios, because the DP synchronizes the transmit signals such that all lines send their downstream and upstream signals at the same time, this is known as Synchronous TDD-OFDM (STDD-OFDM).

So, NEXT is interference between upstream signals and downstream signals of different pairs at the same edge of the cable, while FEXT is interference between upstream signals of different pairs or between downstream signals of different pairs, measured at the other end of the cable with respect to the interfering transmitter.

So, NEXT, where the transmit signal of one line disturbs the receiver of another line at the near-end, e. g. transmitter and receiver are within the same mini-cabinet, exists for the FTTC scenarios with VDSL and G.fast in the same binder. This is shown in figure 25 (b). Due to the fact that G.fast uses TDD and VDSL uses FDD, a street cabinet DP with both services experience near-end crosstalk in addition to FEXT at the overlapping frequency spectrum.

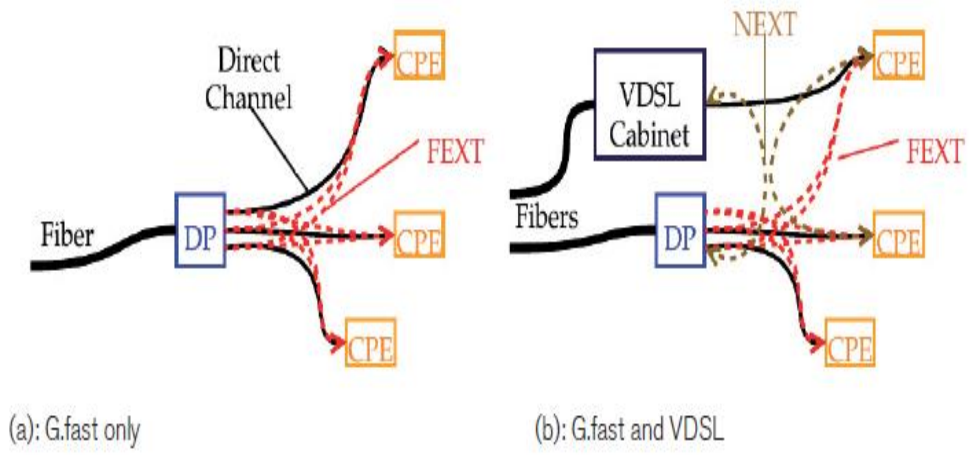

Figure 25: FEXT and NEXT

5.4.1 Overcoming FEXT Crosstalk

So, while, NEXT can be eliminated due to STDD-OFDM, FEXT on the other hand is more complicated and more serious threat for G.fast than the other DSL technologies, due to the high frequencies, and it can lead to signal-to-noise ratio (SNR) decrease, which reduces the line data rate or increases the bit error rate (BER), or potentially resynchronization, severely affecting system stability and customer experience.

In order to cope with FEXT and cancel it, vectoring technology or Self-FEXT cancellation must be used.

Vectoring is a transmission method that employs the coordination of line signals for reduction of crosstalk levels and improvement of performance. The degree of improvement depends on the channel characteristics. Vectoring may be for a single user or for multiple users' benefit [1].

It removes the FEXT created within a vectored group (self-FEXT) by performing pre-coding at the transmitter (downstream), where the signal is pre-distorted such that the received signals are free of crosstalk at the CPE side and crosstalk cancellation at the receiver (upstream), through matrix equalization. Downstream vectoring is able to cancel only the crosstalk within a given vectored group of lines, but not the crosstalk generated by lines outside the vector group. The downstream and upstream transmissions of all the lines in a vectored group are synchronized to a common clock, which allows transmitters to cooperate in the removal of self-FEXT.

More specifically, in the downstream, transmitters collocated at the DSLAM cooperate to eliminate crosstalk by performing pre-subtraction of the crosstalk that will be found at the receiver. As self-FEXT is pre-subtracted at the DSLAM, the modem at the customer premises experiences a signal that is self-FEXT free. In the upstream, receivers collocated at the DSLAM cooperate to cancel crosstalk and here there are more degree of freedom for mitigating non-crosstalk noises like impulse noise, etc.

Except for self-FEXT, there is also the alien-FEXT, i.e. the crosstalk generated by lines that are either non-vectored or that belong to other vectored groups, which vectoring cannot mitigate them, so these must be addressed by other management techniques.

For the precoder, two methods are under investigation, linear precoding and nonlinear precoding. Linear precoding is widely used in VDSL vectoring systems and gives a good performance with limited complexity. The disadvantage of linear crosstalk cancelation is a power increase caused by the precoder in downlink direction. The nonlinear precoder has a small power increase, but it requires much higher hardware complexity and increases power consumption. Figure 26 below shows the SNR comparison between the precoding methods.

For 106 MHz G.fast systems, a spectrum optimization step at the precoder input, combined by a linear precoder (blue curves) gives the best performance. However, for some special channel conditions in the 212 MHz profile, the nonlinear techniques (red curves) give higher performance than optimized linear coding.

As indicated in figure 26, the nonlinear precoder and the optimized linear precoder also supports priorities, such that there is an achievable SNR range between the red curves rather than a single SNR curve. The precoder without spectrum optimization step (green curve), as it is used for VDSL vectoring, results in weak performance under the G.fast channel conditions.

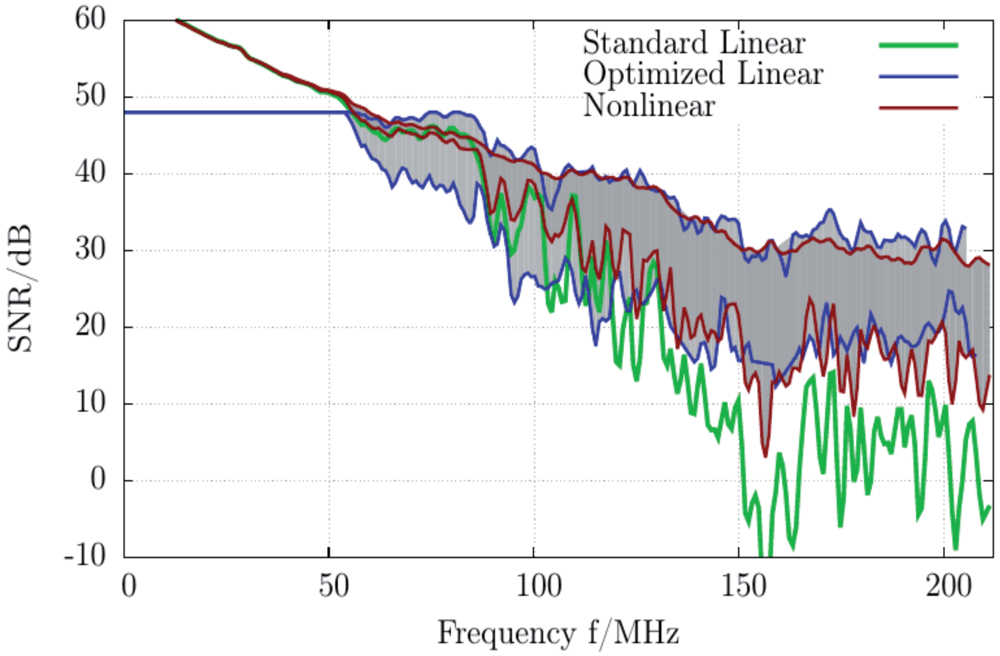

Figure 26: Methods for FEXT cancellation

In the end, all the technical documentations for G.fast referred to optimized linear precoding as the chosen crosstalk cancelation method for the 106MHz, while nonlinear precoder is estimated to be utilized for 212MHz. Through it, individual high priority lines can achieve even higher performance than without even the crosstalk. This is shown with the blue curves in figure 26 above and the shaded area between them. Optimized linear precoding can achieve any point in this area, outperforming even the crosstalk-free case. This fact makes crosstalk cancelation in G.fast different to Vectoring for VDSL where the intention was just to remove the crosstalk. Crosstalk can be used to enhance the link quality of a specific line rather than reduce it. The individual user data rates can be optimized with respect to their specific rate requirements.

5.5 G.fast framing

The frame structure of G.fast is different to VDSL due to TDD. Figure 27 illustrates the G.fast frame structure. The data is organized in superframes, where each superframe starts with a sync frame that is followed by multiple data frames. The default setting is a superframe that consists of 8 TDD frames.

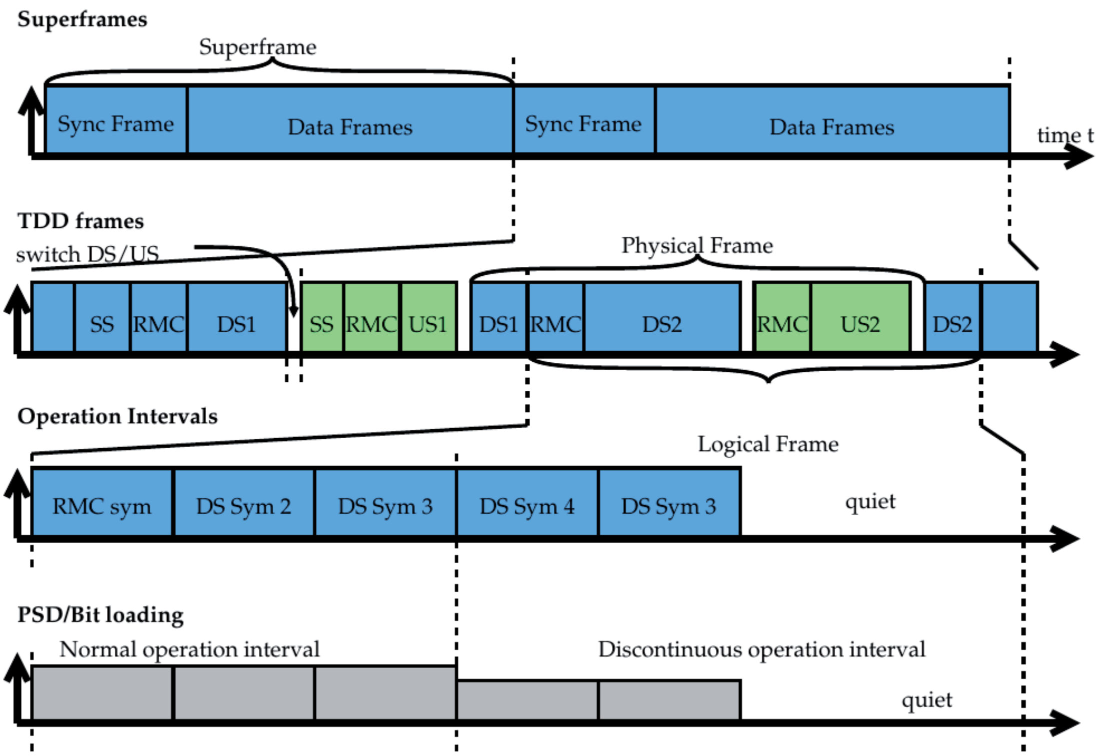

Figure 27: G.fast frame structure

Each TDD frame has the length of an integer number of DMT symbols. It contains a group of downstream symbols and a group of upstream symbols as well as guard times between upstream and downstream data. Both guard times of a TDD frame sum up to the length of one DMT symbol in time (figure 28).

