VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

ÚSTAV TELEKOMUNIKACÍ
DEPARTMENT OF TELECUMMUNICATIONS

METHODOLOGY OF DESIGNING PON NETWORKS

MASTER'S THESIS

Author **Bc. ANAS OMAR DALLAL**

Brno 2010

METHODOLOGY OF DESIGNING PON NETWORKS

MASTER’S THESIS

AUTHOR *Bc. ANAS OMAR AL-DALLAL*
SUPERVISOR *Assoc. Prof. Ing. MILOSLAV FILKA, Ph.D.*

This page is intentionally left blank.

LICENČNÍ SMLOUVA
POSKYTOVANÁ K VÝKONU PRÁVA UŽÍT ŠKOLNÍ DÍLO

uzavřená mezi smluvními stranami:

1. Pan/paní

Jméno a příjmení: **Anas Omar Dallal**

Bytem: **Benghazi, Libya**

Narozen/a (datum a místo): **05/12/1984, Harare, Zimbabwe**

(dále jen „autor“)

a

2. Vysoké Učení Technické v Brně

Fakulta elektrotechniky a komunikačních technologií
se sídlem **Údolní 244/53, 602 00 Brno Česka Republika**
jejímž jménem jedná na základě písemného pověření děkanem fakulty:
prof. Ing. Kamil Vrba, CSc.
(dále jen „nabyvatel“)

Článek 1
Specifikace školního díla

1. Předmětem této smlouvy je vysokoškolská kvalifikační práce (VŠKP):
   - □ disertační práce
   - □ bakalářská práce
   - ▪ **diplomová práce**
   - □ jiná práce, jejíž druh je specifikován jako ....

   (dále jen VŠKP nebo dílo)

Název VŠKP: **Methodology of Designing PON Networks**
Vedoucí/ školitel VŠKP: **Assoc. Prof. Ing. MILOSLAV FILKA, Ph.D.**
Ústav: **Telekomunikací**

VŠKP odevzdal autor nabyvateli v*:

- **tištěné formě** – počet exemplářů 2
- **elektronické formě** – počet exemplářů 2

2. Autor prohlašuje, že vytvořil samostatnou vlastní tvůrčí činností dílo shora popsané a specifikované. Autor dále prohlašuje, že při zpracovávání díla se sám nedostal do rozporu s autorským zákonem a předpisy souvisejícími a že je dílo dílem původním.
3. Dílo je chráněno jako dílo dle autorského zákona v platném znění.
4. Autor potvrzuje, že listinná a elektronická verze díla je identická.

Článek 2
Udělení licenčního oprávnění

1. Autor touto smlouvou poskytuje nabyvateli oprávnění (licenci) k výkonu práva uvedené dílo nevýdělečně užít, archivovat a zpřístupnit ke studijním, výukovým a výzkumným účelům včetně pořizovaní výpisů, opisů a rozmnoženin.
2. Licence je poskytována celosvětově, pro celou dobu trvání autorských a majetkových práv k dílu.
3. Autor souhlasí se zveřejněním díla v databázi přístupné v mezinárodní síti

    ▪ **ihned po uzavření této smlouvy**
    □ 1 rok po uzavření této smlouvy
    □ 3 roky po uzavření této smlouvy
    □ 5 let po uzavření této smlouvy
    □ 10 let po uzavření této smlouvy
    (z důvodu utajení v něm obsažených informací)

4. Nevýdělečné zveřejňování díla nabyvatelem v souladu s ustanovením § 47b zákona č. 111/ 1998 Sb., v platném znění, nevyžaduje licenci a nabyvatel je k němu povinen a oprávněn ze zákona.

Článek 3
Závěrečná ustanovení

1. Smlouva je sepsána ve třech vyhotoveních s platností originálu, přičemž po jednom vyhotovení obdrží autor a nabyvatel, další vyhotovení je vloženo do VŠKP.
2. Vztahy mezi smluvními stranami vzniklé a neupravené touto smlouvou se řídí autorským zákonem, občanským zákoníkem, vysokoškolským zákonem, zákonem o archivnictví, v platném znění a popř. dalšími právními předpisy.
3. Licenční smlouva byla uzavřena na základě svobodné a pravé vůle smluvních stran, s plným porozuměním jejímu textu i důsledkům, nikoliv v tísni a za nápadně nevýhodných podmínek.
4. Licenční smlouva nabývá platnosti a účinnosti dnem jejího podpisu oběma smluvními stranami.

V Brně dne: ………………

……………………….	…………………………
Autor	Nabyvatel
(podpis)	(pdpis)

This page is intentionally left blank.

ABSTRACT

The purpose of this thesis is to analyze the present condition of Access network, in depth research of PON Methodology and network design. I shall design a Network project based on FTTH for building a network of 90 private houses controlled by a central control point from 20km distance.

Where I shall address these issues and expedite the introduction of FTTH, and I will reason behind (PON) network-based solution, and so on ATM-PON and Ethernet PON (EPON), which are based on common network architecture, PON, but adopt different transfer technologies to support integrated services and multiple protocols. After providing the (optimal) network solution that fits to fulfill Triple-Play requirements, I will describe how the network interconnects and how it functions and work, later on I shall go into describing the measuring methods and testing for the defined network “after activating and setting the network” and “before activating the network service” where I will also use the OTDR and practically apply a link characterization test. And suggest the monitoring of the design model of the project.

PROHLÁŠENÍ

Prohlašuji, že svou diplomovou práci na téma **"Methodology of Designing PON Networks"** jsem vypracoval samostatně pod vedením vedoucího diplomová práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

Jako autor uvedené diplomové práce dále prohlašuji, že v souvislosti s vytvořením této diplomové práce jsem neporušil autorská práva třetích osob, zejména jsem nezasáhl nedovoleným způsobem do cizích autorských práv osobnostních a jsem si plně vědom následků porušení ustanovení § 11 a následujících autorského zákona č. 121/2000 Sb., včetně možných trestněprávních důsledků vyplývajících z ustanovení § 152 trestního zákona č. 140/1961 Sb."

