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GIGABIT PASSIVE OPTICAL NETWORKS (GPON) AND THE NETWORK ANALYSIS IN THE FIBER TO THE HOME (FTTH) PROJECT APPLICATIONS IN ANKARA

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ABSTRACT

GIGABIT PASSIVE OPTICAL NETWORKS (GPON) AND THE NETWORK ANALYSIS IN THE FIBER TO THE HOME (FTTH) PROJECT APPLICATIONS IN ANKARA

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In this thesis, the FTTH architectures, which are used by the telecom operators steadily in recent years to provide the increasing subscribers' expectations, and the application of Gigabit Passive Optical Networks (GPON), which has increasing popularity amongst the FTTH architectures in Ankara are examined. The advantages and disadvantages of GPON architecture over traditional copper networks are presented with bit rate and cost comparison of a target site which has both GPON and copper networks. Cost comparisons between the networks are also made.

Keywords: PON, GPON, FTTH, fiber optic, copper networks

ÖZ

GİGABİT PASİF OPTİK AĞLAR (GPON) VE ANKARA'DAKİ EVE KADAR FİBER PROJE UYGULAMALARININ NETWORK ANALİZİ

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Bu tez kapsamında, son yıllarda Telekom operatörlerinin artan kullanıcı beklentileri karşısında sürekli yükselen bir oranda kullanmaya başladığı eve kadar fiber mimarisi ve bu mimariler arasında popüleritesini hızla arttıran Gigabit Pasif Optik Ağların (GPON) Ankara'daki uygulamaları incelenmiştir. GPON mimarisinin geleneksel bakır ağlara olan avantaj ve dezavantajları hem geleneksel bakır hat hem de GPON tesisi yapılmış bir sitede, her iki mimarinin de veri oranı ölçümleri yapılmış ve veri oranı ve maliyet kıyaslamaları ile sunulmuştur.

Anahtar Kelimeler: PON, GPON, FTTH, fiber optik, bakır ağlar.

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LIST OF ABBREVIATIONS

Abbreviation of Symbol	**Term**
ADSL	Asymmetric DSL
AE	Active Ethernet
AES	Advanced Encryption Standard
ATM	Asynchronous Transfer Mode
AU	Arbitrary Unit
BOSA	Bidirectional Optical Subassembly
CAPEX	Capital Expenditure
Cat 5	Category 5
CO	Central Office
DB	Distribution Box
DBA	Dynamic Bandwidth Allocation
DSLAM	Digital Subscriber Line Access Multiplexer
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPON	Ethernet PON
FBT	Fused Biconical Taper
FTTB	Fiber to the Building
FTTC	Fiber to the Curb
FTTCab	Fiber to the Cabinet
FTTH	Fiber to the Home
FTTP	Fiber to the Premises
FTTX	Fiber to the X
GPON	Gigabit-capable Passive Optical Networks
HDTV	High Definition Television
HGW	Home Gateway

HSI	High Speed Internet
IEEE	Institute of Electronic and Electrical Engineering
IP	Internet Protocol
IPTV	Internet Protocol Television
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
Mbps	Megabit per second
MCS	Maximum Communication Speed
MPLS	Multiprotocol Label Switching
MDU	Multiple Dwelling Unit
MTU	Multiple Tenant Unit
NT	Network Termination
OEAC	Opto – Electronic Active Converter
OLT	Optical Line Termination
ON	Optical Network
ONT	Optical Network Termination
ONU	Optical Network Unit
OS	Optical Splitter
OPEX	Operational Expenditure
OTDR	Optical Time Domain Reflectometer
P2MP	Point-to-Multipoint
P2P	Point-to-Point
PLC	Planar Lightwave Circuit
PON	Passive Optical Network
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RF	Radio Frequency
ROI	Return Of Investment

RTD	Round Trip Delay
SLA	Service Level Agreement
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
Teqd	Equalization Delay
TFF	Thin Film Filters
TO-CAN	Transistor Outline Canned Type
VAS	Value Added Services
VDSL	Very-high-bit-rate Digital Subscriber Line
VOD	Video on Demand
VoIP	Voice over Internet Protocol
XOR	eXclusive OR
xDSL	x Digital Subscriber Line

INTRODUCTION

In Telecom sector, everyday users' expectations and requirements are on the increase. As a result of this increase the Telecom Operators have to adjust their investment policies and increase the Capital Expenditures (CAPEX). While the Telecom Operators are planning the investments, their aims are the most effective and economical ways to reach users. In this context an access architecture which was come into being in the 80's, has come out. These architectures are fiber based access networks. At the present and near future, fiber optic based access technologies can support these bandwidth requirements of users and among different architectures the most popular one is called Fiber to the Home (FTTH).

With FTTH architecture it is possible to provide the Value Added Services (VAS) like High Speed Internet (HSI), Voice over IP (VoIP), Video on Demand (VOD), Internet Protocol Television (IPTV) etc. to the users.

Figure 1 shows the traffic increase in the broadband network in the first decade of 2000s. In 2010, according to the paper published by International Conference on Information, Networking and Automation (ICINA), the increase in broadband network traffic will largely be driven by the IPTV [1].

The telecom operators of present day use different technologies and architectures for their access networks investments. The most favored ones are Gigabit Passive Optical Networks (GPON), Ethernet Passive Optical Network (EPON) and Active Ethernet (AE) etc.

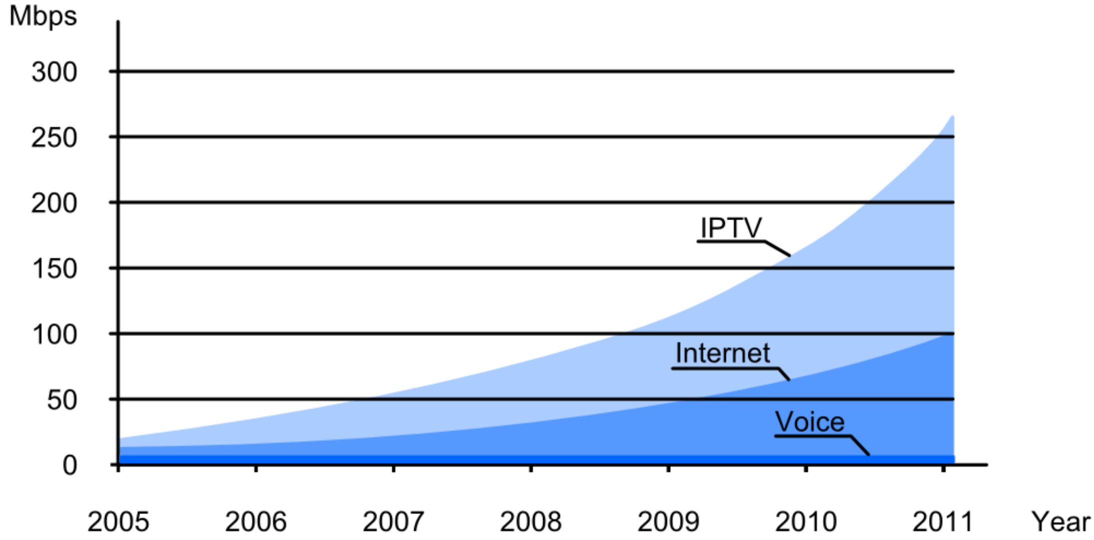

Figure 1: Traffic Increase in Broadband Networks [1]

FTTH infrastructure has started in TURKEY in the first decade of the 2000s. In 2008, TURK TELEKOM, incumbent fixed line operator, started to work on FTTH projects using with GPON and Active Ethernet architectures. In the beginning of 2011 in İstanbul, the first GPON customers were being connected on line. At the same time in İzmir, Diyarbakır and Ankara there were several GPON projects that followed those in İstanbul.

In this thesis, the bit rate performances of a GPON+copper network and full copper network on the same infrastructure were measured and compared. For the full fiber GPON performance of bit rate calculations was made as well. By using the opportunity of the available cost data, the capital expenditures (CAPEXs) for the networks cited above were also calculated and compared.

CHAPTER I

FIBER TO THE HOME (FTTH)

FTTH is the delivery of a communication signal over optical fiber from the operator all the way to a home or business, instead of a conventional copper infrastructure such as telephone wires. FTTH is a relatively new and fast growing method of providing very high bandwidth to subscribers providing more robust video, internet and voice services.

Today the bandwidth requirement of a user is much higher than the copper based xDSL services are able to supply. As seen in figure 1.1, the FTTH can supply the required bandwidth for users' needs better than copper based services [2].

According to the paper published by SHUMATE, P. W. in 2008 [3], FTTH was first tried for video on demand (VOD) based services in 1977 in Japan. After the 1980's, there were more trials for FTTH in the Europe.

The optical part of an access network system may contain either active or passive components and its architecture can be either point to point (P2P) or point to multipoint (P2MP). Figure 1.2 shows the access network architectures according to International Telecommunication Union Telecommunication Standardization Sector (ITU-T) recommendation G.984.1 [4] and the differences of Fiber to the Home (FTTH), Fiber to the Building/Curb (FTTB/C) and Fiber to the Cabinet (FTTCab) scenarios.

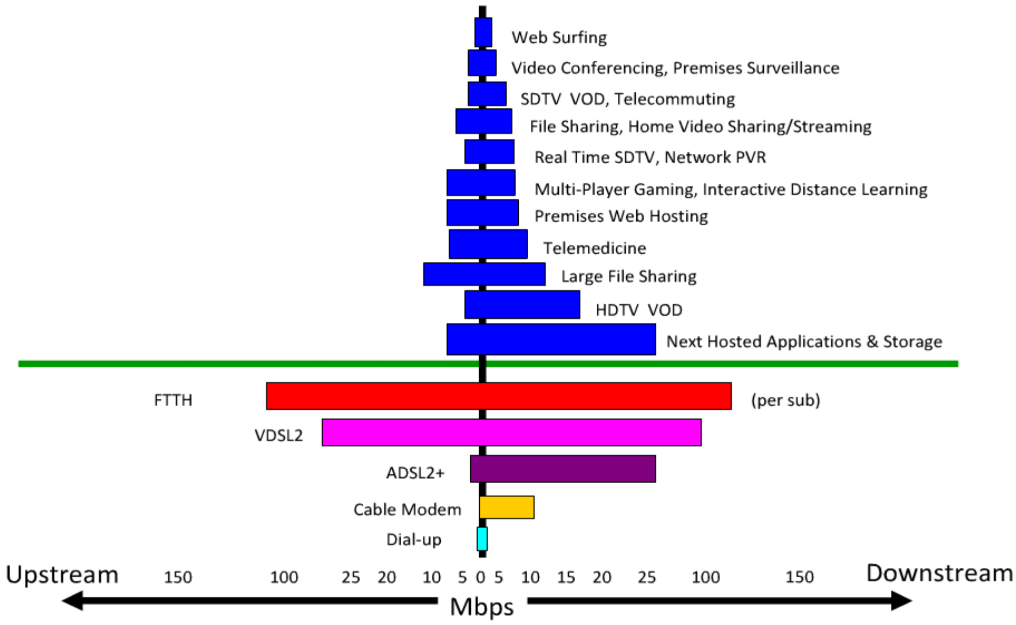

Figure 1.1: Users' Bandwidth Requirements [2]