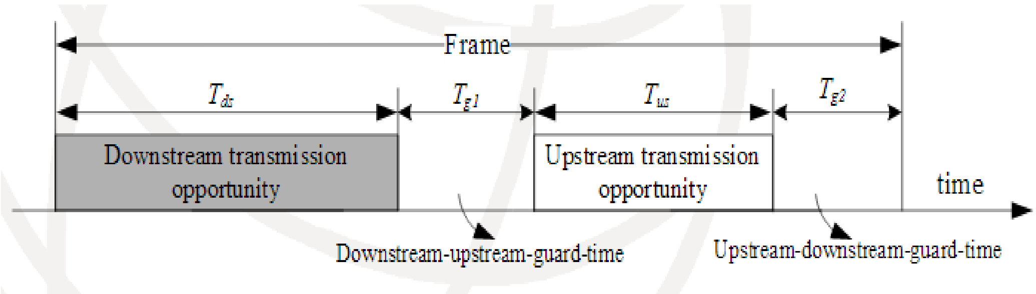

Figure 28: Guard bands in G.fast

Furthermore, each TDD frame contains a Robust Management Channel (RMC) symbol for fast reconfiguration and physical layer management. The TDD sync frame contains a sync symbol for channel estimation and synchronization.

As shown in figure 27, there are two definitions of the TDD frame. The physical TDD frame consists of one downlink and one uplink symbol block and starts with the downlink data block. The logical TDD frame for sync frames starts with the sync symbols and for other TDD frames it starts with the RMC symbol which is somewhere in the middle of the downstream data.

The downstream data symbol block and the upstream data symbol block are further split into a Normal Operation Interval (NOI) and a Discontinuous Operation Interval (DOI) where discontinuous operation can be applied. In the NOI, all lines of a DP are active and transmit or receive data. During the DOI, the lines may stop transmitting to save power.

Discontinuous operation, basically, means that no data symbols are transmitted when there is no data available. While a VDSL system sends idle data packets, the G.fast system can mute these data symbols and switch off the analog front-end components for this time.

G.fast as mentioned earlier is based on TDD making time syncing so sensitive that if it were to mess up only slightly, it would ruin the transmission of the symbols between multiple lines.

The DPU will send symbols downstream on multiple lines, no matter the length, at the same time to keep them synced in time. The challenge with TDD and vectoring comes with sending symbols in sync, upstream on lines with different lengths. To solve this challenge the CPE will learn the time it takes for each of the loops to transmit/receive their symbols during initialization, using that time to delay transmitting symbols on shorter loops, allowing longer loops to "catch up". This ensures the symbols are in sync across each of the lines. This time offset is known as 'Tg1' and is a mandatory function for both the CPE and DPU (figure 29).

When power is shut off the challenge to relearn that time delay is harder. If the CPE is manually shut down it has to relearn that time. If its power is completely cut (like losing power in your house and therefore to the CPE), it will let out a 'dying gasp'. The point of the dying gasp is to send small bit data down the line to the DPU, this allows the DPU to quickly make the required changes in the vectoring calculations to account for the "missing" CPE [25].

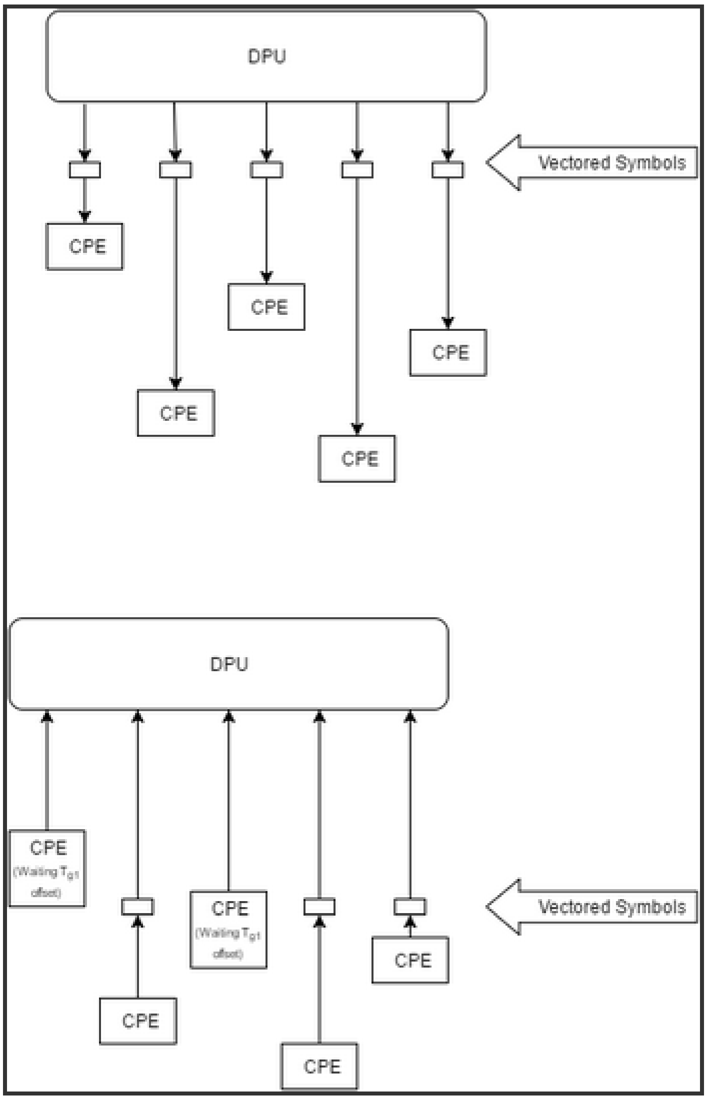

Figure 29: CPEs synchronized send/receive

5.6 G.fast and other FTTx deployment scenarios

In this section a comparative study between FTTdp and other FTTx deployments will take place. It is clear that G.fast is a new and very promising technology that will tender providers the opportunity to offer very high bit rates, while reducing the extra cost by the fiber installation all the way to the customer premises. Below, a short overview over network properties where G.fast is applicable will be examined against other FTTx deployments, answering this way the question, why copper access technologies are still relevant to the NGA networks [26].

5.6.1 G.fast vs. FTTH

Generally, deployments with one fiber link per subscriber are the network topology for rural areas where the population is not too dense. G.fast can help to reduce deployment cost in such areas. At a first glance, there is no copper access technology required to build a FTTH connection. But in practice, connecting the fiber directly to the customer premises causes some disadvantages that can be solved by the hybrid copper/fiber approach, where the fiber is extended with a single-port DP and a short copper wire.

- While fiber connections require a technician to install the customer premises equipment, the copper-based CPE may be installed by customer (customer self-install), because the only action required installing the copper-based CPE is to connect the CPE to the phone plug with the delivered cable. This saves cost for new subscribers and makes the home installation much easier.
- In urban environments, deploying fibers to the subscriber home may not be possible due to legal restrictions or because of difficulties to install fibers in existing buildings.
- Lead times can be unpredictable, particularly if permission for construction work is required from home owners and tenant associations

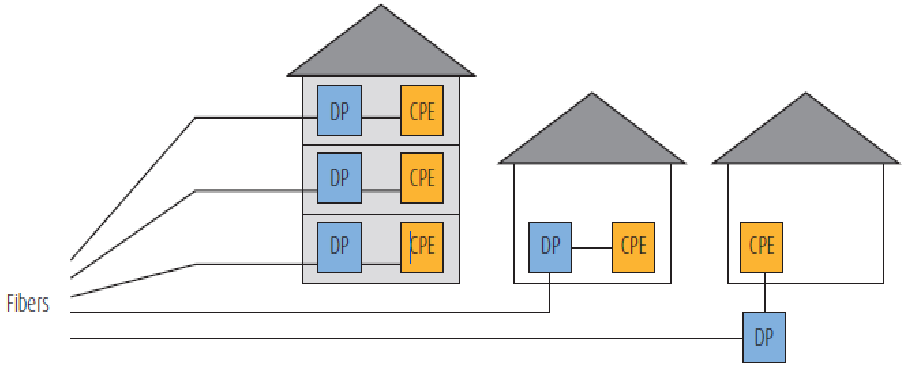

Figure 30: G.fast vs. FTTH

FTTdp is the easiest to implement from a DP box hardware perspective, but also the most expensive one. There is one fiber per subscriber which is very costly for the network operators. Figure 30 shows some FTTdp deployment cases [20]. The distribution point translates the signals from one fiber to one copper twisted pair. No crosstalk cancelation is required and the line length is short, in the range of 100m but in most cases much shorter. The distribution point is supplied from the customer side using reverse power feeding.

5.6.2 G.fast vs. FTTB

FTTH deployments are very limited and cost is not the only reason for that. Multi-line distribution points are a smarter solution to provide fiber-speed services. Deployments with multi-line DPs are used in areas with a more dense population and multi-unit residential buildings.

- Most in-house telephone installations still rely on copper cables for most existing and newly constructed buildings because fibers are expensive and difficult to handle.
- The unbundled lines may not be accessible for the service provider to install individual DP boxes
- Especially in existing buildings, the copper wire bundles may be of a poor quality.

Besides in-building or in-home installations, there are different outdoor locations where the distribution point may be placed. Examples are manholes, pole-mounted distribution points or small street cabinets. The main advantage of FTTdp in comparison to existing FTTB solutions is reverse power feeding. It allows placing the DP box at any appropriate place, without the requirement of a local power supply.

Multi-line DPs with G.fast allow to deliver fiber-speed data rates under these conditions. While the line length of the copper wires is moderate, in most cases shorter than 100m and only in rare cases up to 250m and the cable binder are small, usually no more than 16 pairs. But crosstalk between the pairs limits the achievable data rates for a G.fast service.