V Brně dne ……………

..………………………..
(podpis autora)

PODĚKOVÁNÍ

Děkuji vedoucímu diplomové práce Doc. Ing. Miloslav Filka, CSc., za velmi užitečnou metodickou pomoc a cenné rady při zpracování diplomové práce. A docentovi na VUT a Ústavo telekomunikací.

V Brně dne ……………

………………………..
(podpis autora)

ACKNOWLEDGEMENTS

I am thankful to God, to my self, and to my parents, for showing me the right path. I would like to thank Assoc. Prof. Ing. Miloslav Filka. Ph.D. for his guidance and all the support, I would like to thank my dear family for supporting me in my endeavors, they have been my pillar of support in my difficult times and have encouraged me throughout it, in all circumstances and under all conditions. Last, but not the least, I am grateful to all my teachers at Brno University of Technology and the sweet city of Brno in southern Czech Republic, I also owe my deepest regards to my beloved country Libya, and thanks to all my friends and people that wished me best of luck and success.

In Brno, Czech Republic 2010

…………...…………………………

TABLE OF CONTENTS

TABLE OF CONTENTS

Tables:

Figures:

List of Abbreviations:

DWDM	Dense Wavelength Division Multiplexing
TDMA	Time Division Multiple Access
PON	Passive Optical Network
LTE	Logical topology emulation
FTTH	Fiber-to-the-Home
BPON	Broadband Passive Optical Network
GPON	Gigabit capable Passive Optical Network
EPON	Ethernet Passive Optical Network
ATM	Asynchronous Transfer Mode
SDH	Synchronous Digital Hierarchy
WDM	Wavelength Division Multiplexing
LED	Laser or Light Emitting Diode
LAN	Local Area Network
WAN	Wide Area Network
DSLAM	Digital Subscriber Line Access Multiplexer
VDSL	Very High Speed Digital Subscriber Line
IPTV	Internet Protocol Television
VoD	Video on Demand
VoIP	Voice over Internet Protocol
HDTV	High Definition Television
DSL	Digital Subscriber Line
HFC	Hybrid Fiber-Coaxial
OLTS	Optical Loss Test Set
MLS	Monitoring Line System
VFL	Visual Fault Locator
DUT	Device Under Test
LFD	Live Fiber Detector
OTDR	Optical Time Domain Reflectometer
LLIDs	Logical link identifiers
OLT	Optical Line Terminal
SDM	Space Division Multiplexing
FSAN	Full Service Access Network
ITU	International Telecommunication Union
IEEE	Institute of Electrical and Electronics Engineers
AGC	Automatic gain control
PSTN	Public Switched Telephone Network
ODN	Optical Distribution Network
OSP	outside plant
EDFA	Erbium-Doped Fiber Amplifier
APC	Angle-Polished Connectors
PC, SPC, UPC	Flat-Polished Connectors
ORL	Optical Return Loss

1. INTRODUCTION

PON Passive Optical Network has been considered an ideal solution for access networks since the invention of optical fiber communications because of huge capacity, small size and lightness, and immunity to electromagnetic interference of optical fibers it is shown that the information capacity of an optical fiber can exceed 100 Tb/s under propagation nonlinearity for a typical Dense Wavelength Division Multiplexing (DWDM) system with coherent detection where I shall go through an overview of the optical system concept of fibers. Because optical fibers are widely used in backbone networks, Wide Area Networks (WANs), and Metropolitan Area Networks (MANs), and are also being deployed in Local Area Networks (LANs) with the introduction of optical Ethernet standards, the implementation of the FTTH Fiber-to-the-Home in access networks, which are also called 'the last mile', will complete all-optical-network revolution.

As I previously mentioned in the abstract, I will analyze the present condition of Access network, in depth research of PON Methodology and network design. I shall design a Network project based on FTTH for building a network of 90 private houses controlled by a central control point from 20km distance.

Where I shall address these issues and expedite the introduction of FTTH, and I will reason behind (PON) network-based solution, and so on ATM-PON and Ethernet PON (EPON), which are based on common network architecture, PON, but adopt different transfer technologies to support integrated services and multiple protocols. After providing the (optimal) network solution that fits to fulfill Triple-Play requirements, I will describe how the network interconnects and how it functions and work, later on I shall go into describing the measuring methods and testing for the defined network "after activating and setting the network" and "before activating the network service" where I will also use the OTDR and practically apply a link characterization test. And suggest the monitoring of the design model of the project.

2. OPTICAL TRANSMISSION SYSTEM

The idea of using optical fiber to carry an optical communications signal originated with Alexander Graham Bell, However this idea had to wait some 80 years for better glasses and low-cost electronics for it to become useful in practical situations. Development of fibers and devices for optical communications began in the early 1960s and continues strongly today, but the real change came in the 1980s. During this decade optical communication in public communication networks developed from the status of a curiosity into being the dominant technology. Among the tens of thousands of developments and inventions that have contributed to this progress four stands out as milestones:

- The invention of the LASER (in the late 1950's)
- The development of low loss optical fiber (1970's)
- The invention of the optical fiber amplifier (1980's)
- The invention of the in-fiber Bragg grating (1990's)

The continuing development of semiconductor technology is quite fundamental but of course not specifically optical. The predominant use of optical technology is as very fast “electric wire”. Optical fibers replace electric wire in communications systems and nothing much else changes. Perhaps this is not quite fair. The very speed and quality of optical communications systems has itself predicated the development of a new type of electronic communications itself designed to be run on optical connections. ATM and SDH technologies are good examples of the new type of systems.

It is important to realize that optical communications is not like electronic communications. While it seems that light travels in a fiber much like electricity does in a wire this is very misleading. Light is an electromagnetic wave and optical fiber is a waveguide. Everything to do with transport of the signal even to simple things like coupling two fibers into one is very different from what happens in the electronic world. The two fields (electronics and optics) while closely related employ different principles in different ways.

Many studies look ahead to development of “true” optical networks. In 1998 optically routed nodal wide area networks are imminently feasible and the necessary components to build them are available. However, no such networks have been deployed operationally yet. In 1998 the “happening” area in optical communications is Wavelength Division Multiplexing (WDM). This is the ability to send many (perhaps up to 1000) independent optical channels on a single fiber. The first fully commercial WDM products appeared on the market in 1996. WDM is a major step toward fully optical networking.