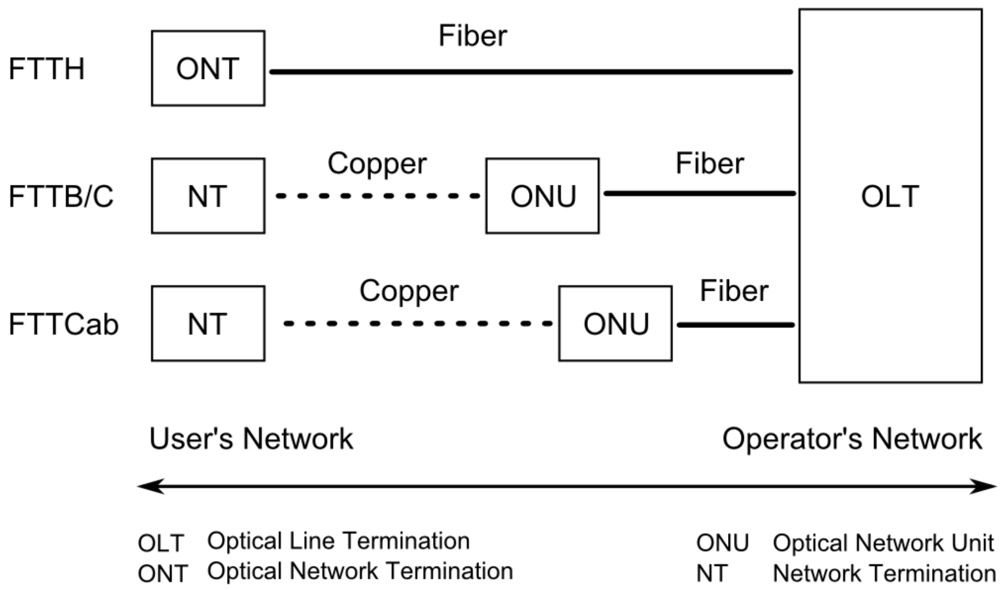

Figure 1.2: Optical Access Network Architecture

Fiber optic networks can easily meet high performance levels and have the possibility of evolving to the future applications based on the same optical architecture without radical changes. A simplest way to install the fiber optic cable in the access network is using P2P topology with allocated fiber optic cable from the Central Office (CO) to the each subscriber. Although, this topology is the simplest one, the fiber optic cable installing process requires a considerably high investment cost. An example scenario is given in figure 1.3. As seen in figure 1.3, there are S subscribers at the distance D km from the CO. In a P2P FTTH topology 2S transceivers and SD fiber optic cable in total must be used.

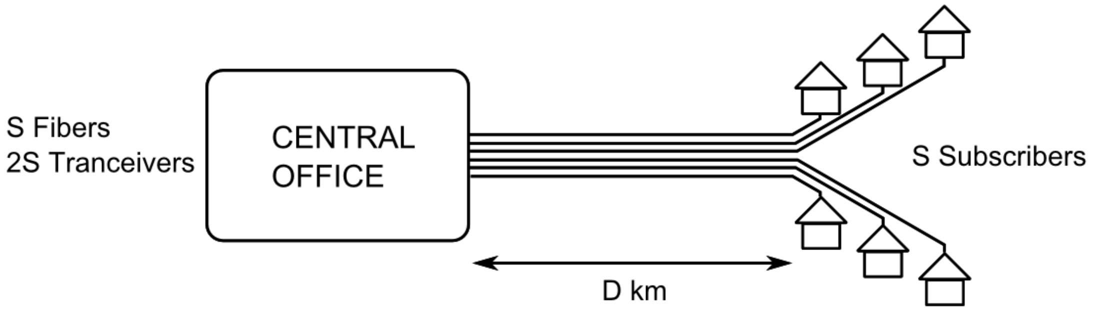

Figure 1.3: Point to Point (P2P) FTTH Scenario

The reason of the high investment cost of P2P FTTH topology is usage of too long and too much fiber optic cable per subscriber. To reduce the cable length in total, a switch may be deployed near the subscribers. This topology is called P2MP FTTC. An example scenario is given in figure 1.4. As seen in figure 1.4, there are S subscribers at the distance D km from the CO. In the P2MP FTTC topology 2S+2 transceivers and D km fiber optic cable must be used (the distance between the switch and the subscribers is neglected).

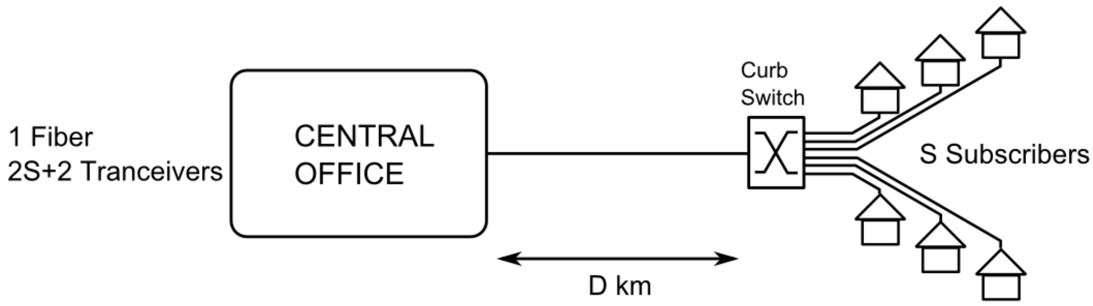

Figure 1.4: Point to Multi Point (P2MP) FTTC Scenario

In P2MP FTTC topology, the curb switch requires electricity to operate. Electricity in the active components increases the operational expenses (OPEX) like; back-up power units for continuous operation and air conditioner for controlled climate for active components.

To decrease the OPEX, all of the active components and the external operational devices (like UPS and air conditioner) must be removed from the field or replaced with passive components. With the implement of cheap and passive optical devices (optical splitter) another topology can be gathered; P2MP PON. An example scenario for P2MP PON is given in figure 1.5. As seen from figure 1.5, for S subscribers there is only one fiber optic cable at the length of D km and S+1 transceivers are required.

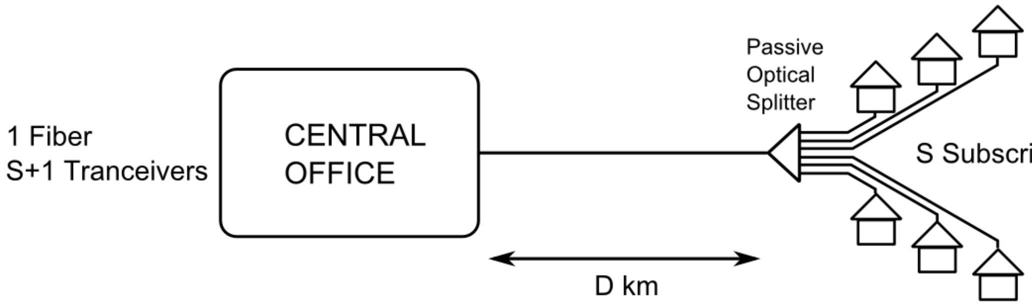

Figure 1.5: Point to Multipoint (P2MP) PON Scenario

FTTH is basically simple, effective and easy to operate network architecture. As mentioned above, basically there are two structures; first one uses active components and second one uses passive components.

In planning and designing the network the most important issue is the cost. In figures 1.3, 1.4, 1.5, we discussed the three scenarios with their advantages and disadvantages. In calculation of the cost, the distance between the Central Office and the subscriber is the determining part. In figure 1.6, the difference regarding the cost between the P2P and the P2MP systems is shown. According to the paper published by SHUMATE, P. W. in 2008 [3], the initial cost of the P2MP system is higher than that of the P2P due to the extra hardware used in the field, and this steadily decreases as the distance from the service provider increases up to a certain distance, where the costs of both will be equal (the breakeven point). Beyond that distance the P2MP will always be less expensive than the P2P, and the difference in the cost between the two systems increases linearly as the distance gets larger.

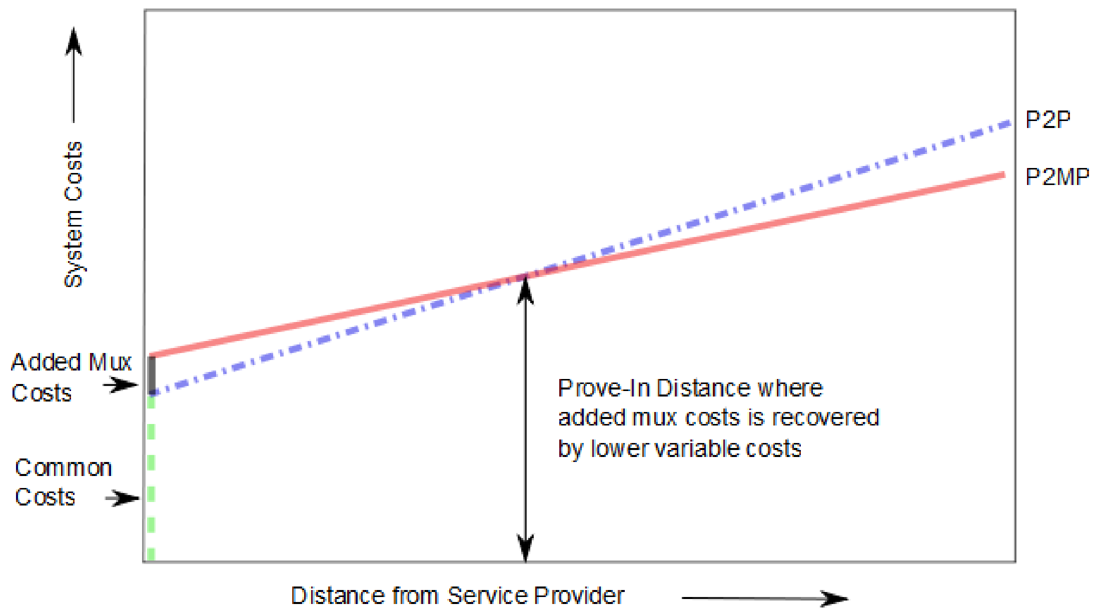

Figure 1.6: The Cost-Distance Relation of P2MP and P2P [3]

1.1. PASSIVE OPTICAL NETWORKS (PON)

PON is named as a passive network, as its distribution networks do not use electronic signal regeneration. Passive optical components are deployed in the access network instead of active components to lead the different light wavelengths (1310 nm. for upstream, 1490 nm. for downstream and 1550 nm. for Radio Frequency Television) through the fiber optic cable from CO to subscriber and vice versa. Passive optical components do not require electricity to operate or any other signal routing/regenerating processes. These specifications reduce the additional operational costs for the operator. Having passive components making up the distribution network means any future upgrade is cheaper and less painful because only the two end-point devices need to be upgraded or changed.

There are two major standards in the present PON architecture; the first one, Ethernet Passive Optical Networks (EPON), is controlled and developed by Institute of Electrical and Electronics Engineering (IEEE), the second one, Gigabit Passive Optical Networks (GPON), is controlled and developed by International Telecommunication Union (ITU). In this thesis, only GPON is discussed, because the project site has both copper and passive optical networks.

1.2. GIGABIT PASSIVE OPTICAL NETWORKS (GPON)

GPON is another FTTH architecture that has been used for over 20 years. GPON was thought as access network architecture in the 1980s. Its simple architecture made cheap and easy to operate fiber based networks possible. A typical GPON architecture is shown in figure 1.7.