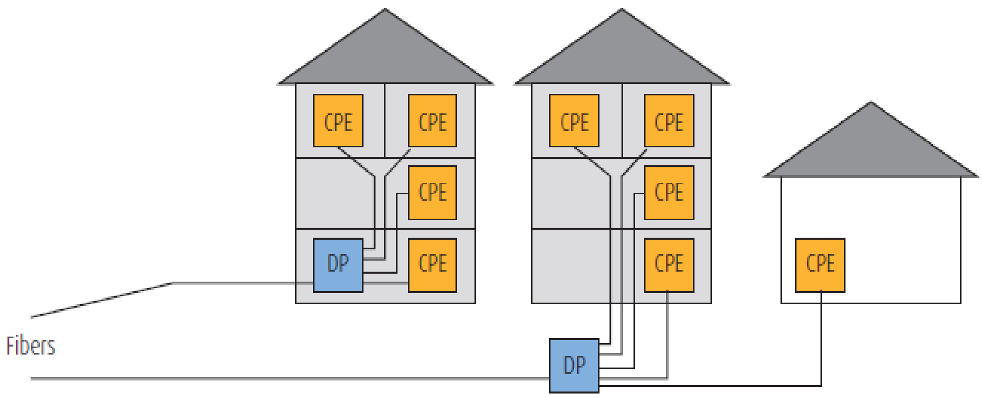

Figure 31: G.fast vs. FTTB

Figure 31 above shows Multi-line FTTdp scenarios. The DP may be placed inside the building or outside, with one or more buildings connected. The subscribers of one DP share the data rate of one or more GPON links. As for crosstalk cancelation FTTB and multi-port FTTdp is not the most demanding environment for G.fast systems.

5.6.3 G.fast and FTTC

The transition from current VDSL technology to the new G.fast service is a very critical step, because in that time, VDSL and G.fast will coexist in the network. The next generation vectoring chips will support crosstalk cancelation for up to 48 G.fast channels.

Up to 48 G.fast ports are expected for FTTC. Due to the fact that these binders may not only contain G.fast lines, but also legacy VDSL 2 lines, interoperability between G.fast and VDSL must be considered, here.

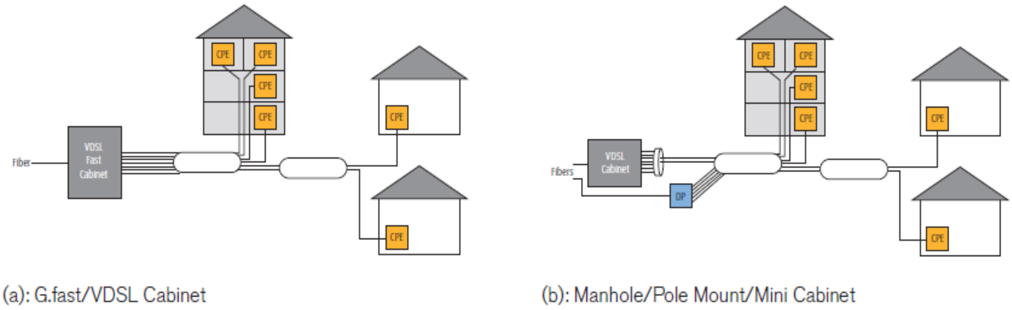

Figure 32: G.fast and FTTC

Street cabinets with G.fast support may serve G.fast and VDSL from one location, depending on the rate requirements and line length as shown in figure 32 (a). For manholes and pole-mounted distribution points, the VDSL signals may be provided from a street cabinet at some distance from the DP as shown in figure 32 (b). For the G.fast FTTC scenario the distance of the cabinet of the end users must not be further than 250m in order for it to be feasible. Subscriber lines with longer lines may exist in both FTTC scenarios, but they are served using VDSL and not G.fast.

But for the scenario of figure 32 (a) with a multi-service cabinet, near-end crosstalk between G.fast and VDSL may become very strong. Therefore, NEXT in addition to FEXT must be considered in the crosstalk scenario. A channel model is required to describe near-end and far-end crosstalk correctly.

Chapter 6: Techno-economic analysis and models

6.1 Introduction

All of the profound changes on the structure of the telecommunication markets, discussed before, resulted from technological developments and their bidirectional impact on economic and regulation trends. These changes depend on the way the technology is being implemented and how it is used to develop new network architectures and new services, which in turn depends on the demands, strategy of the different actors, separation between network and service provisioning, integration of various sectors and branches of telecommunications, Information Technology or broadcasting, public policies and regulations. In this context, NGA networks aim to provide a future proof network infrastructure that it will be able to implement the services, emergency and legacy. The big question arises has to do with the economic viability of each solution proposed. Towards this, a techno-economic analysis needs to be done in order to ensure the economic viability.

A techno-economic analysis is a complex operation, since it requires a combination of estimating the total cost of ownership (TCO), which comprises two types of expenditures:

- Capital Expenditures (CapEx), which refer to the costs pertaining to the infrastructure, e.g. the cost of the actual equipment and its installation [27],
- Operational Expenditure (OpEx) costs, which is related with the use of the network, e.g. energy consumption, maintenance, repairs and billing etc. [27]

CapEx and OpEx calculations, generally, are being made a function of time. For example, estimates for the duration of the roll-out program for the technology deployment, as well as the anticipated time for the investment to pay for itself (amortization), all within an economic environment of inflation and varying cost of money; i.e. net-present values and discounting over time needs to be taken into account. In addition, there is the issue of learning curves, whereby new technology equipment tends to become cheaper over time as the cost-benefit efficiencies of volume production can be assumed.

Also, relation to the business plan side of the analysis displays the issue of the impact that regulatory pressures (e.g. open access considerations, and ubiquitous or universal coverage requirements) will have on the techno-economic results. Furthermore, a SWOT analysis has also an imperative role in the strategic planning process. This refers to an analytical description of the internal and external environment and it will be discussed below.

6.2 Techno-economic framework

Today network and telecom operators must carefully weight and choose the network designs on which they plan to build/operate. Network design plays a major roll on the possible portfolio offered and possible revenues defining this way CapEx and OpEx. Thus, it is crucial for operators to correctly dimension the network due to the demand for competitive subscriber prices and steady increasing bandwidth. The first stage considered for techno-economics models is the market analysis, which comprises both, the services to be offered, new or upgraded ones, and the architectures to support those services. It is really important to take in consideration that network design is a technical process, but it is only to be undertaken if it can be successfully commercially explored.

Figure 33 gives an overview of the methodology for performing a complete techno-economic evaluation. It starts from determining the scope of the problem and detailing the inputs for the study based on a market analysis. The most important outcomes here are indicated by the building blocks services and architectures. They contain all input information necessary for building the techno-economic model in the second step. Often, in a telecom project the network is the central piece and contains most optimization opportunities. Moreover, a proper network design also reflects suitability of a certain network infrastructure to the considered scenario, and therefore it supports the optimal choice among the competing technologies. As such, network design is given a central position in figure 33 as the link between market analysis and calculations. Calculations in turn, are split into economic calculations, in which an estimation of costs and revenues is given, and the technical calculations, in which an estimation of the performance metrics of the proposed network solution is given. In the final step, an evaluation will be based on the outcomes – economic and technical – of the calculations step. This step is split between investment analysis and performance analysis. In the first part, an estimation of the (expected) profitability of a project is carried out. In the second part, a comparison of different alternatives and tradeoffs of costs vs. performance is implemented. Both results are the final outcome of a well-balanced techno-economic study.

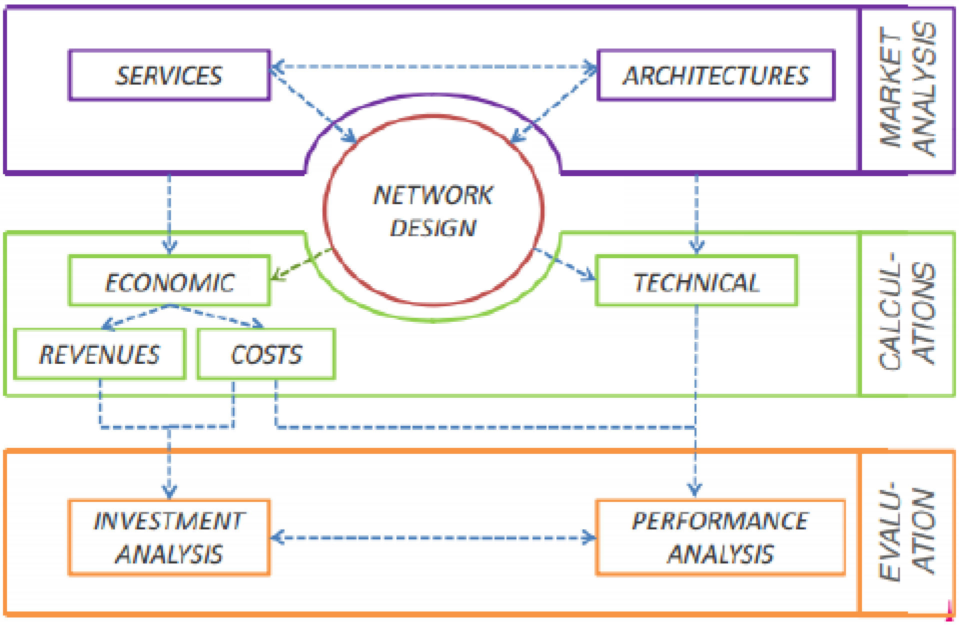

Figure 33: Techno-economic framework

6.3 Approach

In the process of defining both the services to offer, as well as architectures to consider, network designers usually follow one of the two approaches for network and cost modeling in optical access networks: the top-down, or bottom-up approach.

The first approach, the *top-down* method, starts from the existing network infrastructure. In this case, the actual network dimensioning is a result from fluctuations in historic and current demand, e.g. a growing number of customers and increasing traffic volume for several services, but also a declining service demand for other services (e.g. fixed telephone lines). This approach starts from the existing network infrastructure, but then subsequently uses engineering experience and guiding tendencies over time to dimension specific or general services. The network is therefore less efficient than a new network (specifically designed for the current traffic demand). The cost of existing equipment is then allocated to the elements needed to deliver the service [28].

The second approach, the *bottom-up method*, requires as starting point the demand for the services. This is the driver for both upgrading a network or creating a new one, the dimensioning, the cost, and the service/resource usage that is expected to emerge from the up and coming needs. The network is dimensioned in such way that it is optimal for the current situation: it can serve all customers with the requested services at the proposed quality of service. Service costs are allocated according to their required network equipment and usage. The bottom-up method can be used for different studies. It can be used for calculating the costs when designing a completely new network-architecture. It can also be used for making the comparison of the costs in an existing network considering an optimized (bottom-up calculated) network-architecture providing the same services [29]. In figure 34 the two approaches are presented.