2.1 Optical Transmission System Concepts

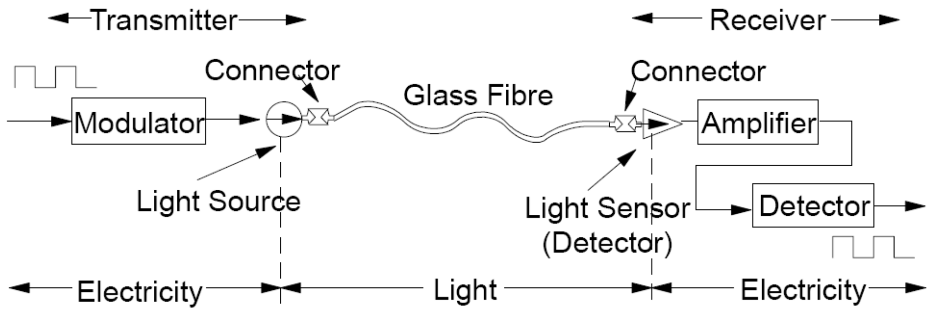


Fig. 1: Optical Transmission - Schematic

The basic components of an optical communication system are shown in this figure.

- A serial bit stream in electrical form is presented to a modulator, which encodes the data appropriately for fiber transmission.
- A light source (laser or Light Emitting Diode - LED) is driven by the modulator and the light focused into the fiber.
- The light travels down the fiber (during which time it may experience dispersion and loss of strength).
- At the receiver end the light is fed to a detector and converted to electrical form.
- The signal is then amplified and fed to another detector, which isolates the
- Individual state changes and their timing. It then decodes the sequence of state changes and reconstructs the original bit stream.
- The timed bit stream so received may then be fed to a using device.

2.2 Optical communication advantages:

Optical communication specifically optical fiber has several important advantages over traditional copper cables. Optical fibers are therefore increasingly being used to replace copper cables not only in communications systems, but in various other applications. The advantages include:

Weight and Size:

Fiber cable is significantly smaller and lighter than electrical cables to do the same job. In the wide area environment a large coaxial cable system can easily involve a cable of several inches in diameter and weighing many pounds per foot. A fiber cable to do the same job could be less than one half an inch in diameter and weigh a few ounces per foot. This means that the cost of laying the cable is dramatically reduced.

Material Cost:

Fiber cable costs significantly less than copper cable for the same transmission capacity.

Information Capacity:

The usual rate for new systems is 2.4 Gbps or even 10 Gbps. This is very high in digital transmission terms. In telephone transmission terms the very best coaxial cable systems give about 2,000 analog voice circuits. A 150 Mbps fiber connection gives just over 2,000 digital telephone (64 Kbps) connections. But the 150 Mbps fiber is at a very early stage in the development of fiber optical systems. The coaxial cable system with which it is being compared is much more costly and has been developed to its fullest extent.

Fiber technology is still in its infancy. Using just a single channel per fiber, there are now trial systems in operation that communicates at speeds of 100 Gbps. By sending many (wavelength division multiplexed) channels on a single fiber, we can increase this capacity a hundred and perhaps a thousand times. Recently researchers at NEC reported a successful experiment where 132 optical channels of 20 Gbps each were carried over 120 km. This is 2.64 terabits per second! This is enough capacity to carry about 30 million uncompressed telephone calls (at 64 Kbps per channel). Thirty million calls are about the maximum number of calls in progress in the world at any particular moment in time. That is to say, we could carry the world's peak telephone traffic over one pair of fibers. Most practical fiber systems don't attempt to do this because it costs less to put multiple fibers in a cable than to use sophisticated multiplexing technology.

No Electrical Connection:

This is an obvious point but nevertheless a very important one. Electrical connections have problems.

. In electrical systems there is always the possibility of “ground loops” causing a serious problem, especially in the LAN or computer channel environment. When you communicate electrically you often have to connect the grounds to one another or at least go to a lot of trouble to avoid making this connection. One little known problem is that there is often a voltage potential difference between “ground” at different locations. The author has observed as much as 3 volts difference in ground potential between adjacent buildings (this was a bad situation). It is normal to observe 1 or 2 volt differences over distances of a kilometer or so. With shielded cable there can be a problem if you earth the shields at both ends of the connection.

. Optical connection is very safe. Electrical connections always have to be protected from high voltages because of the danger to people touching the wire.

. In some tropical regions of the world, lightning poses a severe hazard even to buried telephone cables! Of course, optical fiber is not a subject to lightning problems but it must be remembered that sometimes optical cables carry wires within them for strengthening or to power repeaters. These wires can be a target for lightning.

No Electromagnetic Interference:

Because the connection is not electrical, you can neither pick up nor create electrical interference (the major source of noise). This is one reason that optical communication has so few errors. There are very few sources of things that can distort or interfere with the signal.

In a building this means that fiber cables can be placed almost anywhere electrical cables would have problems, (for example near a lift motor or in a cable duct with heavy power cables). In an industrial plant such as a steel mill, this gives much greater flexibility in cabling than previously available. In the wide area networking WAN environment there is much greater flexibility in route selection. Cables may be located near water or power lines without risk to people or equipment.

Low loss:

The light signal traveling in a fiber optic cable will lose its energy very slowly, usually at less than 1 dB/km

Distances between Regenerators:

As a signal attenuates and picks up noise. The traditional way to regenerate the signal, restoring its power and removing the noise, is to use a either a repeater or an amplifier. (Indeed it is the use of repeaters to remove noise that gives digital transmission its high quality.) In long-line optical transmission cables now in use by the telecom companies, the repeater spacing is typically 40 kilometers. This compares with 12 km for the previous coaxial cable electrical technology. The number of required repeaters and their spacing is a major factor in system cost. Recently some installed systems has spacing of more than 120 kilometers

Much larger bandwidth and open ended capacity:

A fiber optic cable can sustain a much higher data rate than a copper cable. Typical bandwidths are 500 MHz to 100 GHz over 1 km for different kinds of optical fibers.