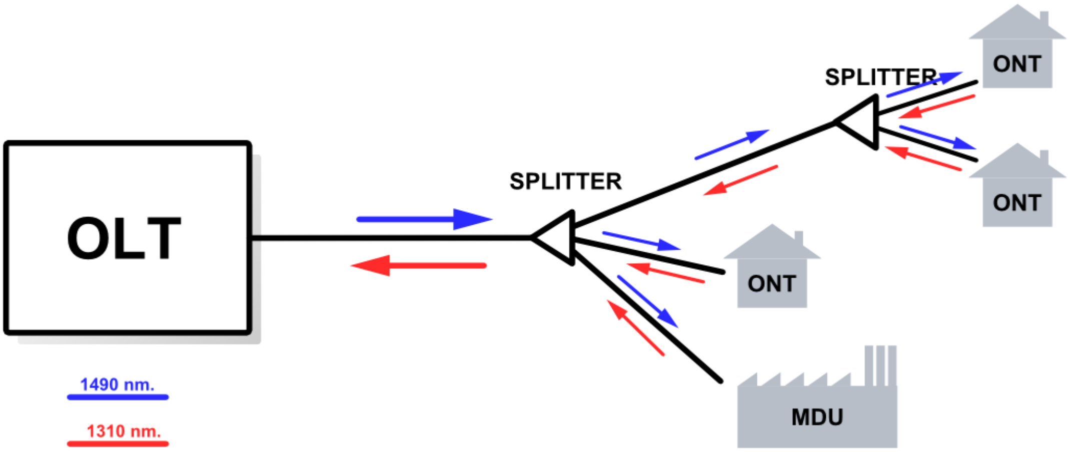

Figure 1.7: Typical GPON architecture

GPON can support seven different transmission bit rates, which are shown in table 1.1 below;

Table 1.1: Transmission Bit Rates of GPON

No	Download Bit Rate	Upload Bit Rate
1	1.2 Gbps	155 Mbps
2	1.2 Gbps	622 Mbps
3	1.2 Gbps	1.2 Gbps
4	2.4 Gbps	155 Mbps
5	2.4 Gbps	622 Mbps
6	2.4 Gbps	1.2 Gbps
7	2.4 Gbps	2.4 Gbps

The most popular bit rate is the sixth one, 1.2 Gbps upstream direction, 2.4 Gbps downstream direction.

1.2.1. Advantages and Disadvantages of GPON

Light from a laser source can travel greater distance in the fiber optic cable than an electronic signal on a copper line with less attenuation and its distribution network could be consist of passive elements, whereas the copper networks should always include active elements.

The benefits of GPON are listed below;

- Although cabinets should be used in harsh outside environments for copper networks, there are no optoelectronic and electronic devices, which are needed to be deployed in an outdoor cabinet.
- There are no electricity and backup power sources in the field.
- There are no dangers based on the power sources.
- There is no external noise that would originate from power sources.
- There is no Electromagnetic Interference (EMI) or Electromagnetic Compatibility (EMC).
- There is no need for environmental control devices.
- There is no Operational Expenses (OPEX) like utility or electricity costs
- There are no powered Opto-Electronic Active Converters (OEAC) that would contribute to the increasing failure rate
- Future applications which require high bandwidth will be easy due to the simple upgradable components.

Because of these advantages GPON is the most popular architecture among others. For example, the capability to carry signals greater distance means less equipment, such as repeaters. Less equipment means fewer points of failure in the network and fewer points of failure leads to improvement in network reliability and quality of services.

Besides these advantages, there are also some disadvantages of GPON; the optical splitters have optical losses that will limit the range of GPON and if one of the fiber optic cables which are located between the OLT and optical splitter is broken off, more than one subscriber will be out of service.

1.2.2. Components of GPON

According to ITU-T G.984 recommendation, the fundamentals of GPON are shown in figure 1.7. These components can be summarized as Optical Line Termination (OLT), Optical Network Termination (ONT) and Optical Splitters (OS).

1.2.2.1. Optical Line Termination (OLT)

The OLT is deployed in the central office (CO) of the operator and controls all the traffic on the optical network (ON). According to ITU-T G.984 recommendation, an OLT must be able to support optical traffic across the ON. In the downstream direction, OLT has to take voice, data and video traffic from the service provider's systems which are located backplane of the OLT and broadcasts to all the ONTs on the ON. In the upstream direction, OLT has to accept and dispatch all types of voice, data and video traffic from the subscribers.

To be able to support different services simultaneously on the same fiber and for each direction, different wavelengths for each service are used. In the downstream direction, GPON uses 1490 nm wavelength for combined data and 1550 nm wavelength for Radio Frequency (RF) video. In the upstream direction GPON uses 1310 nm wavelength for combined data. Passive wavelength division multiplexing (WDM) couplers fulfill the wavelength consolidating and separating functions. The wavelengths being used in GPON are shown in figure 1.8 [4].

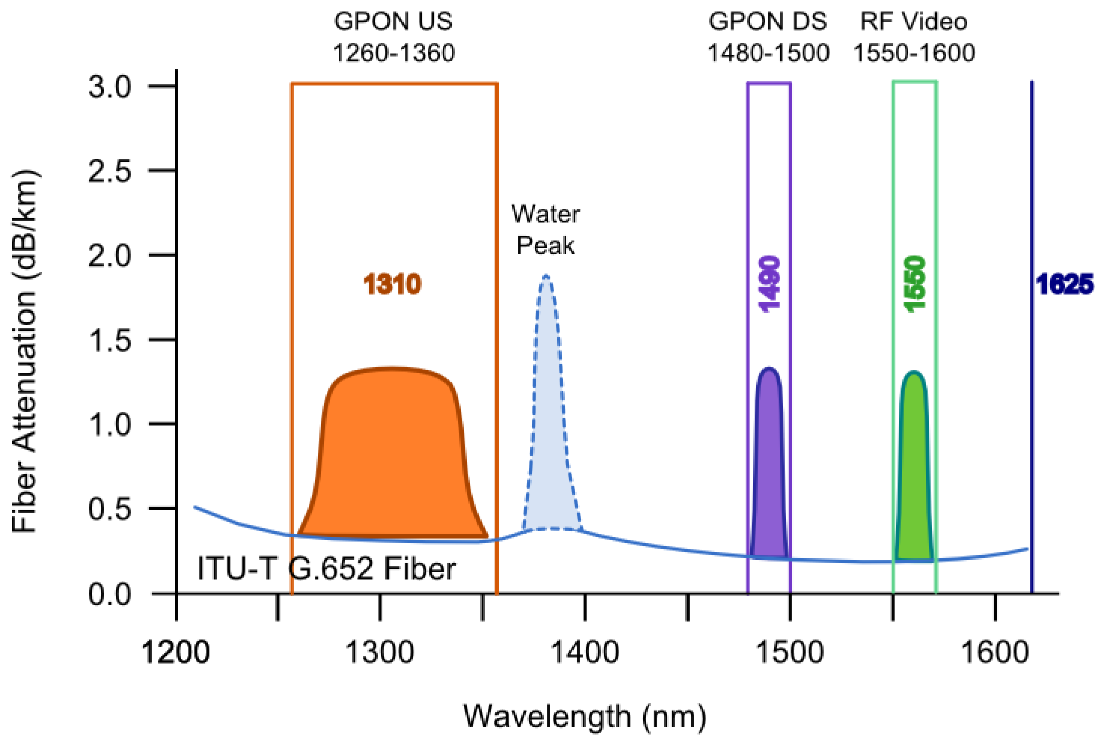

Figure 1.8: G.984.2 GPON Wavelength Allocation Plan [4]

1.2.2.2. Optical Network Termination (ONT)

The ONT is deployed at the subscriber. In the upstream direction the ONT has to transmit data coming from the user's devices like computer, television or telephone to the OLT and in the downstream direction it has to distribute the data coming from the OLT to the user's devices. An ONT can aggregate, set in order and transport different types of data from the user. The ONT is an active device and has an opto-electronic active converter embedded inside and electrical interfaces to the user side. The ONT can support different types of telecommunication services for requirements.

For different types of telecommunication services and subscribers in numbers there are different types of ONT designs and configurations. An ONT can be built in small size and installed to the outside of a premise just for one user or can be built in complex and bigger size like Multiple Dwelling Unit (MDU) or Multiple Tenant Unit (MTU) and installed inside of a building for more than one user.

To support different services, different wavelengths are used by GPON. For this basic Wavelength Division Multiplexing (WDM), at the ONT side a triplexer device which can be defined as the Bidirectional Optical Subassembly (BOSA) is used. The BOSA takes up a major portion of the total cost of PON transceivers itself. The BOSA device is based on bulk-optic assembly technology using thin-film filters (TFF). In figure 1.9 the schematics of BOSA is shown.

First Dichroic mirror is used to reflect 1550 nm to the analog detector and allow 1490/1310 nm wavelengths pass. Second Dichroic mirror is also used to reflect 1490 nm to the digital detector and let the 1310 nm pass through to the fiber optic.

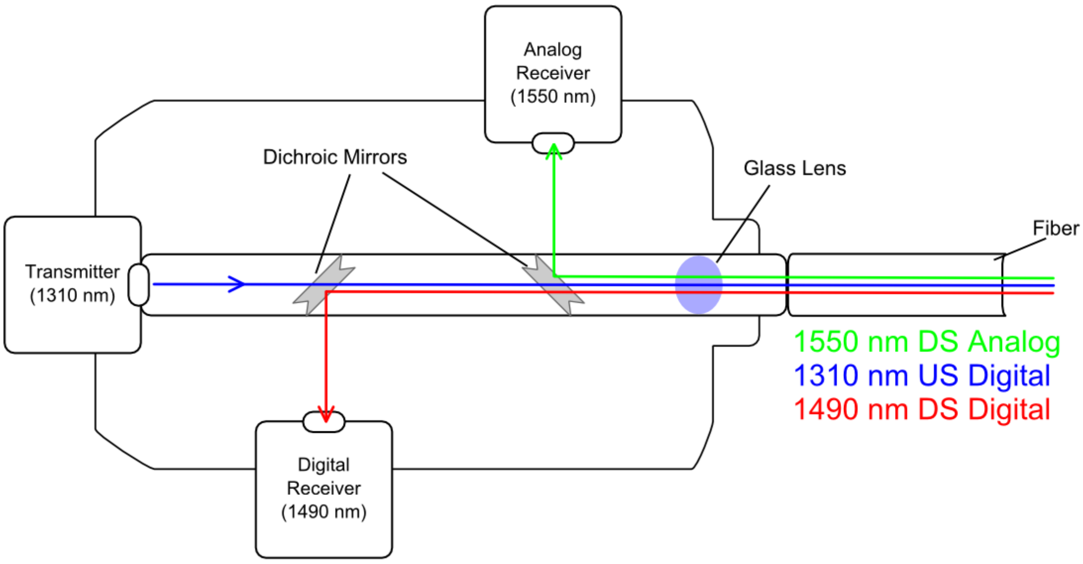

Figure 1.9: BOSA schematics for three wavelengths

1.2.2.3. Optical Splitter (OS)

Optical Splitters are the main components of GPON. The optical splitter is a passive device which gives to GPON its name. Depending on the light direction, this device either distributes the incoming light to the multiple fibers or gathers it onto one fiber.