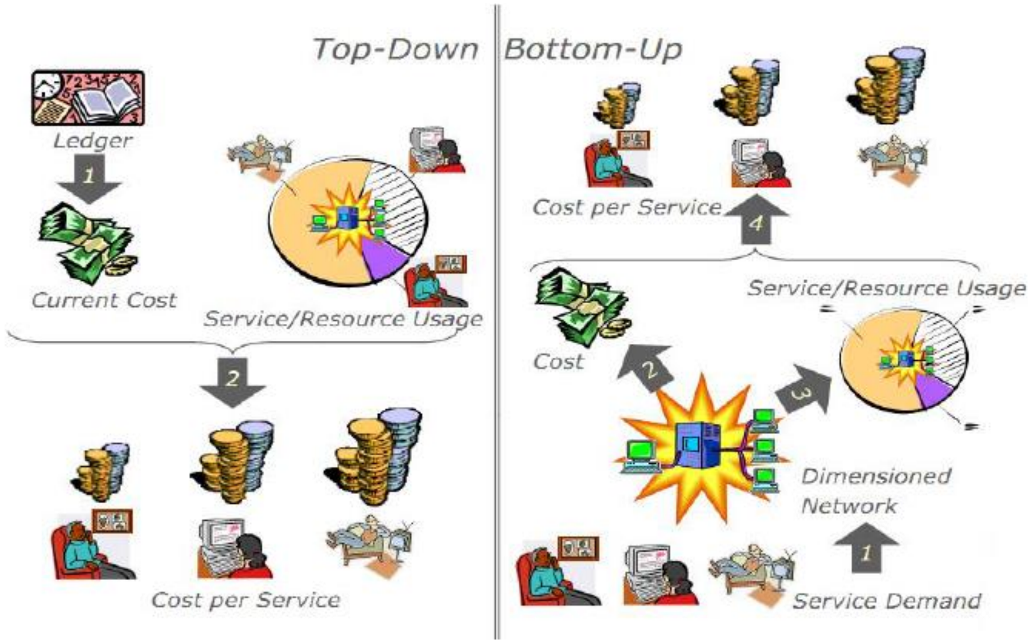

Figure 34: Top-down and Bottom-up approaches

6.4 Business models

The traditional telecom model is based on vertical integration, in which one entity delivers the service, operates the network, and owns the network infrastructure. Originally, the available services were mainly limited to telephony, radio, and television. This has justified dedicated infrastructures, each optimized to transmit information carried by a specific physical signal, and with inherently different traffic patterns.

Technology has evolved dramatically. Today the amount of available services is booming: from well-established ones such as telephony (mobile or fixed), web access, emailing, television (standard quality and HDTV) to rapidly growing ones such as video conferencing, video and music streaming and sharing, online gaming, e-health, to new and emerging ones such as 3D TV, grid computing, etc. For all these services information is stored and transmitted digitally, and it is increasingly delivered using the IP protocol. Moreover, the end user is no longer just a consumer of contents but has also become a producer (sometimes called prosumer) of e.g., photos and video material using a variety of applications. A vertically integrated model with a dedicated network infrastructure for each service may therefore become rather inefficient. Some degree of convergence has indeed taken place during the past 15 years, but this has been a slow and incomplete process, hampered in great part by the resistance from the traditional vertical-integration business model. Ideally, there is no reason today, why telecommunication services should be delivered by a network infrastructure that is optimized to the type of end-user termination (urban vs. rural dwelling, heavy-vs.-light user, mobile-vs.-fix, etc.) rather than the services being delivered.

The open network model, in which services are provided on a fair and non-discriminatory basis to the network users, is enabled by conceptually separating the roles of the service provider (SP), and those providing the network infrastructure and connectivity (NP / CP). Moreover, due to the different technical and economic nature of the different parts of the network, a further role separation between a physical infrastructure provider (PIP), which owns and maintains the passive infrastructure (typically real estate companies, municipalities etc.); and the network provider, which operates (and typically owns) the active equipment (incumbent operators, new independent operators, broadband companies). In addition, a connectivity provider can be present as an interface between the Network Provider (NP), merely operating the active equipment, and the Connectivity Provider (CP), taking care of the connection of the service providers to the network (with their relative roles and functions largely dependent on the specific case) [30]. These four basic business roles, i.e. PIP, NP, CP, SP, are mapped to different network layers defined by OSI model (figure 35).

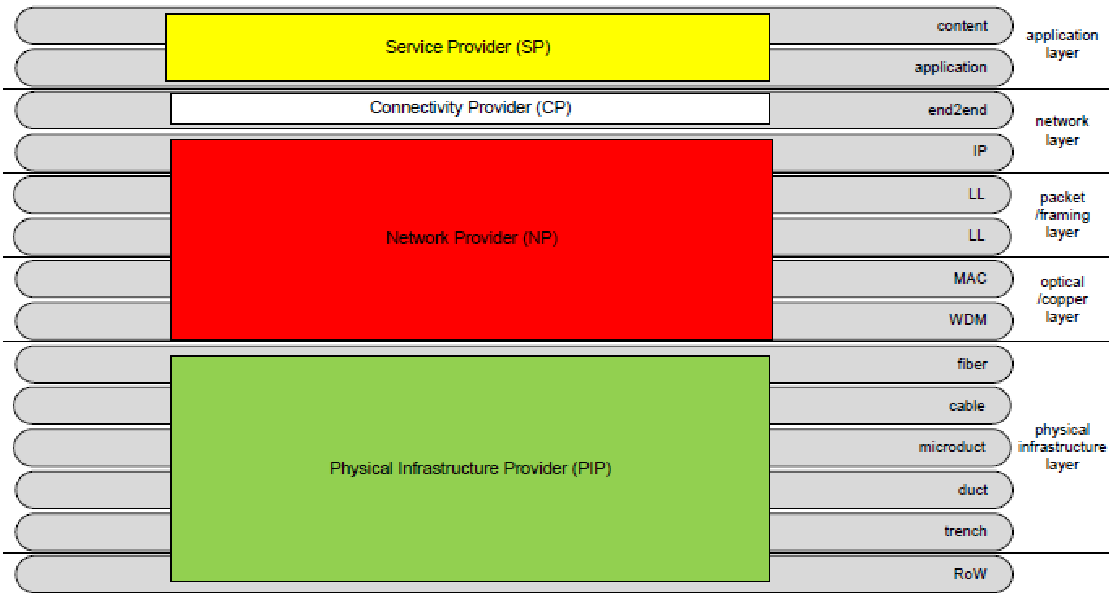

Figure 35: Business roles mapped to network layers

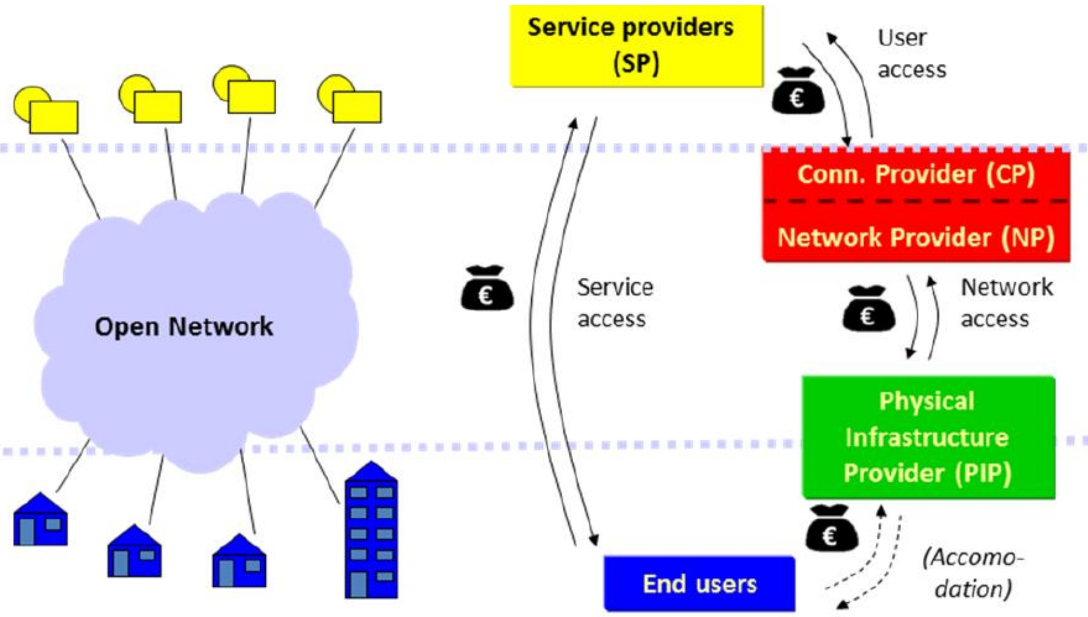

Figure 36: The open network model and typical open access value chain

Depending on which roles different market actors take up, the network will be open at different levels and different business models will arise. A single actor may act as PIP and NP (figure 37 - a), in which case the network is open at the service level. If the roles of NP and PIP are separate (figure 37 - c, d), then openness at infrastructure level is achieved. Generally, one PIP operates the infrastructure, while one or several NP can be allowed to operate the active infrastructure over a fixed period of time, at the end of which the contract may or may not be renewed (in which case a new NP is designated and active equipment may need to be replaced). Most often, economies of scale make it impractical to have a truly multi-NP network (although larger networks may assign the operation of different geographical parts of the network to different NP). Independently of the specific model, however, the NP should offer different service providers access to the network (and therefore the users) on non-discriminatory conditions. In some cases, a connectivity provider can be present as an interface between the Network Provider (NP) merely operating the active equipment, and the Connectivity Provider (CP), taking care of the connection of the service providers to the network (with their relative roles and functions largely dependent on the specific case). The end users typically purchase services directly from the service providers. The NP receives revenue from the SP and pays a connection fee to the PIP for network access [31]. Another possible value chain sees money flow from the end user to the vertically integrated operator, which in turn pays the content providers and service providers for the content it sells to the subscribers – as in figure 36 - but this is a variation of the traditional telecommunications chain value.

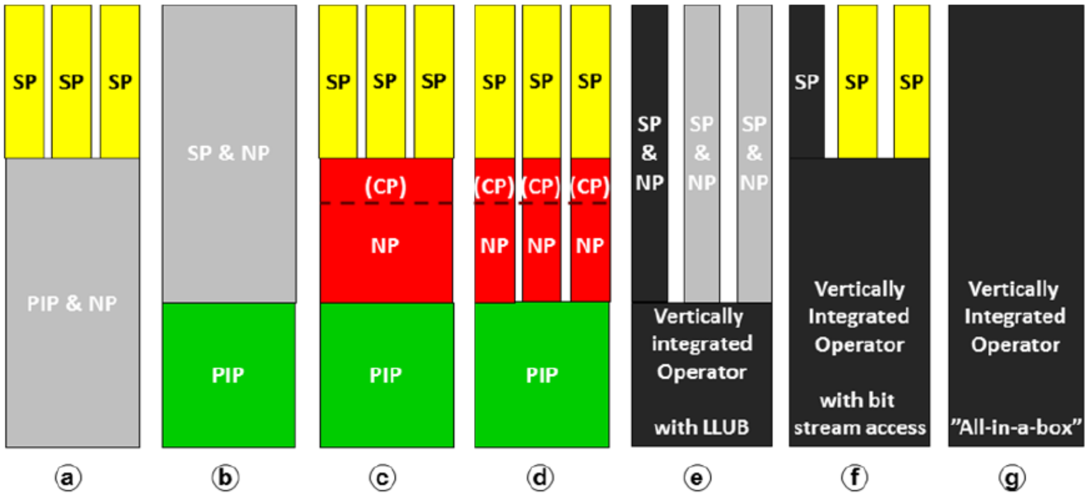

Figure 37: Business models

If the NP also acts as SP (figure 37 - b) the network cannot be described as being really open according to the definitions here, but it is still - more open than the conventional vertically integrated model in (figure 37 - g), which most incumbents worldwide follow today, because the NP/SP may be changed when the lease runs out. In case of LLU (figure 37 – e, f), a vertically integrated operator is still present, but there can be multiple actors working as combined NP and SP. In case of bitstream access the vertically integrated operator assumes the role of NP, but there can be multiple SPs offering their services in the networks.