The maximum theoretical capacity of installed fiber is very great (almost infinite). This means that additional capacity can be had on existing fibers as new technology becomes available. All that must be done is change the Equipment at either end and change or upgrade the regenerators.

Small crosstalk and high security:

Since there is no electrical radiation from the fiber optic cables, they have a high degree of security when compared to copper cables. Although fiber optic cables are not easy to tap, it is possible. Security must be taken into consideration when “dark fibers” from telephone companies or other vendors providing network services are used. As the transmitted light is converted to electrical signals in repeaters, data may be exposed.

However, there are some limitations:

Joining Cables:

The best way of joining cables is to use “fusion splicing”. This is where fiber ends are fused to one another by melting the glass. Making such splices in a way that will ensure minimal loss of signal is a skilled task that requires precision equipment. It is particularly difficult to do outdoors in very low temperatures, such as in the North American or European winter. In the early days of optical fiber systems (the early 1980s) connectors which allowed cables to be plugged and unplugged were unreliable and caused a large amount of signal loss (as much as 3 dB per connector). Of course, the larger the core diameter of the fiber, the easier it is to make a low-loss connector. In the last few years connector systems for fibers with thicker cores (multimode fibers) have improved to the point where the use of a large number of connectors in a LAN system can be very reliable.
Typical connector loss for an “SC” coupler (a popular modern type) using is around 3 dB. It is not this good with single-mode fibers of small core diameter. One of the major system costs is the cost of coupling a fiber to an integrated light source (laser or LED) or detector on a chip. This is done during manufacture and is called “pigtailing”. Although the cost of optical transceivers has decreased rapidly in the last few years, these are still twice the cost (or less) of the same transceivers using electrical connection.

Bending Cables:

As light travels along the fiber, it is reflected from the interface between the core and cladding whenever it strays from the path straight down the center. When the fiber is bent, the light only stays in the fiber because of this reflection. But the reflection only works if the angle of incidence is relatively low. If you bend the fiber too much the light escapes. The amount of allowable bending is specific to particular cables because it depends on the difference in refractive index, between core and cladding. The bigger the difference in refractive index, the tighter is the allowable bend radius. There is a tradeoff here because there are many other reasons that we would like to keep this difference as small as possible.

Slow Standards Development:

This is nobody's fault. Development is happening so quickly, and getting worldwide agreement to a standard is necessarily so slow that standards setting just can't keep up. Things are improving considerably and very quickly, however. Cable sizes and types are converging toward a few choices, although the way they are used is still changing almost daily. There are now firm standards for optical link connections in LAN protocols

Gamma Radiation:

Gamma radiation comes from space and is always present. It can be thought of as a high-energy X-ray. Gamma radiation can cause some types of glass to emit light (causing interference) and also gamma radiation can cause glass to discolor and hence attenuate the signal. In normal situations these effects are minimal. However, fibers are probably not the transmission medium of choice inside a nuclear reactor or on a long-distance space probe. (A glass beaker placed inside a nuclear reactor for even a few hours comes out black in color and quite opaque.)

Electrical Fields:

Very high-voltage electrical fields also affect some glasses in the same way as gamma rays. One proposed route for fiber communication cables is wrapped around high-voltage electrical cables on transmission towers. This actually works quite well where the electrical cables are only of 30 000 volts or below. Above that (most major transmission systems are many times above that), the glass tends to emit light and discolor. Nevertheless, this is a field of current research - to produce a glass that will be unaffected by such fields. It is a reasonable expectation that this will be achieved soon. Some electricity companies are carrying fibers with their high voltage distribution systems by placing the fiber inside the earth wire (typically a 1 inch thick aluminum cable with steel casing). This works well, but long-distance high-voltage distribution systems usually don't have earth wires.

Sharks Eat the Cable! :

Back, early 2008 when I was working on my bachelor’s thesis, usual daily news has reported of an incident at the cost of Alexandria in Egypt, where a new undersea fiber cable was broken on the sea floor. Publicity surrounding the event suggested that the cable was attacked and eaten by sharks. It wasn't just the press, this was a serious claim. It was claimed that there was something in the chemical composition of the cable sheathing that was attractive to sharks! Another explanation was that the cable contained an unbalanced electrical supply conductor. It was theorized that the radiated electromagnetic field caused the sharks to be attracted. Other people have dismissed this claim as a joke and suggest that the cable was badly laid and rubbed against rocks. Nevertheless, the story has passed into the folklore of fiber optical communication and some people genuinely believe that sharks eat optical fiber cable.

2.3 Optical Networking:

A network may be defined as a collection of transmission links and other equipment which provides a means of information interchange within a group of end users. The concept includes a number of key notions:

. The objective of the network is to provide a means of information interchange between end users.

. The network usually contains some shared resources. That is, links and switching nodes are shared between many users.

. Most networks have a common (often centralized) network management system.

. Information may be exchanged between any user and any other user. This concept while common in communication networks is far from being universal. Many networks exist for the purpose of connecting a few thousand devices to only one (or a few) central device(s). For example in a network of cash dispensers there is no communication (and no conceivable need for communication) between the cash dispensers - all communication is to/from a central computer.

. A single user may communicate with multiple other users either simultaneously or serially using only a single connection to the network. Again, this is a very common characteristic of networks but it is by no means universal. Some networks provide fixed connections between pre-determined end users with no possibility for quick changes. The characteristic here that qualifies such a system to be called a network would be the sharing of intermediate switching nodes and/or transmission links within the network.

. The term “network” also usually implies a geographic separation between end users. This is not always true in the sense that communicating end users may be across the room or across the world. There are many types of networks.

. Perhaps the simplest kind provides a fixed communication path (or rather, a collection of fixed paths) between end users.

. A slightly more complex type is where there is only one connection allowed per user but users may make arbitrary connections at will with other end users. The telephone network is a good example here.

. More complex are so-called “packet switching” networks where information is carried between end users in the form of packets (a.k.a. frames or cells). In these networks a single end user is usually capable of communicating with a large number of other end users at the same time.