An NxN star coupler or splitter is a more common form of the 2x2 coupler and shown in figure 1.10.

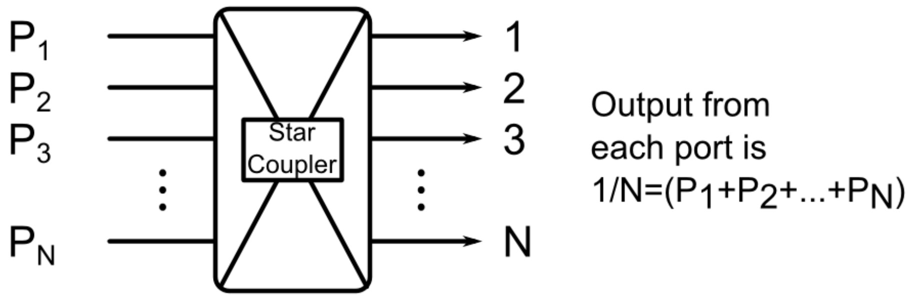

Figure 1.10: An NxN Star Coupler

The star coupler splits all the wavelengths uniformly so that every output of N outputs receives the 1/N of input powers.

In an identical star coupler the input power of any input is equally divided among the outputs. The total loss of the coupler is composed of its splitting loss plus the surfeit loss in each way through the coupler. The splitting loss is given in decibels by formula 1.1 [6].

$$\textit{Splitting Loss}\,(dB) = -10\log\frac{1}{N} = 10\log N \qquad (1.1)$$

In table 1.2, splitting losses of the optical splitters which are being used in the GPON architecture is shown.

Table 1.2: Splitting Losses of the Optical Splitters

Splitting Ratio	**Splitting Loss (dB)**
1:2	3,01
1:4	6,02
1:8	9,03
1:16	12,04
1:32	15,05
1:64	18,06

There are two main types of splitters which relate to the way they are manufactured; Fused Biconical Taper (FBT) and Planar Lightweight Circuit (PLC).

1.2.2.3.1. Fused Biconical Taper (FBT)

The Fused Biconical Taper couplers are also known simply as fused fibers or tubes. The FBT is the simplest form of the optical couplers. Basically it made up of two optical fibers that the cladding sections have been fused together. Figure 1.11 shows the FBT splitter.

The manufacturing process is simple but effective;

- Place two single-mode fibers side by side,
- Bend them together tightly,
- Fuse them at the contact section with fire or high voltage,
- Apply some tension to the both ends of the fibers to the reverse direction.

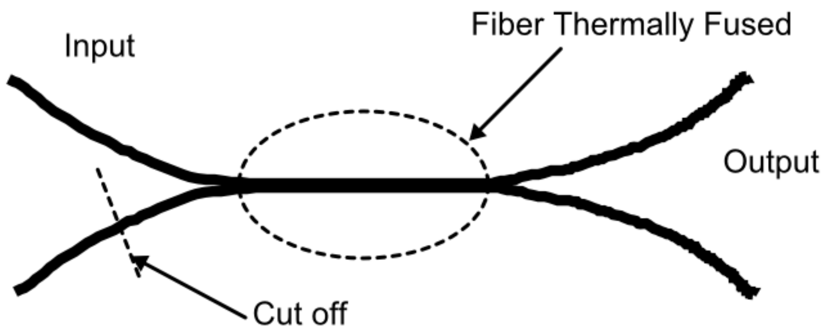

Figure 1.11: FBT Splitter

1.2.2.3.2. Planar Lightwave Circuit (PLC)

These splitters are typically not fused, but created by a variety of circuit manufacturing processes. These optical splitters are very efficient and dependable compared to the FBT splitters. The process of PLC manufacturing is similar to the semiconductor manufacturing process; applying the silicon dioxide waveguides onto the silicon substrate. This integrated splitter will have a single input and an array of output fibers. A PLC splitter is shown in figure 1.12.

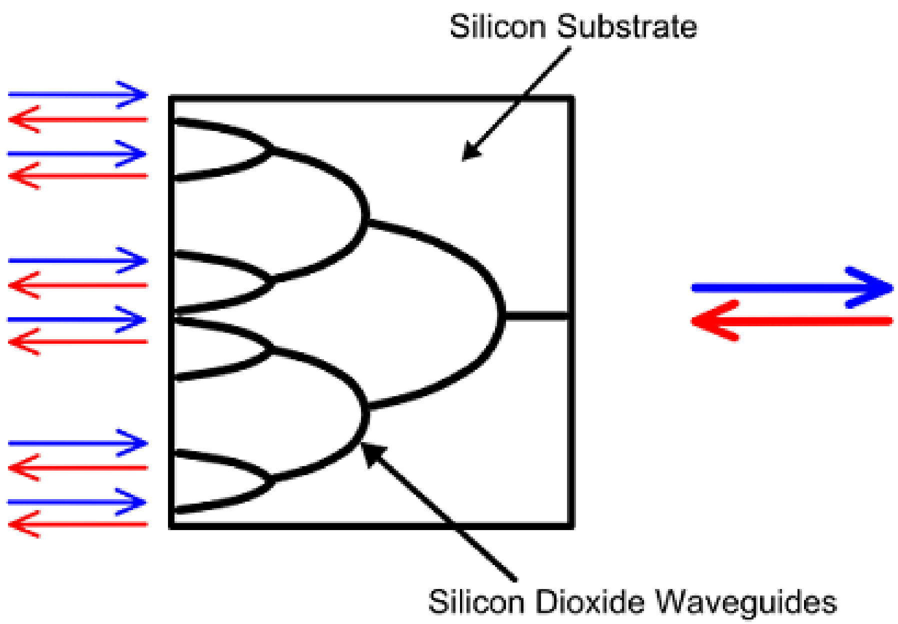

Figure 1.12: A PLC Splitter

1.2.3. GPON Concepts

The OLT broadcasts all the services to the ONTs through the optical network. To achieve this job it uses Time Division Multiplexing (TDM) / Time Division Multiple Access (TDMA). Figure 1.13 shows the traffic in the downstream direction and figure 1.14 shows the traffic in the upstream direction.

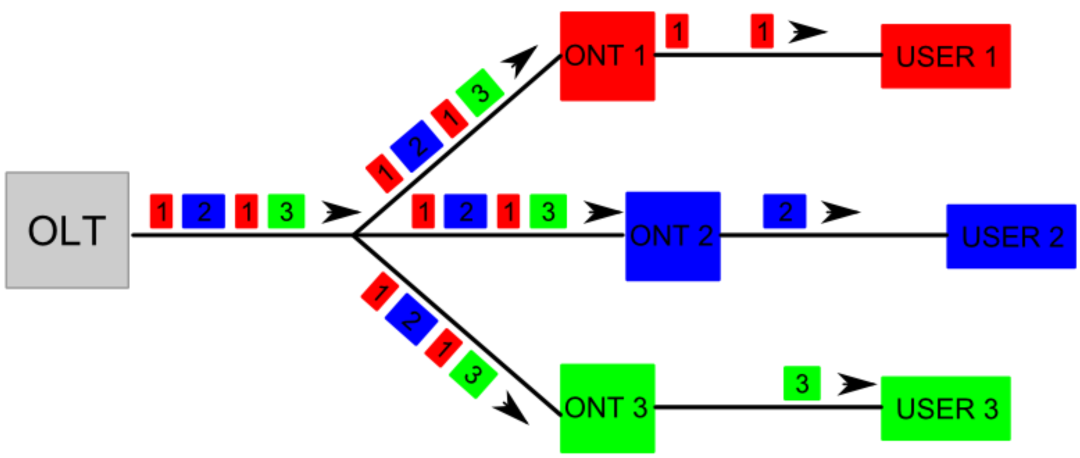

Figure 1.13: Downstream Traffic in GPON

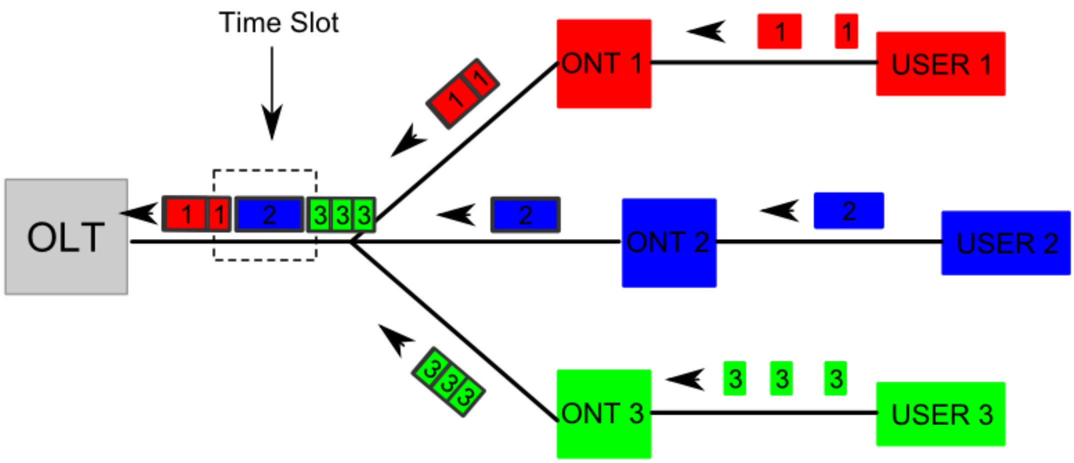

Figure 1.14: Upstream Traffic in GPON

The downstream traffic contains the multiple signals dedicated to ONTs and is broadcast to the all users through the ONTs by the OLT. Each and every one of the ONTs only accepts the packets dedicated to it and sifts the remaining packets. To achieve this filtering like process, OLT uses packet headers for addressing the packets and the ONTs look for these packet addressing data to accept or sift the packets.

The OLT is the ruler of the GPON for traffic streaming. The OLT assigns a time slot dedicated to ONTs to each ONT for transmitting data. The time slots must be synchronized precisely to prevent the collision. Since each and every one of the ONTs is deployed at different locations, the OLT uses a ranging process to evaluate the optical distance between the CO and ONT. This ranging process provides for preventing the collision.

1.2.4. Ranging

Ranging is a process for computing the logical distance between the OLT and ONT and then compensating for that distance to allow multiple ONU transmissions without collisions. All ranging process is initiated by the OLT; it computes the Round Trip Delay (RTD) based on the transmission. This delay information is used to create *the equalization delay (Teqd)* which is required to prevent traffic collisions.

1.2.5. Bandwidth Allocation

The GPON is being used for carrying different types of services and some of them require fixed bandwidth and the OLT, as a ruler of GPON, may assign the required bandwidth in two ways [6].

1.2.5.1. Static Bandwidth Allocation (SBA)

To allocate the required bandwidth, a TDM like allocation technique is used in the prior generations of PON. OLT assigns a static predefined bandwidth to every one of ONTs whether it is used or not. This technique could be ideal if all the services that are being carried in the ON require the fixed bandwidth allocation.

In figure 1.15, a statically bandwidth allocation process is shown. According to figure 1.15, as long as the upstream data flows at certain rate, the statically bandwidth allocation technique has a good usage. But, once the ONT stops the streaming like ONT A or C; the allocated bandwidth will be a waste for the overall upstream traffic.