6.5 SWOT analysis

SWOT analysis is an examination of a provider's internal strengths and weaknesses, i.e. the internal environment, its opportunities for growth and improvement, and the threats the external environment presents to its survival. The SWOT analysis provides information that is helpful in matching provider's resources and capabilities to the competitive environment in which operates. As such, it is crucial in strategy formulation and selection. The following diagram (figure 38) exhibits how SWOT analysis fits into environmental scan.

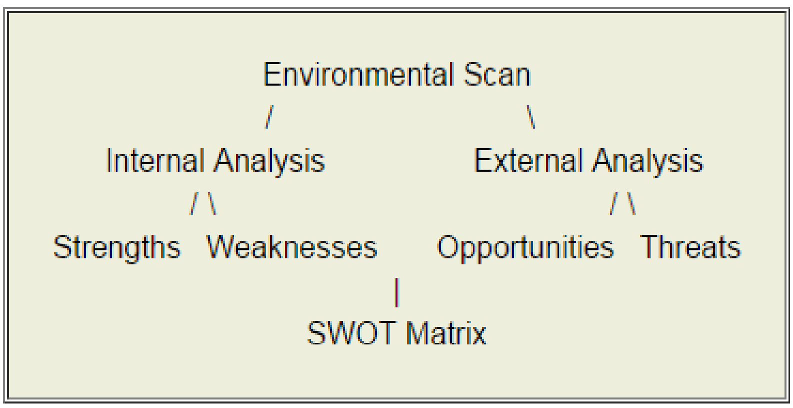

Figure 38: Environment and SWOT analysis

Environmental factors internal to the company usually can be classified as Strengths (S) or Weaknesses (W), and those external to the company can be classified as Opportunities (O) or Threats (T).

6.5.1 Strengths

SWOT analysis views strengths as current factors that have prompted outstanding organizational performance and can be used as a basis for developing a competitive advantage. Examples of such strengths include:

- patents
- strong brand names
- good reputation among customers
- cost advantages from proprietary know-how
- favorable access to distribution networks

6.5.2 Weaknesses

The absence of certain strengths may be viewed as weaknesses. They have the potential to reduce progress or to give an important edge to the competition. For example, each of the following may be considered weaknesses:

- lack of patent protection
- a weak brand name
- poor reputation among customers
- high cost structure
- lack of access to key distribution channels

In some cases, a weakness may be the flip side of a strength as well as weaknesses can also breed other weaknesses.

6.5.3 Opportunities

Opportunities refer to favorable external factors that a provider can use for his benefit. If utilized effectively, opportunities have the potential to create a competitive advantage, leading to increased profit and growth. Some examples of such opportunities include:

- an unfulfilled customer need
- arrival of new technologies
- loosening of regulations

- removal of international trade barriers

6.5.4 Threats

Threats refer to factors that have the potential to negatively impact a provider. Changes in the external environment also may present threats. Some examples of threats include:

- shifts in consumer tastes away from the firm's products
- emergence of substitute products
- new regulations
- increased trade barriers

It is prudent for a provider to have a comprehensive contingency plan that addresses possible risks and specifies how to deal with them.

6.5.5 The SWOT Matrix

A provider should not necessarily pursue the more lucrative opportunities. Rather, it may have a better chance at developing a competitive advantage by identifying a fit between the provider's strengths and upcoming opportunities. In some cases, the provider can overcome a weakness in order to prepare itself to pursue a compelling opportunity.

To develop strategies that take into account the SWOT profile, a matrix of these factors can be constructed. The SWOT matrix, also known as TOWS matrix, is shown below:

	Strengths	**Weaknesses**
Opportunities	S-O strategies	W-O strategies
Threats	S-T strategies	W-T strategies

Figure 39: SWOT/TOWS matrix

- S-O strategies pursue opportunities that are a good fit to the company's strengths.
- W-O strategies overcome weaknesses to pursue opportunities.
- S-T strategies identify ways that the firm can use its strengths to reduce its vulnerability to external threats.
- W-T strategies establish a defensive plan to prevent the firm's weaknesses from making it highly susceptible to external threats.

Chapter 7: Techno-economic analysis

7.1 Introduction

Internet at home is becoming as common as any other utility service. Every day, more operators offer services on the Internet. These services have impact on bandwidth usage because they need more bandwidth due to the integration of demanding audiovisual material and enhanced interactivity with numerous services. On fixed connections is observed that the bandwidth demand grows approximately 30% to 40% per year between now and 2020. Current home connections of telecom operators are not prepared to meet the demands. Operators have to make the costly step either to FTTC or to the FTTdp, or, even more costly, the step to FTTH.

Such technology and infrastructure migration may require a huge investment cost as it depends on the strategic orientation of each operator. So, for example, if an operator has as starting position a full copper topology deployed in a rural area, then has to decide on the next step: bring the fiber connection all the way to the customers or use an intermediate step, where the fiber's termination point is closer to the customer, e.g. FTTC or FTTdp. To make this decision, a comparative study must take place in order to highlight the pros and cons of all options. For example, the implementation of FTTC can be much faster than FTTH, as it requires less digging - the last part of the connection from the street to the access node in the house does not have to be installed - and it meets the growing bandwidth demand for the present and the near future. If, in the future, this demand exceeds the supplied bandwidth, the remaining part to the residence can be connected with Full Fiber or using Hybrid Fiber as an intermediate step.

So, there is an imperative need for a comprehensive techno-economic study, prior to network deployment, in order to get an estimation of the required investment cost. The cost assessment allows operators to calculate their revenues and to be able to determine if it is worth to migrate towards new technologies or architectures. In addition to the cost some other aspects, i.e. survivability, energy consumption etc., may also play an important role for network design and/or deployment.

In this chapter a techno-economic analysis is being presented in order to compare G.fast to VDSL and GPON in economic viability terms. For this purpose, a brief description of important aspects of SWOT analysis will take place as well as a description of the assumptions made for this techno-economic study

7.2 Assumptions

The assumptions adopted for the network analysis implementation are presented below.

7.2.1 Geotype

The type of geo-demographic area (the "geotype") that will be used in the analysis is a rural area as there is small scale deployment of NGA networks. So, policy makers and operators are examining different possibilities and technologies to provide high-speed fixed broadband services there. In this way an operator can assume that a rural area constitutes Greenfield in terms of network design, i.e. no constraints are imposed by prior work in the area.

Also, broadband services today are promising services for rural areas as well, since they can bring substantial social and economic benefits to rural residents [32]. For instance, broadband Internet access enables remote access to health care and education and expands the market potential for rural businesses. Moreover, broadband implementation in rural areas addresses the inequality in the access to information and communication services, i.e. the digital divide between rural and urban areas [33].

Two main factors on the geotype selection are the population density and the building clustering. Looking from the perspective of network deployment, the key element for these factors is the location of the CO. For instance, CO tends to cover the central core of a settlement and at the same time some wider areas where the settlement is sparser (figure 40). [34]

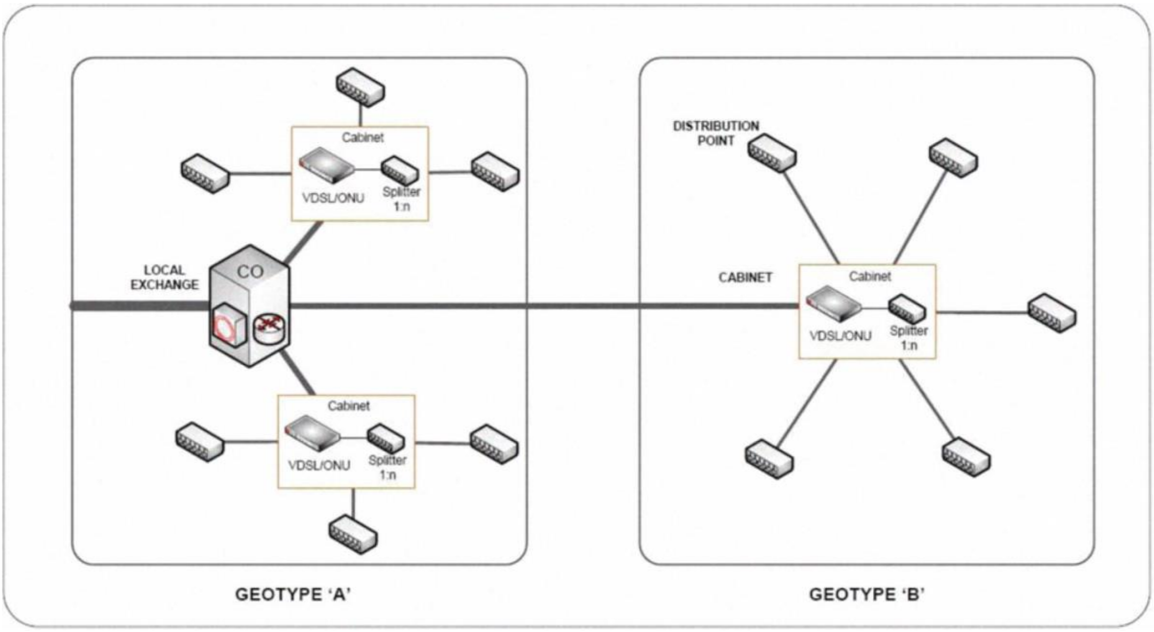

Figure 40: Different geotypes

Herein, the model of geotype which will be the base for the analysis is depicted below. As it can be seen, it is composed of a CO connected to all street cabinets and all the sparser areas of the map, providing 100% coverage.