. Packet switched networks themselves come in many types. In a “connection-oriented” network paths through the network are defined before information is transferred. Information is always transferred along the predefined path. In a “connectionless” network frames of data are routed through the network based on a destination address carried within the data itself. In this case there is no necessary correlation between the path through the network taken by one particular frame of information and the next frame of data sent by the same user to the same destination.

. Another major distinction between networks comes from the method by which switching is performed.

. Most networks (especially wide area ones) contain nodal points where information is switched from link to link. The nodes typically consist of a computer-like device.

. Other networks switch information by placing frames onto a shared medium (such as a bus) to which many end users are connected. Each end user filters the information and pays attention to only information addressed to it. This type is typical of Local Area Networks (LANs). Networks may be further characterized by their geographic extent such as:

- Local Area Network (LAN)
- Metropolitan Area Network (MAN)
- Wide Area Network (WAN)

These names don't only delimit or suggest geographic extent but also denote quite different types of networks which have evolved to meet the requirements of the different environments. Optical networking is just beginning! In some areas (such as the LAN) quite large experimental (but nevertheless operational) networks have been built. In other areas (such as packet networks) researchers are still wrestling with the problems of applying the concepts, where I will discuss the TDM Ethernet technology of the Passive Optical Networking in this thesis.

The simplest type of network is where a single link is shared by many different communications between different end users. This is achieved in commercial operation today in Wavelength Division Multiplexing (WDM) systems. A simple extension of WDM allows for long links where channels are tapped off to service individual end users along the way. Networks using this principle (add/drop multiplexing) are possible today and a number of very large networks are planned.

Wide area switched networks (similar to the telephone network) could be built today as all of the required components are available. Networks of this kind are becoming common the recent years.

However to realize the benefits of optical technology it will be necessary to build fully optical networks. It is self-defeating to convert the signal from optical to electronic form every time it needs to be routed or switched. It seems likely that fully optical networks will not be just optical copies of concepts well explored in the electronic networking world. Over time we can expect new types of networks to evolve which may have some similarities with electronic networks but which will make use of the properties and characteristics of unique optical components.

2.3.1 Optical Fibers:

An optical fiber functions as a kind of waveguide for light. It is usually made of silica glass. The fiber itself has a central core and a surrounding cladding of slightly different glass material. These are protected by a plastic or nylon coating, sometimes called a buffer. The physical size of an optical fiber is determined by the diameter of the core and cladding, expressed in microns (um). One micron is a millionth (1/1,000,000) of a meter. A fiber optic cable having a core diameter of 62.5 um and a cladding of 125 um is designated as 62.5/125 um optical fiber.

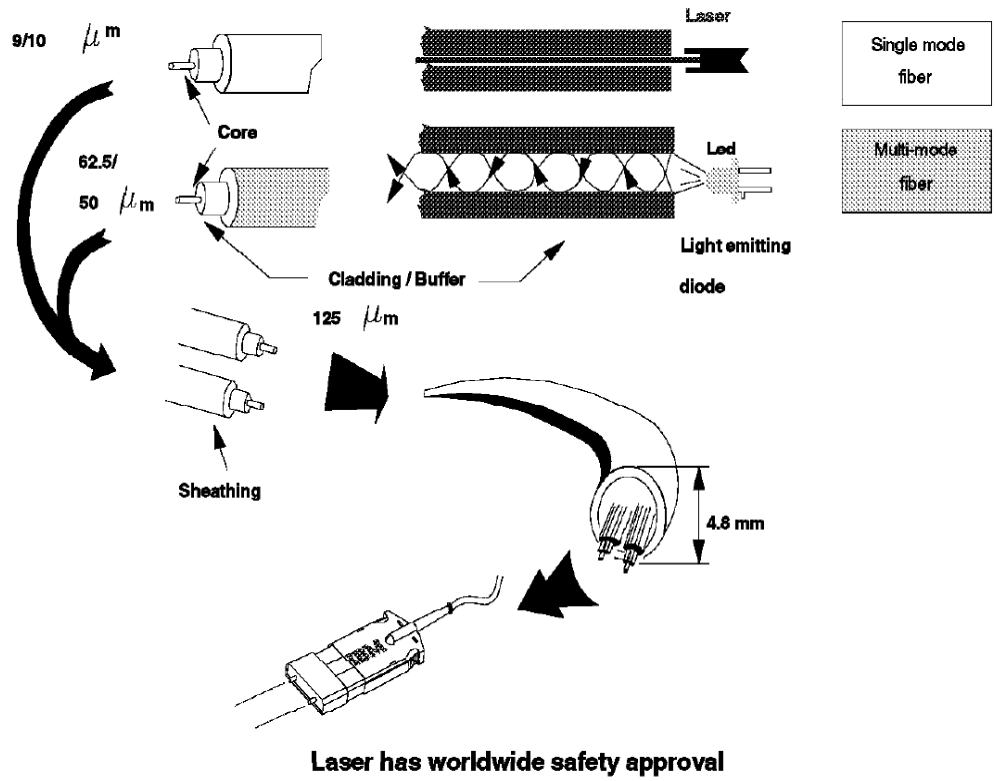


Fig. 2: Fiber Optic Cable

The optical fibers are coated with several kinds of protective layers. The material and the thickness of these layers depend on the usage of the cable. An optical fiber cable normally contains a pair of fibers, or several pairs of fibers. The former is called a jumper cable and the latter a trunk cable. The outer diameter of a jumper cable is typically 4.8 mm, or 0.19 inch, while a trunk cable with 72 pairs of fibers measures about 12.5 mm, or half an inch in diameter. Optical fiber cables are manufactured for different environments and they should always be used within their design criteria.

Propagation of Light in an Optical Fiber:

The light used for transmitting signals in fiber optic communication systems could be visible light or invisible light such as infrared or ultraviolet. However, only certain frequencies are suitable for use in optical fibers, as the attenuation of the signal varies with the wavelength. The wavelengths of 850 nanometers (nm) and 1300 nm have the lowest attenuation. The power of light used to transmit a signal in an optical fiber is relatively small 10-50 milliwatts. Still, we should follow all the safety precautions when we work with devices transmitting light. As the light used is invisible, you may not know if the transmission is on. The light used may cause harm to human tissues and even blindness if aimed at an eye.