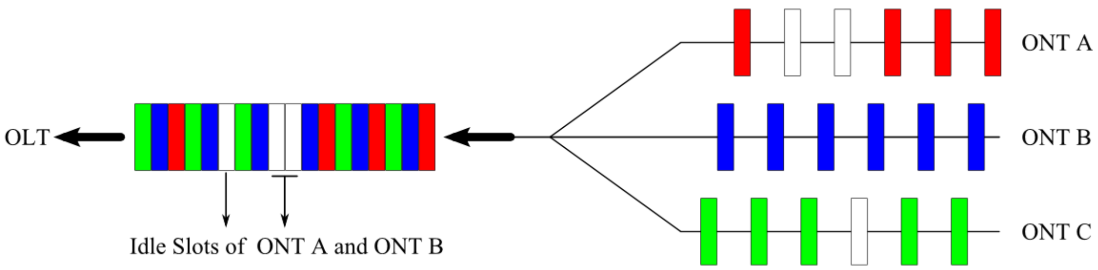

Figure 1.15: Static Bandwidth Allocation [6]

To improve the overall upstream traffic usage, the unused slots which are statically allocated to ONTs, may be assigned to the other ONTs usage that require more bandwidth for high speed connections and specific data. Delivering the unused slots to other ONTs usage will improve the users' expectations and upstream QoS in a positive way.

1.2.5.2. Dynamic Bandwidth Allocation (DBA)

According to ITU-T G984 standard [4], the DBA is a process which is controlled and managed by the OLT. The DBA process improves the upstream traffic usage of the ONTs, the operators' subscriber numbers due to the efficient bandwidth usage.

In figure 1.16, a dynamically bandwidth allocation process is shown. According to figure 1.16, if the ONT stops the streaming like ONT A or C, there will be some idle slots which are contains no data. And if an ONT requires more bandwidth because of the high speed services like ONT B, the idle slots from the ONT A or C will be used by the ONT B. DBA process will increase the Service Level Agreement (SLA) of the subscriber and allows oversubscription of upstream bandwidth beyond the 1.2 Gb/s bandwidth limitations.

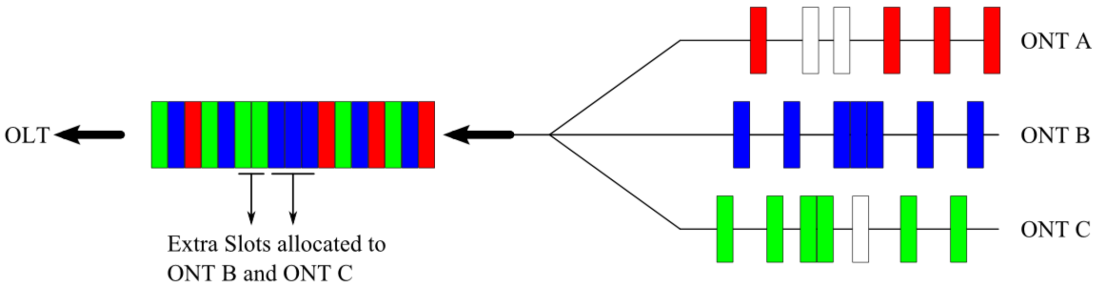

Figure 1.16: Dynamic Bandwidth Allocation [6]

On a GPON, the upstream traffic is not fixed; because of fast changing stream a DBA process algorithm must adjust the traffic bandwidth with quick response.

1.2.6. Security

The basic concern in GPON is that the downstream data is broadcasted to all ONTs attached to the GPON. Because of this structure some malicious users can listen to all the downstream data of all the users. This is called *eavesdropping threat* that the GPON security system is intended to counter. In ITU-T G984 standard [4], a security mechanism to prevent the users who are not permitted to access other users' data is described.

Furthermore, the GPON itself has the unique property as it is highly directional. So any ONT cannot observe the upstream traffic from the other ONTs on the GPON. This allows privileged information (such as security keys) to be passed upstream clearly. While there are threats that could jeopardize this situation, such as an attacker tapping the common fibers of the GPON, these are considered as not being realistic; since the attacker would have to do so in public spaces, and would probably attenuate the GPON he is tapping.

1.2.6.1. Encryption System

Every packet transmitted by ONTs can be seen by all the users' member of GPON because of the PON architectures which broadcasts the data to the downstream direction. A security mechanism is described in the standard which is called Advanced Encryption Standard (AES). The AES is an encryption mechanism which prevents to access to the data field in the GPON frame.

The AES mechanism encrypts the data in the data field to an impenetrable form called cipher text and decrypts the cipher text to their original format. The cipher texts can be a 128, 192 or 256 bits long word which renders hacking very hard. To decrypt the cipher text to plain text, a key word which is changed periodically is needed.

A simple example, a plain text, a key word and a 128 bits long cipher text which is generated by them is shown in figure 1.17.

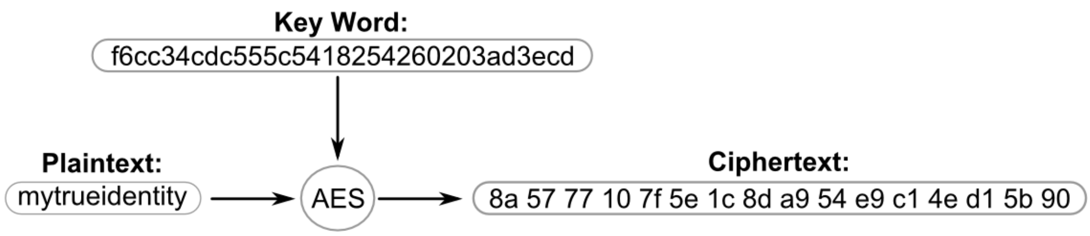

Figure 1.17: AES Example

CHAPTER II

COMPARISON OF GPON AND CONVENTIONAL COPPER ACCESS NETWORKS

In this chapter, a detailed comparison of the GPON and the conventional copper access networks is given on two different architectures in a pilot region in Ankara. In this specific experiment, we took the opportunity to take measurements and carry out tests and perform a comparison between a GPON and a copper back-up network installed in a newly built construction site project in Ankara.

2.1. THE CONVENTIONAL COPPER NETWORK

The copper cable schematic of the project which inspected in this thesis is shown in figure 2.1. The red line indicates the main copper cable which is terminated to the Central Office (CO). The green line indicates the local copper cable which is used for distribution. The blue lines indicate the subscribers’ copper cables (Cat5e).

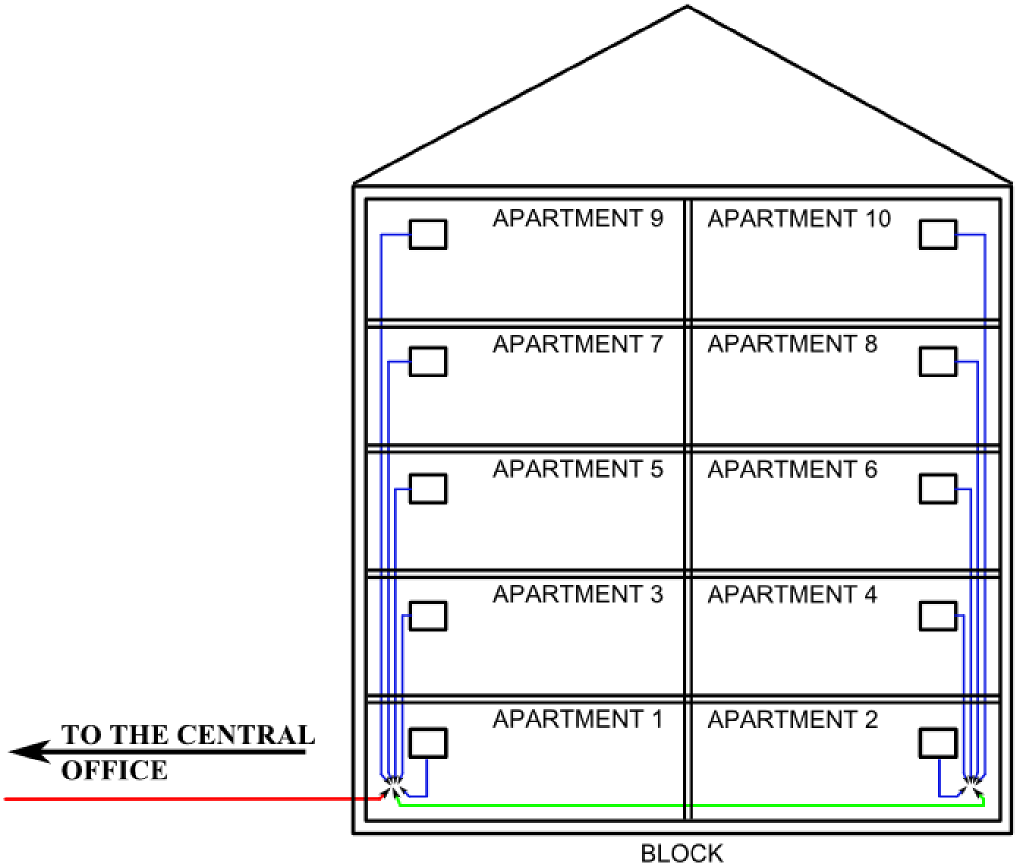

Figure 2.1: Copper Cable Schematic

2.2. THE GPON

The GPON cable schematic for the same facility is shown in figure 2.2. Copper network and GPON network were installed simultaneously into the same building for each user. In other words, the users in the building have two networks: GPON and copper. The operator took this approach in the case of unavailability of the GPON, which is considered more risky since it is new and not used before; the copper network would continue to provide the connection as a back-up. We used this opportunity to compare the networks, because in the project there are two networks established on the same facility. Since all the physical parameters are the same (the distances, the infrastructure) it would be meaningful to compare the performances of these networks.