Figure 41: Rural area

So, in the case shown in figure 41, two types of households are identified:

1) those that are close to the Central Office located in the village (in pink)
2) those that are far away (in yellow)

7.2.2 Network topologies

In order to exhibit the importance and the potential of G.fast technology, it will be exploited in two different architectural flavors; the first as an FTTdp architecture where distribution point will be either in a street cabinet or in a Power Public Corporation's (PPC's) column and secondly as an FTTB architecture, where it will be installed in the building premises.

These two different architectural flavors of G.fast, will be compared to a FTTC system employing VDSL with vectoring technology and to a FTTH system enabling GPON technology with two stages of splicing, the first 1:8 and the second 1:4. All these different network topologies are explained and illustrated below.

It must be noted that only the access segment is included and not the backbone of the network in the analysis. Therefore, it is assumed that the backbone is capable of handling traffic for any network architecture.

Aiming at fully understanding these different topologies, some major concepts in access segment domain and equipment, which can be employed, are going to be analyzed and explained.

Feeder segment: The feeder cabling runs from the CO to the street cabinet. It may cover a few kilometers distance before terminating and will generally consists of larger fiber count cables (100s of fibers) to provide the necessary fiber capacity to serve an area.

Distribution segment: The distribution cabling runs from the street cabinet further into the network and closer to the customer base. Distribution cabling may only need to cover distances less than 1km before final breakout to the customers. Generally consists of medium-sized fiber counts targeted to serve a specific number of buildings.

Drop segment: The drop cabling forms the final external link to the customer and runs from the last breakout of the distribution cabling to the customer building with a distance restricted to less than 500m and often lesser for high density areas. The drop cables will contain only 1 or 2 fibers for the connecting circuitry and possibly additional fibers for backup or for other network architecture needs. The drop cable will normally provide the only link to the customer, with no network diversity.

Optical Distribution Frame (ODF): ODF is a frame used to provide cable interconnections between communication facilities. ODF integrate fibers, splicing, storage and cable connections together in a single unit. It can also work as a protective device to protect fiber optic connections from damage

Optical Line Terminal (OLT): *OLT* is a device that serves as operator's endpoint of a passive optical network. It provides two main functions:

1. performs conversion between the electrical signals used by the service provider's equipment and the fiber optic signals used by the passive optical network.

2. coordinates the multiplexing between the conversion devices on the other end of that network (called either optical network terminals or optical network units).

Multi-Service Access Node (MSAN): MSAN is a network element installed in CO or in cabinet and it multiplexes different customers copper lines, as well as processes the traffic and enables QoS attributes.

Aggregation Switch (AGS): AGS is network element that aggregates the traffic of multiple OLTs and/or MSANs and usually is located in CO.

Customer Premises Equipment (CPE): CPE refers to a telecommunication hardware device located on customer's premises, which facilitates the delivery of services provided by the network operator.

Distribution Point Unit (DPU): DPU includes typically a DSL Access Multiplexer (DSLAM) that can support up to 16 users - in the near future it will support 24 - and an Optical Network Terminator (ONT), which connects the DPU to a CO where the Optical Line Terminator (OLT) is located.

Reverse Power Feeding (RPF): RPF is an active element, located in customer premises and is in charge of sending energy to the DPU

Main Distribution Frame (MDF): A Main Distribution Frame (MDF) is a signal distribution frame or cable rack used in telephony to interconnect and manage telecommunication wiring between itself and any number of intermediate distribution frames and cabling from the telephony network it supports.

Optical Network Terminal (ONT): ONT converts fiber-optic light signals to copper/electric signals

7.2.2.1 FTTC – VDSL

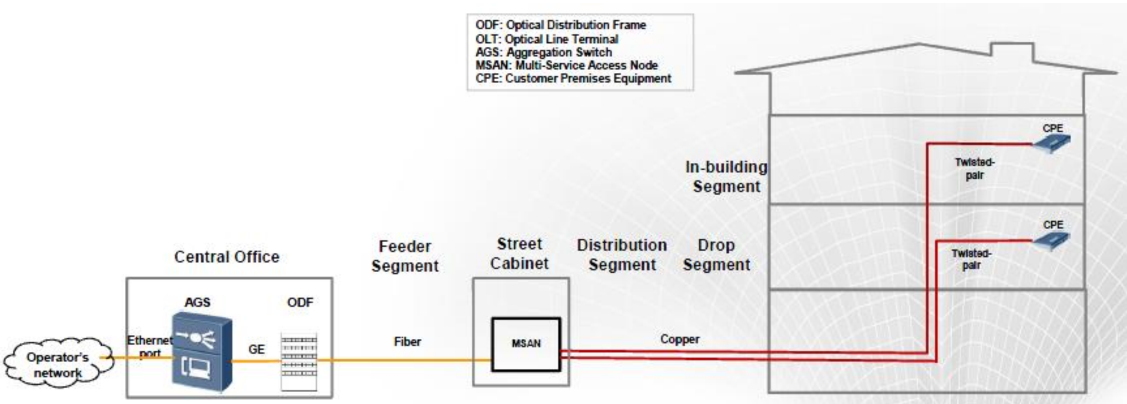

Figure 42: FTTC-VDSL network architecture

Figure 42 depicts a detailed FTTC topology where fiber starting from CO terminates at the street cabinet and, from there, copper wires are extended to customer's premises. It must be noted that ODF is used to provide cable interconnections between communication facilities, i.e. in this example between CO and street cabinet. Also in street cabinet, there is the MSAN, where the customers copper lines terminate.

7.2.2.2 FTTdp – Street (G.fast implementation)

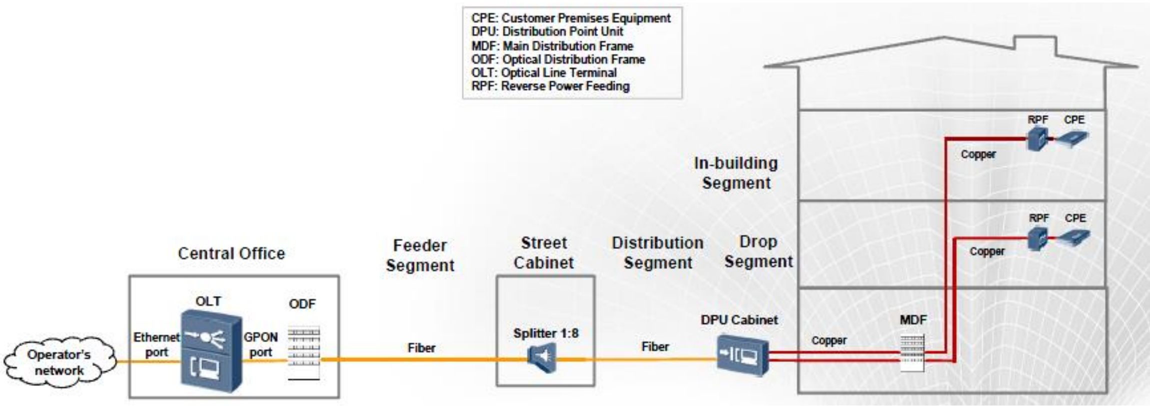

Figure 43: FTTdp-Street network architecture

In FTTdp (figure 43), as described in previous chapter, fiber extends to the distribution point and terminates in DPU. More specifically, fiber extends from OLT, where all optical lines from different DPUs terminate, towards street cabinet. In there an optical splitter with splitting ratio 1:8 distributes to 8 different fibers the traffic until the DPU in the DP. From there, copper wires reach MDF, which interconnects copper wires from DPU and customers apartments.

7.2.2.3 FTTdp – Building (G.fast implementation)

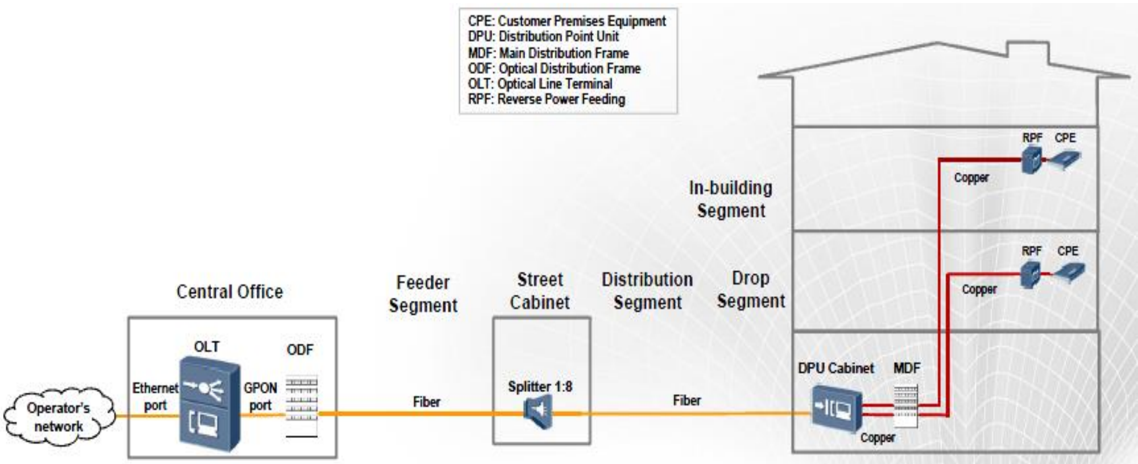

Figure 44: FTTdp-Building network architecture

It is feasible to implement an FTTB (figure 44) network architecture by taking advantage of G.fast technology capabilities. This network topology looks alike with the FTTdp - Street, with only difference being, between the two implementations, the installation point of DPU. While in FTTdp - Street DPU was installed in DP, here it is installed in building premises reducing further this way the copper length.

7.2.2.4 FTTH – GPON

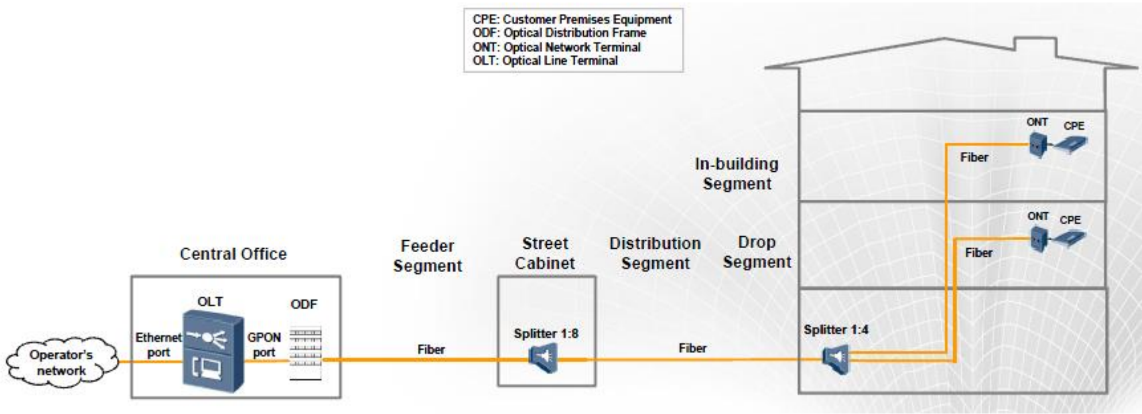

Figure 45: FTTH-GPON network architecture

FTTH (figure 45) is the only scenario where the whole access network consists of fibers and also integrates two splitting stages. In particular, fiber extends from CO to street cabinet, where the first stage of splitting occurs with a ratio of 1:8, as it also was in FTTdp and FTTB scenarios. Finally a second stage of splitting takes place in building premises with a ratio of 1:4.