Bandwidth:

Light travels in a vacuum at a speed of 300,000,000 meters per second. In glass, the speed is slower, 200,000,000 meters per second. However, the data transmission capacity is determined by the bandwidth used. The higher the bandwidth, the greater the amount of data carried through an optical fiber. Normally the bandwidths for optical fibers are given in MHz-km. A bandwidth of 500 MHz-km denotes that a 500 MHz signal can be transmitted over a 1 km distance. This is the typical bandwidth for multimode fibers. Bandwidths for single-mode fibers are in the GHz range, typically 100 GHz over a 1 km distance. Using lower frequencies we can send light signals, or pulses, over longer distances. The distance is limited due to dispersion, or scattering, of the signal so that the pulses cannot be separated from each others at the receiving end.

Transmission Modes:

There are two transmission modes we can use to send light signals through an optical fiber: single-mode or multimode. The optical fibers used are called single-mode or multimode fibers. These optical fibers have different physical dimensions and light transmission characteristics. The term mode is related to the number and variety of wavelengths that may be propagated through the core of an optical fiber. In other words, it describes the propagation path of a light ray in the core of an optical fiber. When the core has a comparatively large diameter, light rays enter the optical fiber at different angles compared to the central axis of the core. These light rays will reflect from the interface of the core and cladding and their paths in the core follow a zig-zag pattern. Light rays also enter the core parallel to the central axis of the core. These light rays will follow a straight path through the core. We have now light rays in different modes traveling in an optical fiber. This is called multimode transmission. Small cores allow only the light rays almost parallel to the central axis of the core to enter an optical fiber. So we have fewer modes traveling in the fiber. This is called single-mode transmission, where only one frequency of light, or one mode, is propagated.

Single-Mode Fiber:

A single-mode fiber which is the one used in the FTTH Network using single mode for the EPON Network which is farther on described in this thesis, it usually has a core diameter of 8 to 10 microns and a cladding diameter of 125 microns. The light source used for single-mode optical fibers is a laser (Light Amplification by Stimulated Emission of Radiation). A laser commonly used in communication systems is generated by a semiconductor laser diode (LD). Light generated by a laser diode is very coherent. The maximum distance for a single-mode optical fiber link is 20 km.

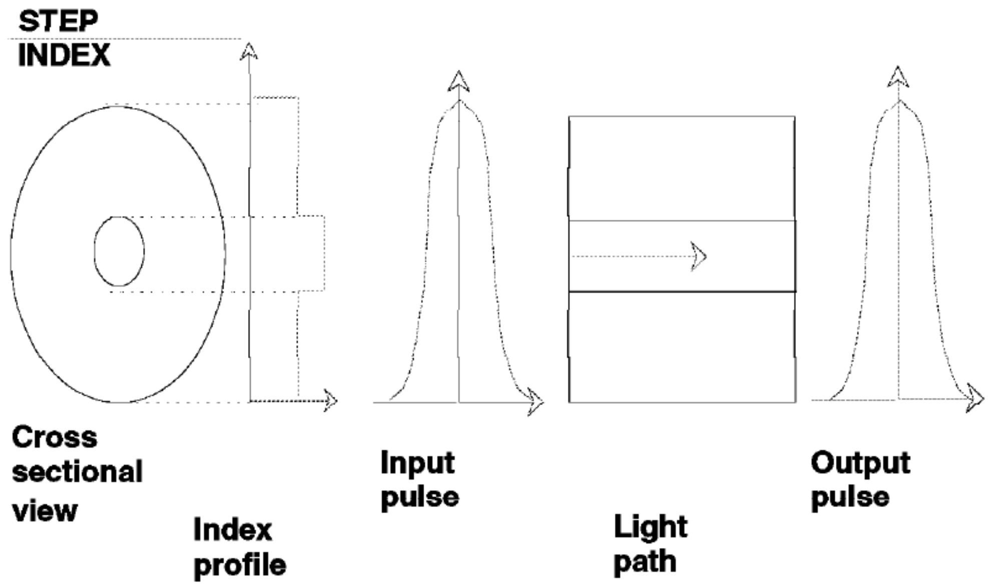


Fig. 3: Single-Mode Fiber Profile

Multimode Fiber:

Multimode fibers carry several modes concurrently. The 62.5/125 or 50/125 um, A light emitting diode (LED) is usually the light source for multimode fibers. The maximum distance for a multimode optical fiber link is 3 km using a 62.5/125 um optical fiber. Even though the distance achieved by multimode fibers is relatively short compared to that for single-mode fibers, multimode fibers have several advantages and therefore were selected for some campus-wide communications architecture. For several years to come, the multimode fiber is the right choice, although further in the future single-mode fibers will be used more frequently.

Refractive Index Profile:

Beside transmission mode, another important term is refractive index profile. The refractive index profile describes the relationship between the index of the core and the cladding. There are two commonly used types of refractive index profiles, step and graded:

Step Index:

In a step-index fiber, the core has a uniform index, but there is an abrupt change in the refractive index between the core and the cladding.

Graded Index:

In a graded-index fiber the core has a gradually decreasing refractive index from the center of the core outward to the cladding boundary. This causes the light rays propagated in a graded-index optical fiber to travel at almost the same speed even though they have different geometrical paths. The graded-index fibers are made by doping the glass material used to manufacture the fibers.