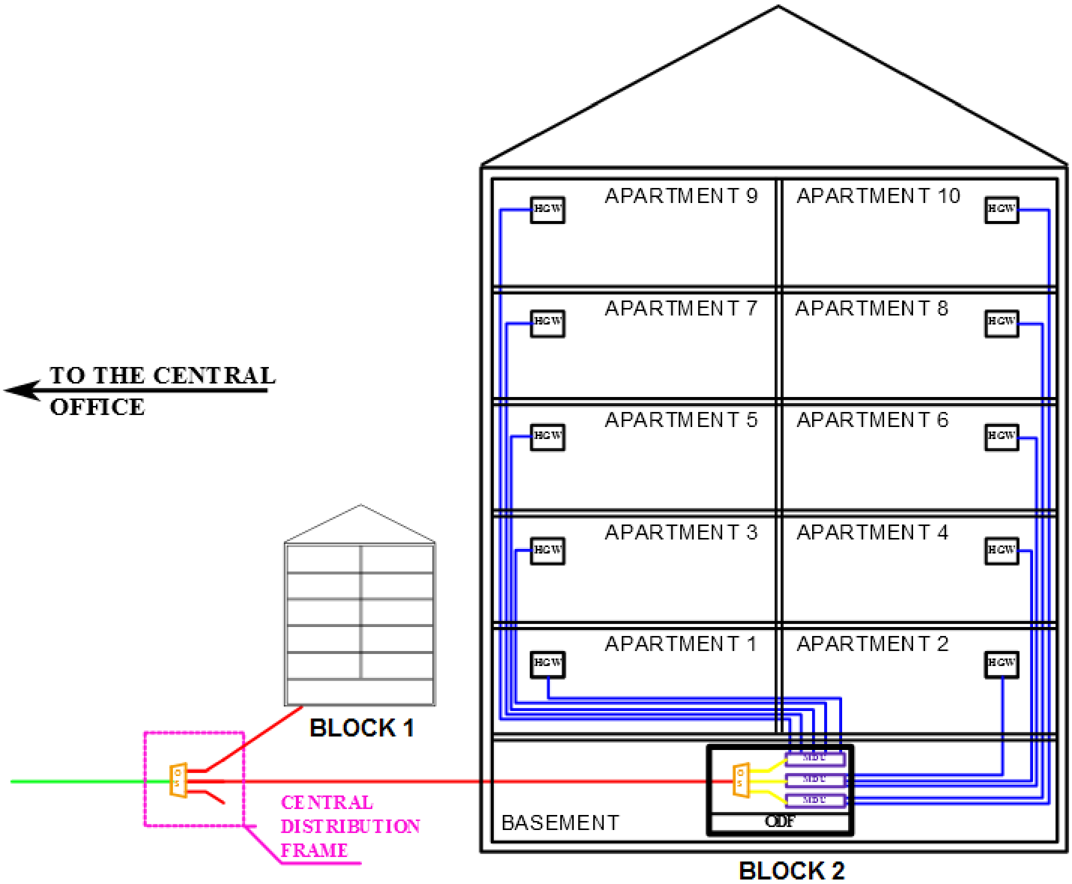

Figure 2.2 GPON: Cable Schematic in the Same Block

The green line indicates the fiber optic cable which is terminated to the CO. The orange trapezoid indicates the OS (Optical Splitter). The pink box indicates the central distribution frame for the buildings. The red lines indicate the fiber optic cables which are terminated between the central distribution frame and the blocks. The yellow lines indicate the patch-cord cables which are terminated between the OS and the Multiple Dwelling Unit (MDU), represented by the purple box. The blue lines indicate the Category 5e (Cat 5e) type copper cables between the MDU and the Home Gateway (HGW).

In this specific project the lines between the home gateways and the MDUs are not fiber but copper cables. That is, fiber is not installed between the apartments and MDUs. The operator made a decision of not installing the fiber fully to the end; instead, they preferred installing the fibers to the buildings and not more beyond that. This was assumed because of the operator's investment policy.

2.3. COMPARING THE NETWORKS

To compare the networks in terms of data bit rate and the total capital expenditure (CAPEX), detailed and sensitive measurements were done first. For this purpose every network was measured individually and the results were discussed in the following.

2.3.1. Measuring the Copper Network

Measuring the copper for determining the bit rate of the data transmission through the 0.5 mm copper cable was carried first. In figure 2.3 the measurement method and configuration is shown.

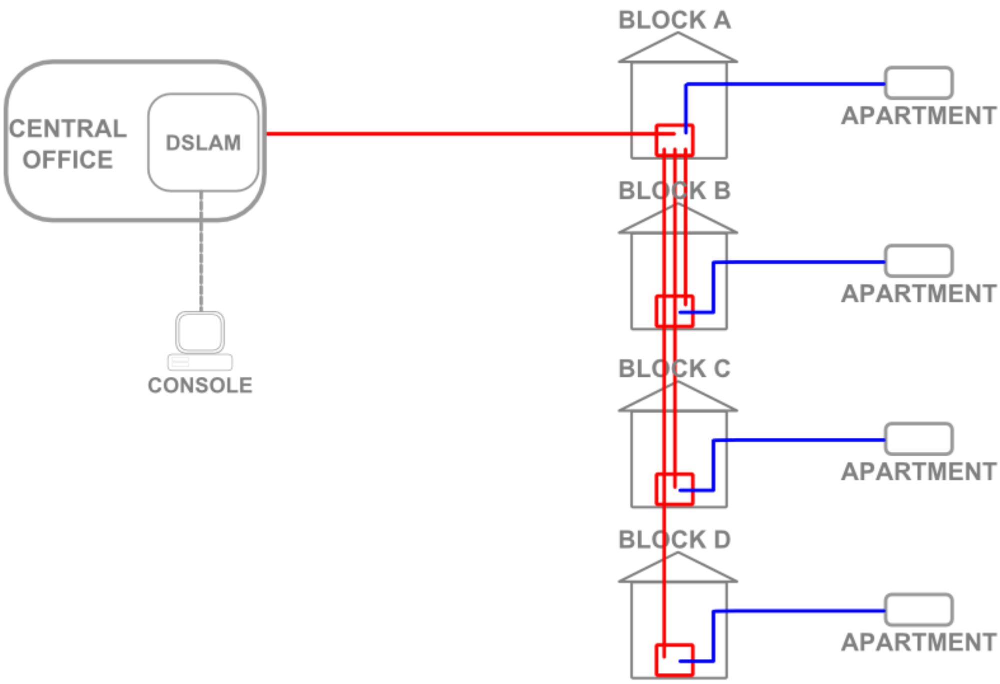

Figure 2.3: The Measurement Method of Copper Network

As seen in figure 2.3, the red line between the CO and Block A indicates the main copper cable; the red rectangle indicates the Distribution Box (DB); the blue line indicates the CAT-5 cable between the DB and the Apartment; the Digital Subscriber Line Access Multiplexer (DSLAM) is the active device which detaches the voice signals from the data signals and rules traffic between the digital subscriber line (xDSL) devices and the users' devices; and the console is the interface to configure, control and route the DSLAM.

The bit rate for the copper cable was measured at the console from the CO to the subscriber's equipment. For this measurement the standard ADSL2+ and VDSL2 profiles were used to configure the DSLAM. The profile specifications are 24 Mbps upload and 2 Mbps upload for ADSL2+ and 100 Mbps download and 2 Mbps upload for VDSL2. The upload bit rates for ADSL2+ and VDSL2 were same because the operator allowed only 2 Mbps for testing.

The copper networks in the four different blocks and four different apartments in each block were measured and the results of the measurements are shown in table 2.1, 2.2 and figure 2.4, 2.5.

Table 2.1: Bit Rate Measurements of the Copper Network (ADSL2+)

Copper Cable Length (m)	Configured Adsl2+ Downstream Bit Rate (Mbps)	Adsl2+ Downstream Bit Rate (Mbps)	Configured Adsl2+ Upstream Bit Rate (Mbps)	Adsl2+ Upstream Bit Rate (Mbps)
598	24.000	23.994	2.048	1.119
634	24.000	23.994	2.048	1.051
682	24.000	23.994	2.048	1.031
731	24.000	23.994	2.048	1.095

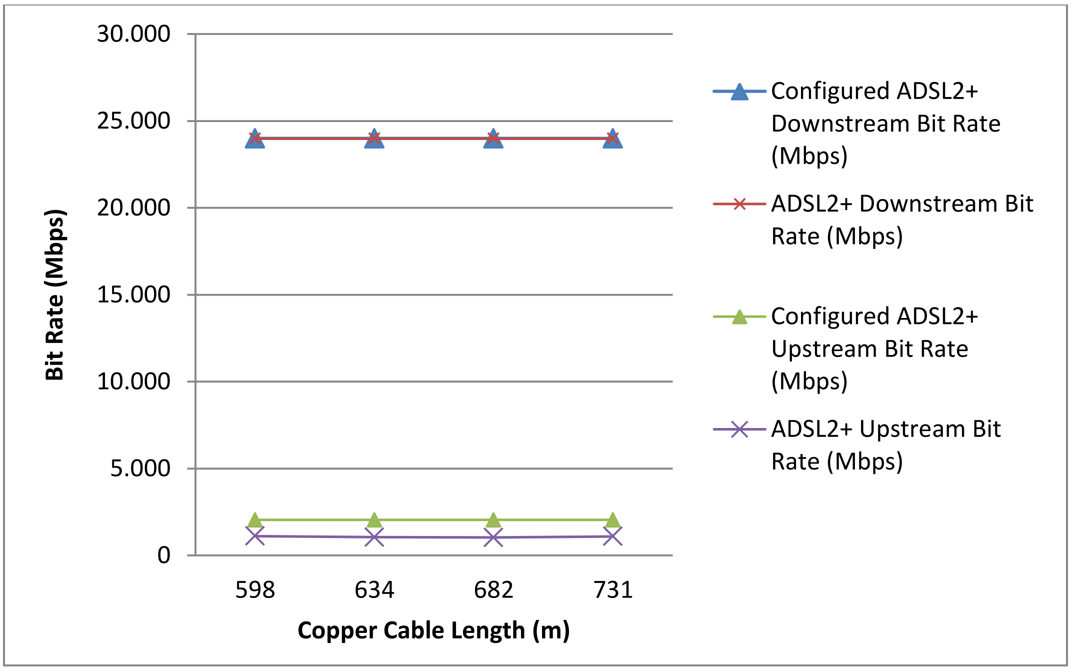

Figure 2.4: Bit Rate / Distance Relation of the Copper Network (ADSL2+)

Table 2.2: Bit Rate Measurements of the Copper Network (VDSL2)

Copper Cable Length (m)	Configured Vdsl2 Downstream Bit Rate (Mbps)	Vdsl2 Downstream Bit Rate (Mbps)	Configured Vdsl2 Upstream Bit Rate (Mbps)	Vdsl2 Upstream Bit Rate (Mbps)
598	100.000	74.181	2.048	2.044
634	100.000	70.004	2.048	2.044
682	100.000	67.330	2.048	2.044
731	100.000	62.986	2.048	2.044

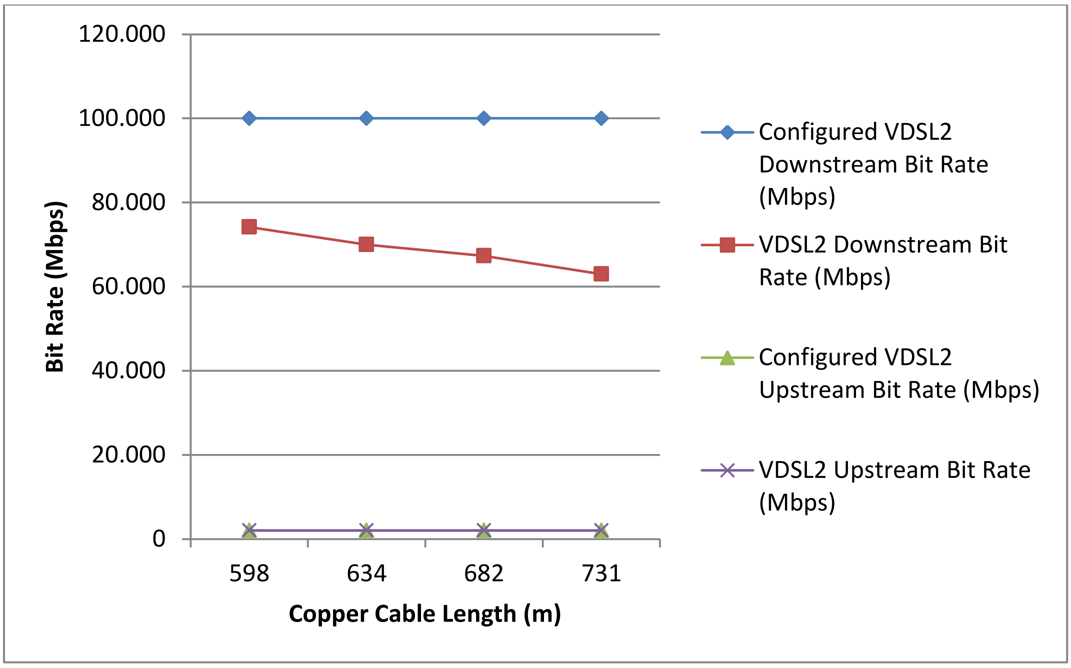

Figure 2.5: Bit Rate / Distance Relation of the Copper Network (VDSL2)

The measured upload bit rates of both ADSL2+ and VDSL2 profiles are same because of the cable lengths being not long enough. The download bit rates of ADSL2+ profile for four different cable lengths are same due to the same reason as the upload bit rates. The download bit rates of VDSL2 profile for four different cable lengths are not same but decreasing linearly as the cable lengths increases. The longer cable means lower bit rate.