7.3 Case study

For this analysis, the following assumptions regarding values related to the rural geotype are made. The area has a total of 3000 subscribers and each building contains 5 households, supposing that this is the only type of structure in the area, this leads to a total of 600 buildings in the area.

Item	Value
Total number of subscribers	3.000
Average feeder segment length	2.500 m
Average distribution segment length	220 m
Average drop segment length	26 m
Number of households per building	5

As for the market status, it is assumed that there are two providers that own the infrastructure - passive and active, are responsible for the provision of services and active in the area holding 50% each of the customer base. This is model g based on the distinctions of business models of the previous chapter.

Finally, in the network analysis assumptions for geotype it was made clear that the approach to network infrastructure design will be Greenfield. Also, it is assumed that there is an existing copper network infrastructure in the area, which can be reused for the migration. Based on that and given the fact that an operator must support a plethora of services, the techno-economic approach that will be utilized is a bottom up model, because this model relies on the details of network construction in contrast to top down model**.**

7.4 Costing methodology

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

CAPEX represents the required initial investment cost to deploy the active and passive infrastructure and is calculated by adding the various expenses, like the cost of digging , the deployment of ducts and the rollout of fiber and manholes. All the aforementioned belong to CAPEX for the feeder, distribution, and drop segments respectively. This value is highly related to the network design, fiber layout, population density and some other aspects.

On the other hand, OPEX covers the expenses related to the network operation and specifically, the maintenance of the infrastructure and the repair and replacement of damaged network components.

Furthermore, two metrics were employed for the calculations of the TCO

- Home passed, which refers to the potential number of premises to which an operator has capability to connect in a service area, concerns only CAPEX. It includes all the network components from the CO up to the drop segment
- Home connected, which refers to the number of premises that are connected to an operator's network, concerns CAPEX and OPEX and the market share is 50%. It includes all the network components from the CO up to the customer premises.

For FTTH, the cost of a home passed encompasses the network components located from the CO up to the drop segment. For FTTdp-Building and FTTdp-Street the cost per home passed includes all the network elements from the CO up to the drop segment and distribution segment, respectively. Finally, for FTTC, the cost per home passed includes the network elements from CO up to cabinet.

As for the home connected, the cost is shaped similarly. In particular, for FTTH, the cost of a home connected includes the cost of the splitters in the basement of the building, the in-building fiber cable, and the CPE and ONT. For both FTTdp networks, the cost per home connected also includes the cost of the DPU cabinet, the maintenance cost of the copper line, and the cost of the RPF and CPE. It was assumed that every DPU unit would be installed in the DPU cabinet on an on-demand basis. Finally, for FTTC, the cost of a home connected includes the maintenance cost of the copper line as well as the CPE.

7.5 SWOT analysis

For any provider aiming at migrating to an NGA architecture and employing any of the technologies available, it is crucial to understand the environment, internal and external, and the opportunities and the risks it offers.

SWOT analysis defines the internal strengths and weaknesses of the aforementioned migration, as well as positive and negative external factors; i.e. opportunities and risks in terms of external threats.

The part of strengths for a provider, generally, i) constitute the experience and the high professional capacities of the employees based on the knowledge of the existing network infrastructure, ii) the positive effects of the broadband access in economy empowering this way and consolidating the status of the company in the market and iii) the timeless merit of the fixed access services.

As for weaknesses, a provider must be able to handle i) the complexity of such migration, ii) the long duration of this project, iii) and the financial non profitability in early stages

In the domain of opportunities, a provider must take advantage over i) the public administration support through the evolution of the regulatory framework and the co-financing from institutional bodies, like EU, ii) the increasing demand for broadband internet access in rural areas and iii) the further deployment of e-government services.

Finally, regarding the threats, a provider must pay attention to i) the high number of mobile Internet users only, ii) the lack of information awareness and computer literacy in rural areas and iii) the limited propensity to buy ultra-wide broadband connectivity services offering more than 100 Mbps.

Overall the SWOT analysis is presented below;

Strengths	Weaknesses
- High professional capacities and experience of employees	- Complexity of migration process
- Positive effects of the broadband access	- Long duration of migration
- Timeless merit of the fixed access services	- Financial non profitability in early stages of project

Opportunities	Threats
- Public administration support	- High number of mobile Internet users only
- Increasing demand for broadband internet access	- Lack of information awareness and computer literacy
- Further deployment of e-government services	- limited propensity to buy ultra-wide broadband connectivity services of more than 100 Mbps

7.6 Cost analysis

7.6.1 Cost per home passed

The cost differences and similarities among the four network architectures are explained by chart 1 and table 1, which show the composition of the cost per home passed for the rural area with 100% coverage. The cost of CO and feeder segment is the same for FTTH, FTTdp-Building, FTTdp-Street and FTTC, as the first three use the same OLT and the FTTC's AGS costs the same. Between street cabinet and the distribution segment the cost is the same for FTTH, FTTdp-Building and FTTdp-Street as the same passive equipment will be installed, i.e. splitter, whilst in FTTC, MSAN will be installed in the street cabinet and thus the cost is higher. Finally, for distribution and drop segment, FTTC has no additional cost because it reuses the existing copper infrastructure, while FTTH, FTTdp-Building and FTTdp-Street share, approximately, the same civil works cost.

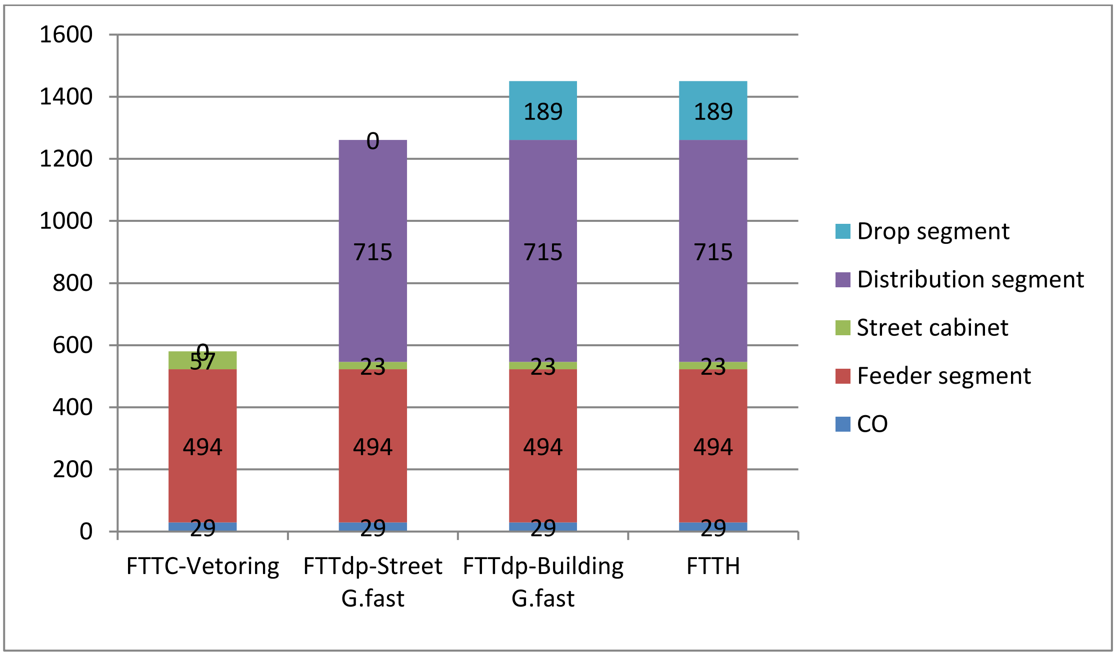

Chart 1: Cost of home passed per technology

	CO	Feeder segment	Street cabinet	Distribution segment	Drop segment	Total
FTTC	29	494	57	x	x	580
FTTdp-Street G.fast	29	494	23	715	x	1261
FTTdp-Building G.fast	29	494	23	715	189	1450
FTTH	29	494	23	715	189	1450

Table 1: Cost breakdown for home passed per segment in access network

Moreover, as depicted in table 1, the largest part of the cost for FTTH, FTTdp-Building and FTTdp-Street depends on the feeder and distribution segments, whilst for FTTC only on feeder segment. Furthermore, for FTTH and FTTdp-Building the cost percentage of both segments is 83 percent of the cost per home passed, whereas it is 97 percent for the FTTdp-Street network. As for FTTC, the largest part of the cost results from feeder segment, which consists the 85 percent of the total cost per home passed.

7.6.2 Cost per home connected

As it is already mentioned, the approach used in the field for the network deployment is Greenfield, meaning that all the network elements located in the access network will be deployed, while also, some sections of the existing copper-based infrastructure and MDF equipment will be reused. So they will be taken into account for the cost analysis below.