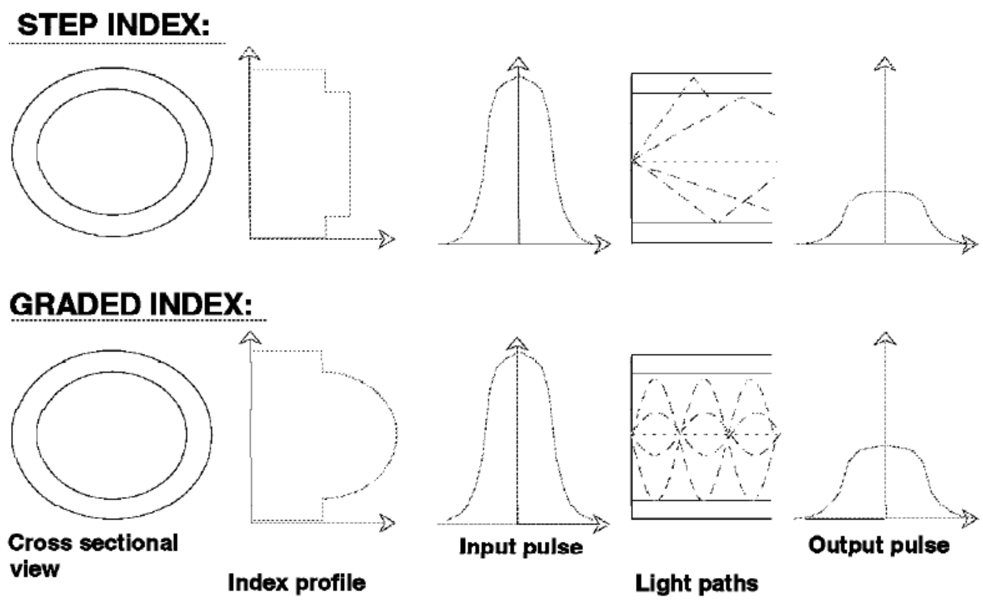


Fig. 4: Step and graded indices of multimode fiber

Dispersion:

Light rays traveling parallel to the central axis of the core, called lower modes, will be faster than the rays reflecting from the interface of the core and the cladding. These reflected rays are called higher modes. If we have both lower and higher mode rays in a multimode optical fiber, the rays will arrive at slightly different times at the receiver. This is called mode delay, or modal dispersion. Modal dispersion may prevent differentiation of the incoming pulses in a receiver. Modal dispersion could significantly limit the useful distance of a multimode optical fiber. Using the graded index optical fibers for multimode transmission decreases the modal dispersion, as both the higher and lower modes proceed at the same speed.

Dispersion is also caused by different wavelengths in the light signal transmitted into an optical fiber. The different wavelengths travel with different speed and so they can cause merging of the pulses. This is a common problem in single-mode fibers. It is best avoided using a light source of coherent light. The impurities in the material used for optical fibers can also cause dispersion, as lower modes may convert to higher modes.

Light Sources and Detectors:

To make use of optical fibers, we have to convert the electrical pulses that electrical devices use to light pulses, and vice versa. This conversion is done using transmitters and receivers. Since we usually have a pair of fibers for a fiber optic link, each end of the link needs a transmitter and a receiver. A brief overview of theses devices:

Transmitters:

A transmitter emits, or sends, light into an optical fiber. The light rays should all be of the same wavelength. The emitted light works as a carrier. For data transmission, we have to add the data in the carrier. We can do this by modulating the emitted light. Data is transmitted through an optical fiber serially. So if data appears as parallel signals to our transmitter, it must first be converted to serial signals. The devices used in transmitters can be LEDs or laser diodes. LEDs generate light that has a narrow range of wavelengths around the central wavelength. It is used for multimode fibers. An LED is a small and quite inexpensive component. Laser diodes are rather complicated devices and therefore usually more expensive than LEDs. Their advantages are the intensity and accuracy of the light. The light is more coherent than the light from a LED. Also, a light of high power can be generated. Laser devices are used with single-mode fibers.

Receivers:

The light traveling through an optical fiber must be detected to convert it back to an electrical signal. Detection is done by light-sensitive devices called photodiodes. After being detected, the signal is amplified and usually digitized.

3. OPTICAL ACCESS NETWORKS

3.1 Fiber-to-the-Home:

The existing “broadband” solutions are unable to provide enough bandwidth for emerging services such as IPTV, video-on-demand (VoD), interactive gaming, or two-way video conferencing. To alleviate bandwidth bottlenecks, optical fibers and thus optical nodes are penetrating deeper into the first mile. This trend is present in both DSL and cable TV worlds. In DSL-based access networks, many remote DSLAMs deployed in the field use fiber-optic links to the central offices. In cable TV networks, optical curbside nodes are deployed close to the subscribers.

The next wave of access network deployments promises to bring fiber all the way to the office or apartment buildings or individual homes. Unlike previous architectures, where fiber is used as a feeder to shorten the lengths of copper and coaxial networks, these new deployments use optical fiber throughout the access network. New optical fiber network architectures are emerging that are capable of supporting *gigabit per second* (Gbps) speeds, at costs comparable to those of DSL and HFC networks.

Before going in to deeper study about the FTTH concept let’s have brief overview about the current statue of FTTH worldwide.

FTTH status:

The total number of homes worldwide that will be reached by next-generation fiber-optic networks will soar from about 11 million in 2006 to about 86 million in 2011, according to study by Heavy Reading, the market research division of Light Reading Inc. USA Courtesy of EE Times.

The FTTH Worldwide Market and Technology Forecast, 2006-2011 said Fiber-to-the-Home expansion will be the most aggressive in Asia over the next five years. There, the number of connected households will grow to 59 million by the end of 2011. The rest of the subscriber base at 2011 will be split equally between the Americas and the Europe/Middle East/Africa region.

In addition, the study said HDTV (Triple-Play) and online next-generation video gaming will contribute to the emergence of a new broadband standard of 100 Mbit/s symmetric over the next 12 to 24 months. Although VDSL2 networks can hardly in principle provide such capacity, which is at the limit of copper's capabilities and will encourage telecom companies to begin transitioning to Fiber-to-the-Home.

"The transition from copper to fiber access networks is now well underway and will result in the replacement of most copper networks over the next two decades," notes Graham Finnie, Senior Analyst with Heavy Reading and author of the report. "Although DSL offers a temporary fix to the ever-growing consumer demand for bandwidth, it will run out of options in the next three to five years, meaning that telecoms must begin the transition to fiber soon."