2.3.2. Measuring the GPON

Prior to the measurements, the fiber optic cable between the CO and the target block was checked to verify that the fiber optic cable is not damaged. For this process a JDSU brand MTS-4000 model Optical Time Domain Reflectometer (OTDR) which has 0.8 m sensitivity was used. An OTDR is an instrument to measure the attenuation, reflectance and loss in a fiber cable.

To measure the fiber cable the OTDR can be placed at either ends of the cable. In this project, it was connected at the CO end of the cable. Figure 2.6 shows the verification setup of the fiber optic cable schematic. The red line indicates the fiber optic cable; the orange triangles indicate the optical splitters; the violet rectangles indicate the MDUs.

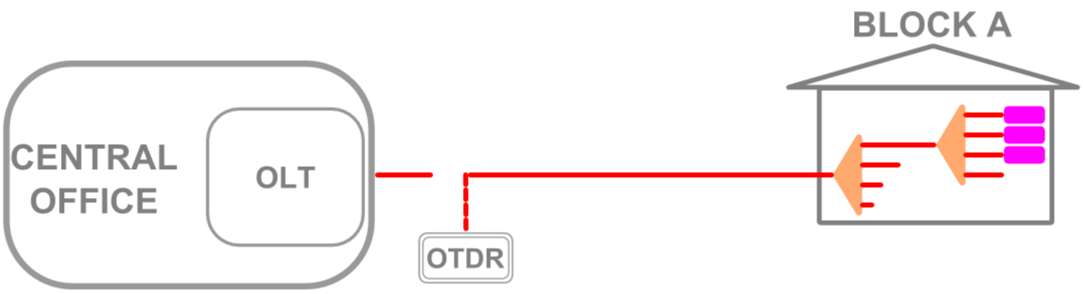

Figure 2.6: The Verification of the Fiber Optic Cable

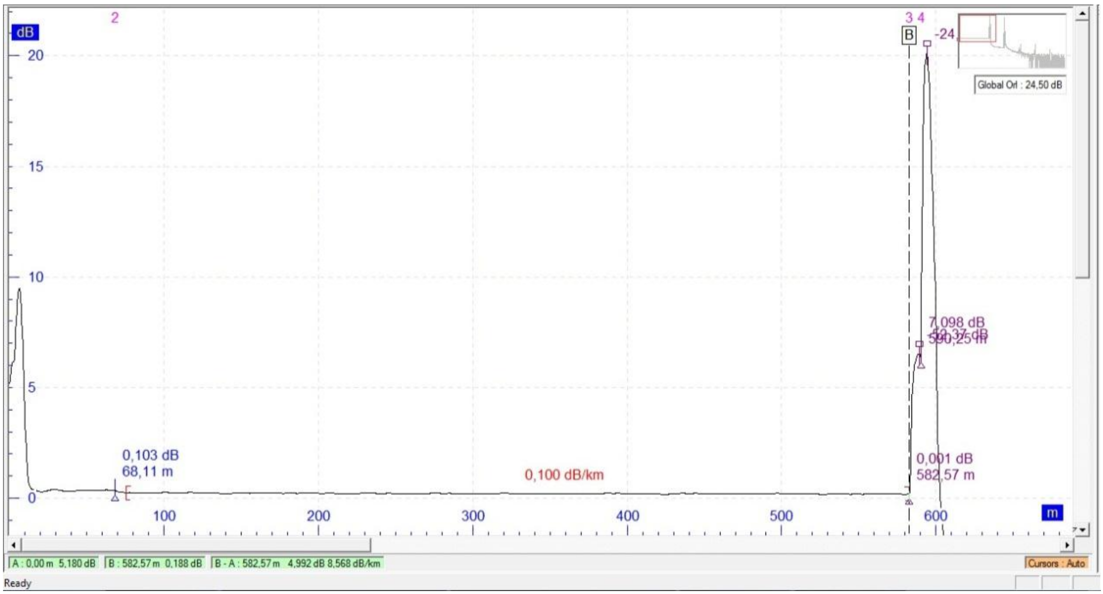

Figure 2.7: The OTDR Trace

In figure 2.7, the OTDR trace of the main fiber optic cable which was installed between the OLT and the OS in the block A is shown. As seen from the trace the fiber optic cable is 582.57 m long and verified.

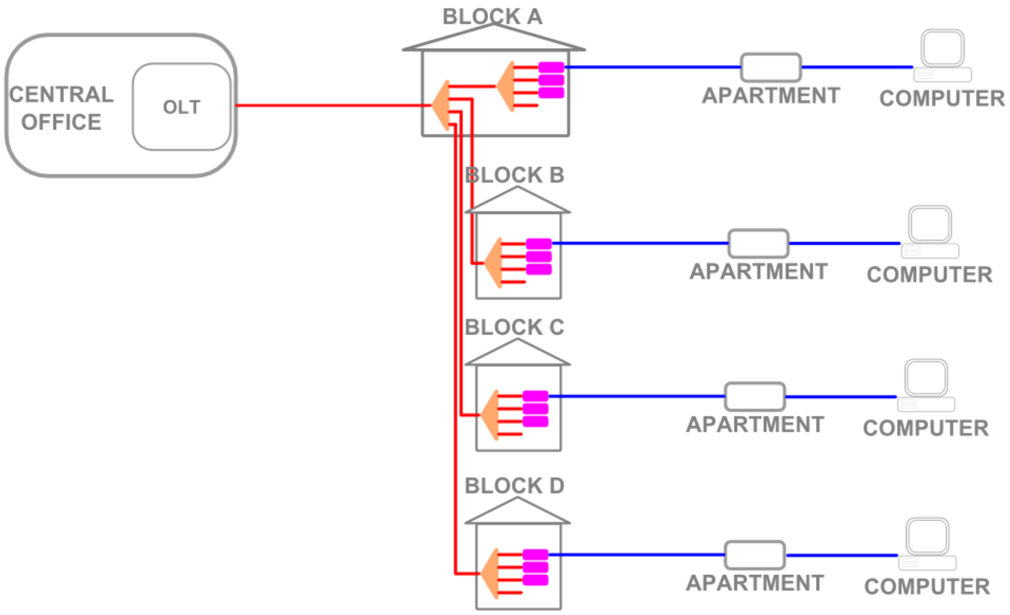

Figure 2.8: The Measurement Method of the GPON

To measure the data speed of the GPON network the architecture as indicated in figure 2.8 was used. As seen in figure 2.8, the red line indicates the fiber optic cable; the orange triangles indicate the optical splitter; the violet rectangles indicate the MDUs; the blue lines indicate the Cat 5 cables. For measurements a laptop computer was connected to the respective Cat 5 cable in each apartment and used the http://hiztesti.ttnet.com.tr and http://speedtest.net portals to measure the bit rates to make more accurate assumptions. In these portals, there are embedded speed measurement routines that can measure the maximum bit rate of the particular line. The method of measuring the line's data bit rate by these portals is unknown so the measurement techniques of the web portals are assumed as correct. We measured the performance of the copper wires from the Cat 5 user end to the respective MDUs.

To carry a more accurate comparison between the networks' bit rates; the same profile specifications which were described for copper networks measurements were used in the GPON measurements too. Table 2.3 and figure 2.9 shows the measurement values of ADSL2+ like profile of GPON.

Table 2.3: Bit Rate Measurements of the Copper Cables in GPON (ADSL2+)

Cat 5 Length (m)	TTNET Downstream Bit Rate (Mbps)	SPEEDTEST Downstream Bit Rate (Mbps)	TTNET Upstream Bit Rate (Mbps)	SPEEDTEST Upstream Bit Rate (Mbps)
20	23.84	23.96	2.05	2.10
25	24.01	24.04	2.08	2.09
30	24.11	24.02	2.10	2.02
35	23.82	24.29	2.08	2.06

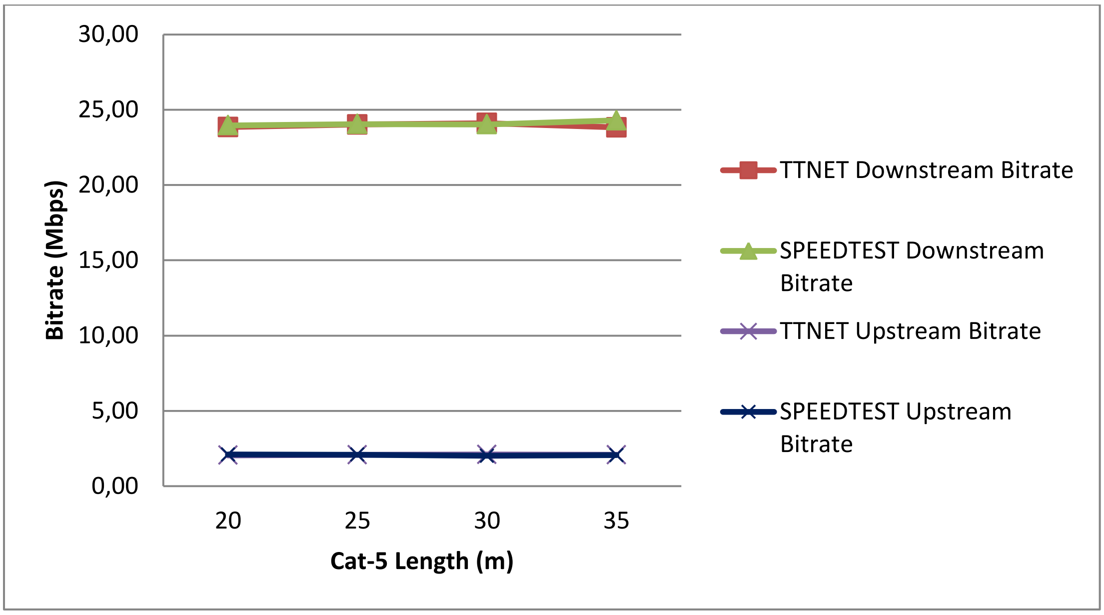

Figure 2.9: Bit Rate / Cable Length Relation of the Copper Cables in the GPON (ADSL2+)

Table 2.4 and figure 2.10 shows the measurement values of VDSL2 like profile of GPON.