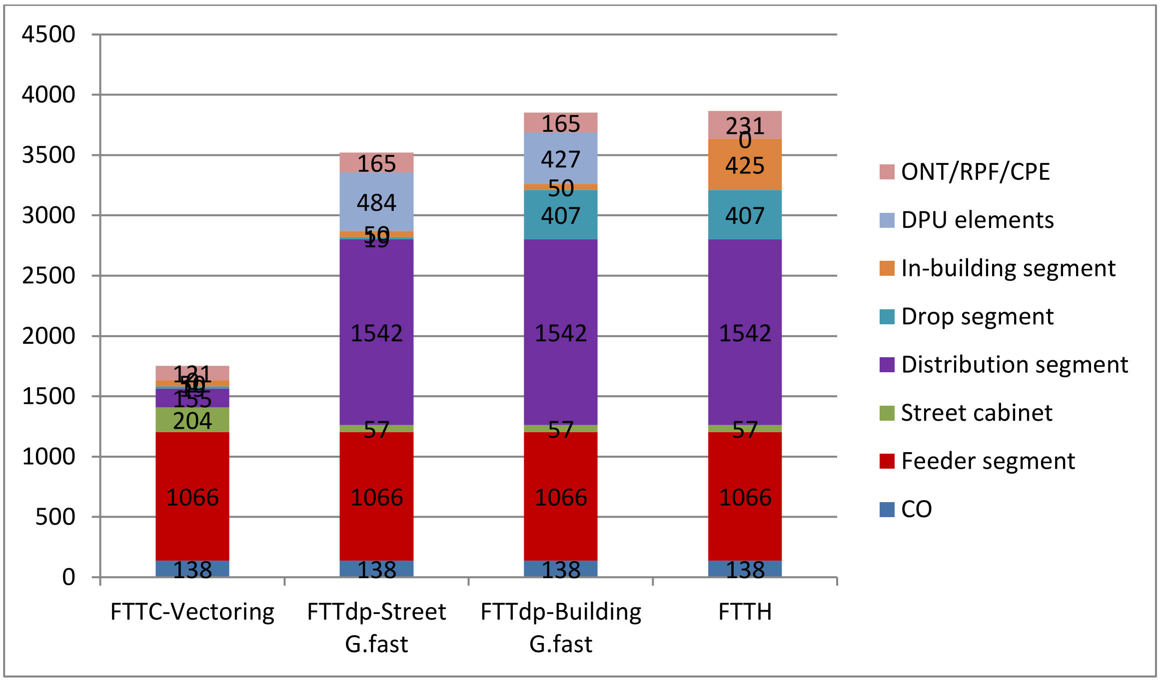

Chart 2: Cost of home connected per technology

	CO	Feeder segment	Street cabinet	Distribution segment	Drop segment	In-building segment	DPU elements	ONT/RPF /CPE	Total
FTTC	138	1066	190	155	19	50	x	80	1622
FTTdp-Street G.fast	138	1066	57	1542	19	50	484	165	3521
FTTdp-Building G.fast	138	1066	57	1542	407	50	427	165	3852
FTTH	138	1066	57	1542	407	432	x	231	3873

Table 2: Cost breakdown for home connected per segment in access network

Based on table 2 and chart 2, it can be derived that the values of CAPEX and OPEX for the three networks, namely FTTH, FTTdp-Building and FTTdp-Street, are the same for the CO, the feeder segment, the street cabinet, and the distribution segment. On the other hand FTTC shares the same cost until feeder segment. From that point on it is differentiated much compared to the previous three architectures.

The cost per home connected, based on table 2, is higher for FTTH than all the other network architectures mainly due to the feeder and the distribution segment, which in particular consists the 67% of the total cost, as with home passed case. The same goes for FTTdp-Building and FTTdp-Street, where they consist 68% and 74% of the total cost respectively. In view of the above, FTTC's main cost driver consists of only the feeder segment which is the 66% of the total cost.

7.7 Assessment of results.

There is a number of points that can be derived from the results presented above.

1) Based on the different scenarios analyzed, the cost of a home passed for FTTdp-Building is equal to the cost of a home passed for FTTH networks. Furthermore, the cost for FTTdp-Street is on average 13% lower than the cost of FTTdp-Building and FTTH. The most inexpensive solution by far is the FTTC which on average achieves 60% and 54% cost reduction against FTTH, FTTdp-Building and FTTdp-Street respectively.
2) Similarly, for the home connected case, the cost of FTTdp-Building is 1% lower than the cost of FTTH, whereas the cost of a home connected for FTTdp-Street is 10% lower than the cost for FTTH. Finally FTTC achieves 58% cost reduction against FTTH and FTTdp-Building and 54% against FTTdp-Street.
3) The cost differences between FTTH and FTTdp network architectures are due to the different network equipment located in the final meters of the end-to-end access network.

4) For the majority of values relating to the deployment and maintenance of the in-building copper cable for FTTC, FTTdp-Building and FTTdp-Street, the cost is lower than the cost of FTTH. However, if the maintenance cost is high enough, the cost of FTTdp-Building, individually, can be higher than the cost of FTTH

Overall, this analysis shows that the cost per home connected for FTTdp networks is lower than the cost of FTTH. In any case the most economic viable solution is FTTC as it displays much lower cost values from all the other architectures. Nevertheless, the main disadvantage of FTTC and a dissuasive factor for deployment constitutes the fact that it can't support higher bitrates from 100Mbps making it a non-future proof solution and thus leading this way to the need for new investment in order to support higher bandwidth. FTTdp networks, on the other hand, will be able to provide several hundred Mbps, which makes it an attractive solution for providing high bandwidth rates.

7.8 Verdict

Various operators are in the process of defining the type of network they will deploy to provide high-speed fixed broadband services. The use of hybrid fiber- and copper-based access networks can complement the deployment of FTTH networks, especially in regions where the deployment of fiber in the final meters is difficult. G.fast, which is mainly used for the deployment of FTTdp, is a copper-based access technology that can provide a combined downstream and upstream capacity of up to 1 Gbps and thus making it an attractive solution compared to FTTH.

Furthermore, and based on the above analysis, FTTdp, with G.fast technology enabled, is 1% and 10% less costly for FTTdp-Building and FTTdp-Street respectively than FTTH, in the home connected case. Furthermore, for monthly maintenance of the in-building copper line, the cost of FTTdp networks is lower than the cost for FTTH. Moreover, it can act as an alternative solution to FTTH in situations where the deployment of fiber in the final meters is complicated. Finally, one advantage of FTTdp network is that the network roll-out will be faster than that of FTTH networks. Given the advantages in terms of cost and deployment time that FTTdp networks offer in comparison with FTTH networks, it is likely that in some cases operators will be fond of deploying FTTdp networks.

Chapter 8: Conclusions

This thesis's aim is to present the new access copper technology G.fast, which is regarded as a major contender for the NGA rollout, through a technical review and an economic viability assessment.

For the technical review, a major overview of a network architecture was given, by describing the different parts that constitute it and the different mediums used in the access segment. Additionally, the NGN concept by ITU-T was thoroughly assessed in order to provide an overview of what the next generation networks will be. Regarding NGA, all the different FTTx systems embodying different access technologies were studied. Herein, FTTdp network was also analyzed, which incorporates G.fast technology. Finally,, the major aspects and characteristics of this technology were assayed.

As for the economic feasibility a brief description of the available techno-economic and business models was given, while a review of the structured planning method called SWOT analysis was held. Finally, a techno-economic analysis of three different access technologies was examined by using as case study a rural area and providing some important assumptions for the calculation of cost. In this analysis, there were considered four different network architectures, and they were evaluated regarding the cost of deployment as well as the required operational expenses. This was achieved by studying two different approaches, i.e. the home passed and the home connected.

In summary, this thesis introduced this new technology – G.fast – which, although is a copper technology, can achieve fiber-like data rates, while also retaining copper's economic efficiency, like in the FTTdp-Street scenario. Moreover, the flexibility and usability of G.fast was exploited by exhibiting the capability of implementing different FTTx systems through this technology, like FTTdp and FTTB. It also must be noted that FTTH council, an industry organization whose mission is to accelerate the availability of fiber based, ultra high-speed access network, follows closely the development of G.fast and has already published a white paper [20], where exhibits the potential of this technology and even proposing an FTTH network with G.fast integration.

So, it can be verified, from the aforementioned, that copper is still viable as a medium, although is not as future proof nor as resilient as fiber. In this direction, and despite the fact that G.fast became commercially available just recently, the research community is already examining and exploring the next big thing in copper access technologies.

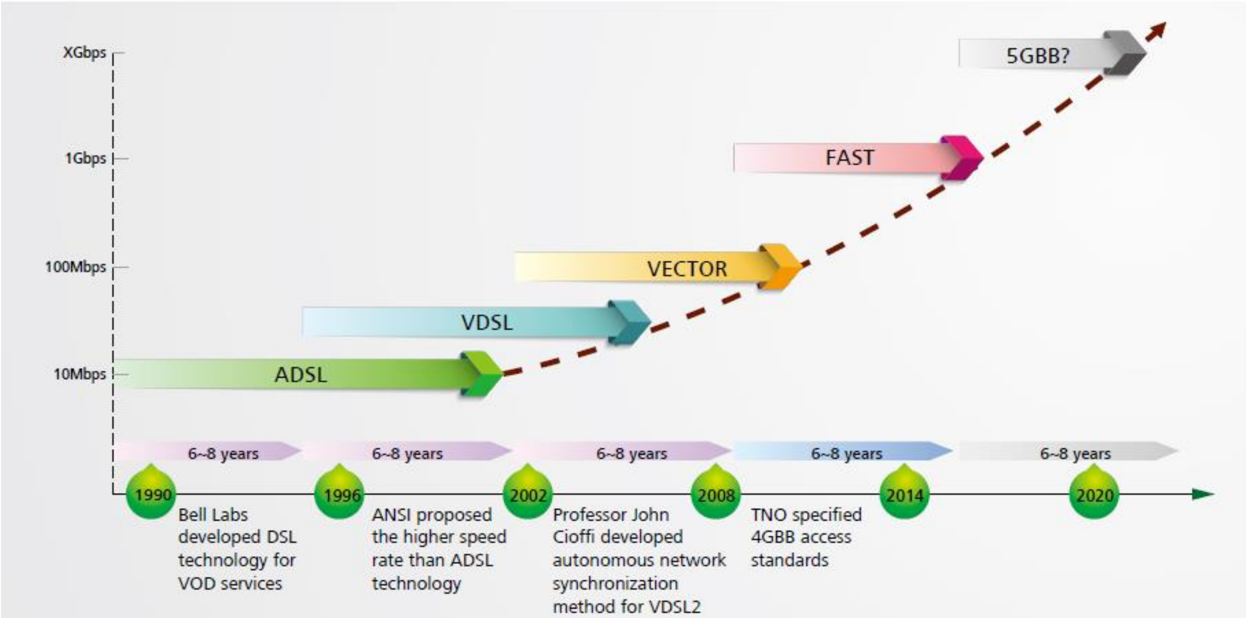

Figure 46: Towards 5GBB

History demonstrates that generational leaps in copper technology are achieved every eight years (figure 46) and thus, given the advent of G.fast, a new proposal has already emerged, wherein the frequency increases at 1GHz and provides 5Gbps, by reducing copper length to 50m. Furthermore, testing and capacity simulations have shown, by this time, that, in the absence of interference, a 30 meter-long loop of category-5 twisted pairs can reach a speed of 12Gbps. However, there are a lot of problems, like noise and radio interference, that must be resolved in order for 5GBB to become viable and to offer these data rates in short length loops.

In conclusion, the ongoing development of copper access technologies facilitates the migration towards full fiber, by providing the opportunity to deploy a stepwise procedure, where a provider can gradually inject fiber in the access segment and at the same time remain relevant to the continuously increasing bandwidth requirements. G.fast technology, as it fits into the aforementioned plan, can offer fiber based bandwidth, and thus it attracted many manufacturers, providers and institutional bodies when was firstly announced at 2009.

Nowadays, the first commercial products are made available and already a number of providers are going through extensive tests for integrating this technology.

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