Table 2.4: Bit Rate Measurements of the Copper Cables in GPON (VDSL2)

Cat 5 Length (m)	TTNET Downstream Bit Rate (Mbps)	SPEEDTEST Downstream Bit Rate (Mbps)	TTNET Upstream Bit Rate (Mbps)	SPEEDTEST Upstream Bit Rate (Mbps)
20	94.21	94.28	2.08	2.10
25	94.08	94.13	2.09	2.10
30	93.98	94.02	2.10	2.10
35	93.81	93.94	2.09	2.10

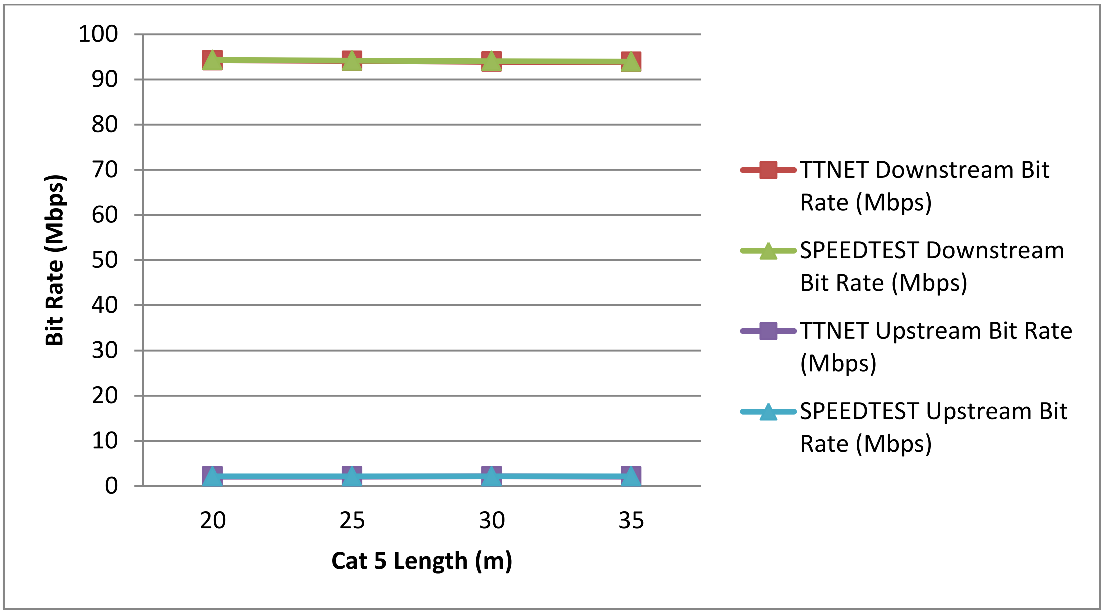

Figure 2.10: Bit Rate / Cable Length Relation of the Copper Cables in the GPON (VDSL2)

In the GPON project, between the CO and the MDUs are fiber optic cable as mentioned before, and therefore we called this network as GPON+copper network. Because of the optical transmission in the fiber cable there is apparently no decrease in the bit rate of data as compared to the transmission speed in a twisted copper cable. So, in this thesis between the CO and the MDUs, where a fiber cable is used, measurements of bit rate of data were not made but calculated.

2.4. COSTS OF THE NETWORKS; CAPITAL EXPENDITURE (CAPEX)

2.4.1. Costs of the Copper Network

While planning a network in an area the most important thing is the total cost and the return of investment (ROI) time of the costs. Approximately the total cost of the project was about **3,365.023 Arbitrary Unit (AU)** which comprises labor, material and transportation costs for 5 buildings of 96 apartments in each (480 apartments) are listed in table 2.5 shown below. Note that the costs are represented with arbitrary units (AU).

Table 2.5: Total Costs of the Copper Network Project

Material Type	Material Costs (Arbitrary Unit – AU)
Copper Cable Used in the Project	2,445.35
Coupling and Termination Materials for the Copper Network	76.753
Labor Costs for the Copper Network	842.920
TOTAL	**3,365.023**

2.4.2. Costs of the GPON

Approximately the total cost of the project was about **29,066.374 Arbitrary Unit (AU)** which comprises labor, material and transportation costs for 5 buildings of 96 apartments in each (480 apartments) are listed in table 2.6 shown below.

Table 2.6: Total Costs for the GPON Project

Material Type	Material Costs (Arbitrary Unit – AU)
Fiber Optic Cable Used in the Project	136.240
Coupling and Termination Materials for the GPON	270.376
Labor Costs for the Copper Network	477.758
Costs of Active Components	28,182.00
TOTAL	**29,066.374**

2.5. Comparison of the Networks

To compare the networks, data bit rates were measured and determined investment costs were calculated. In figure 2.11 the comparison of the bit rate and the Capital Expenditure (CAPEX) of the copper network and the GPON, each comprising 5 buildings of 480 apartments in total are shown.

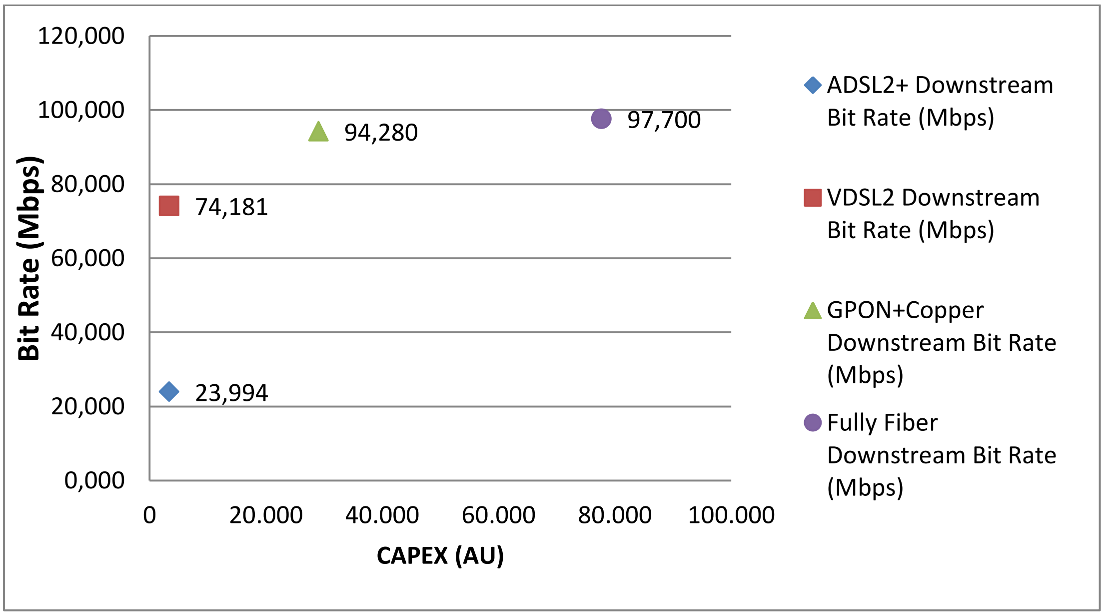

Figure 2.11: Bit Rate and CAPEX Relation of the Networks

Figure 2.11 shows the bit rate and CAPEX relation of the networks installed on the project site. To get the maximum bit rate for copper network 3.365 AU required. For future applications the GPON can provide required bandwidth for 29.066 AU. But for fully fiber GPON the required CAPEX is 77.714 AU and for the VDSL2 profile (100 Mbps download bit rate) used for GPON+copper network measurements the Maximum Communication Speed (MCS) can be calculated as described in [8];

$$MCS = \frac{Ethernet\ Payload - IPMPLS\ Header}{Length\ of\ Ethernet\ Packet} \times (Speed) \tag{2.1}$$

The Ethernet Payload represents how many byte of data (1452 bytes) can be transferred and the Length of Ethernet Packet represents the Ethernet Frame’s length (1518 bytes according to IEEE 802.3).

IPMPLS Header represents the extra data which is needed for MPLS protocol to be used (4 bytes). For 100 Mbps (100 x 1.024.000 bps), the MCS can be calculated as 99.7 Mbps from equation 2.1.

CONCLUSION

The GPON is a turning point for fiber based communication projects all over the world. Some developing countries which could not set their telecommunication network like Poland set their plans for future according to the fiber to the home networks. On the other hand, some developed countries which have already had a complete conventional telecommunication infrastructure like Germany and Turkey have started to convert existing infrastructure to the fiber. This technology can be easily adapted for future applications, according to the increasing subscribers' demands, for FTTH/B networks.

In Turkey, the operators started to establish fiber cables in networks. In this thesis a general performance of the GPON and a FTTB/H project in Ankara, as an example, was analyzed and compared to the conventional copper telecommunication network.

To measure and compare the performances of the copper and the optical networks a pilot site in Ankara, which has both copper and optical network, were chosen. The bit rates that can be provided by the networks were measured. The required capital expenditures (CAPEX) were also inspected for both projects.

The networks that were compared have both copper cables: GPON+copper and full copper. Two networks were established on the same infrastructure in order to provide back up. Therefore, they have the similar physical parameters (similar cable lengths and infrastructures) which presented a good opportunity to compare their performances in terms of their data bit rates and CAPEXs. Considering the fact that the performance in a GPON+copper network is not essentially limited by the optical part but the copper part, the comparisons in data bit rates were actually reduced to comparison of two copper networks of different lengths in both networks.

The GPON+copper network measurements are made after the measurements for the full copper network. The GPON+copper network is, unfortunately, not a full fiber GPON, because in the infrastructure the operator did not provide fully optical network to the customers, instead they provided the fiber up to the MDUs and beyond those points preferred to provide copper as an investment policy. After the GPON+copper network measurements, it was confirmed that the result of performance of the network is limited only by the copper cables (CAT-5) connected from the MDUs to the customer. Therefore the copper part performances were only measured again with respect to the length of the copper in the GPON+copper network.

The opportunity of having the cost data was used to analyze the CAPEX between the two networks, i.e., full copper network and the GPON+copper network.

Calculations were also made for full fiber GPON. The results for these calculations were used for indicating the bit rate versus CAPEX analysis of these networks with those of the full copper, the GPON+copper and the full fiber GPON. The cost data for full fiber networks was taken from the literature in this case.

According to the comparison, the GPON is far more superior in terms of speed. As seen from the calculations the GPON has nearly 4 times higher bit rate for the fully fiber based infrastructure than that for the copper network; however its capital expenditure (CAPEX) is almost 23 times higher than that of the copper network.

From figure 2.11, it is clear that the CAPEX increases as the Maximum Communication Speed (MCS) increases. The CAPEX, on the other hand, depends on the operator’s investment policy. In most scenarios the operator plans the projects according to the social and economic state of the project sites.

In GPON all services that can be supported by the active user devices (ONT, MDU and HGW) can be given to the subscribers at all desired speeds that active devices may provide. In the GPON there is almost no speed limit due to the changes at the subscribers’ devices.

The present users ask not only telephone or internet services but the triple play services like High Speed Internet (HSI), Television and much more like Video on Demand (VoD), Interactive Television (IPTV) and telephone (VOIP). These services can be easily delivered to the end user at high speed and without interruption with GPON.

The GPON is not a perfect telecommunication network yet; it has some issues to be further improved. The passive architecture is an advantage for simplicity and cost efficiency, however it has a disadvantage of the high splitting losses. The high splitting losses are the main causes that limit the GPON in reaching long distances. To overcome this problem high powered LASERs or LEDs can be used, but this time an energy problem will occur. Like every new technology GPON needs time to improve. In time, the developments in the material and semiconductor technology will resolve the problems which limit the GPON presently.

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