3.2 Next-generation subscriber access network:

Optical fiber is capable of delivering bandwidth-intensive, integrated voice, data, and video services at distances beyond 20 km in the subscriber access network. A straightforward way to deploy optical fiber in the local access network is to use a *point-to-point* (P2P) topology, with dedicated fiber runs from the CO to each end-user subscriber.

While this is a simple architecture, in most cases it is cost prohibitive because it requires significant outside fiber plant deployment as well as connector termination space in the local exchange. Considering N subscribers at an average distance L km from the CO, a P2P design requires $2N$ transceivers and $N \times L$ total fiber length (assuming that a single fiber is used for bidirectional transmission).

To reduce fiber deployment, it is possible to deploy a remote switch (concentrator) close to the neighborhood. This will reduce the fiber consumption to only L km (assuming negligible distance between the switch and customers), but will actually increase the number of transceivers to $2N + 2$, as there is one more link added to the network.

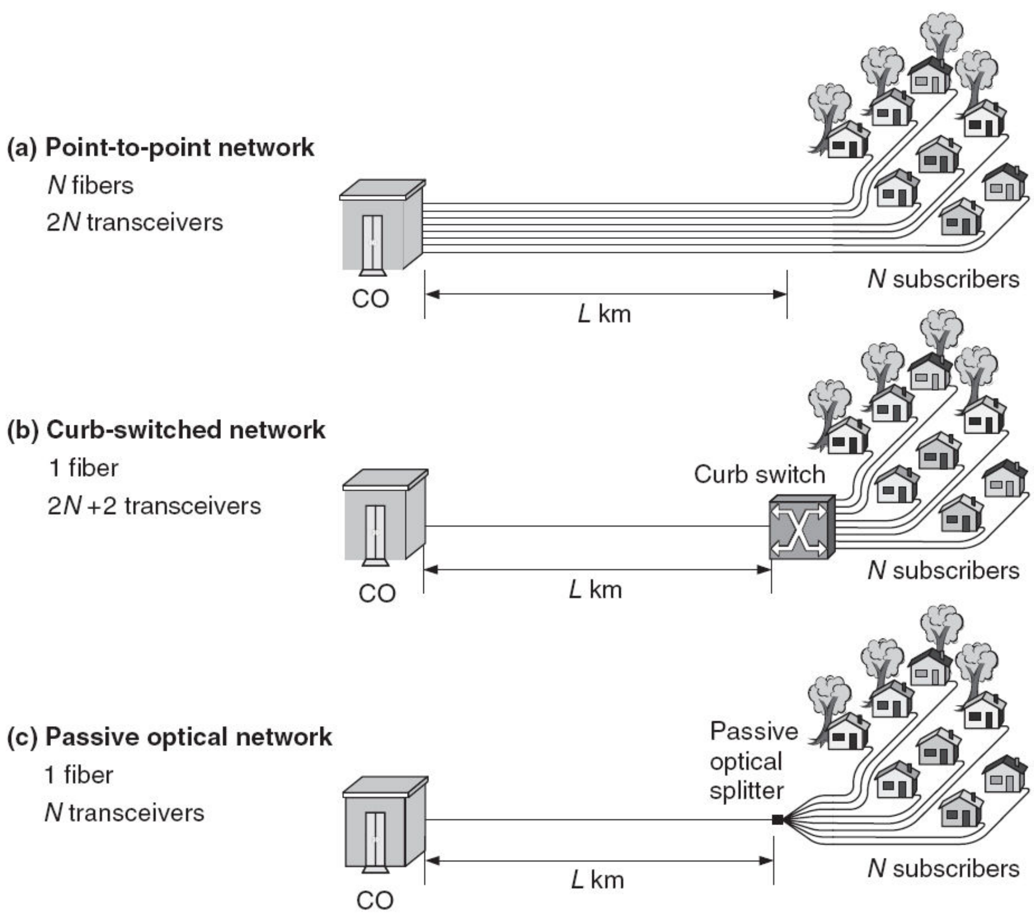


Fig. 5: Fiber-to-the-home (FTTH) deployment scenarios

In addition, curb-switched network AON (Active Optical Network) architecture requires electric power as well as backup power at the curb switch. Currently, one of the most significant operational expenditures for *local exchange carriers* (LECs) is that of providing and maintaining electric power in the local loop.

Therefore, it is logical to replace the hardened (environmentally protected) active curbside switch with an inexpensive passive optical splitter. A *passive optical network* (PON) is a technology viewed by many as an attractive solution to the first mile problem. A PON minimizes the number of optical transceivers, CO terminations, and fiber deployment. A PON is a *point-to-multipoint* (P2MP) optical network with no active elements in the signals path from source to destination. The only interior elements used in PON are passive optical components, such as optical fiber, splices, and splitters. An access network based on a single-mode fiber PON only requires $N + 1$ transceivers and L km of fiber.

3.3 PON is the best candidate:

PON technology is getting more and more attention by the telecommunication industry as the "first mile" solution. Advantages of using PON for local access networks are numerous:

- PON allows for longer distances between central offices and customer premises. A PON-based local loop can operate at distances of up to 20 km, which considerably exceeds the maximum coverage afforded by DSL.

- PON minimizes fiber deployment in both the local exchange and local loop. Only one strand of fiber is needed in the trunk, and only one port per PON is required in the central office. This allows for a very dense CO equipment and low power consumption.

- PON provides higher bandwidth due to deeper fiber penetration. While *fiber-to-the-PC* (FTTPC) , *fiber-to-the-curb* (FTTC) may be the most economical deployment today, *fiber-to-the-Building (*FTTB) which is also a good solutions, But remains *fiber-to-the-home* (FTTH) is the ultimate goal and best solution for real Quality of Service such as Triple-Play.

- As a point-to-multipoint network, PON allows for downstream video broadcasting. Multiple wavelength overlay channels can be added to PON without any modifications to the terminating electronics.

- PON eliminates the necessity of installing multiplexers and demultiplexers in the splitting locations, thus relieving network operators from the gruesome task of maintaining them and providing power to them. Instead of active devices in these locations, PON has passive components that can be buried in the ground at the time of deployment.

- PON allows easy upgrades to higher bit rates or additional wavelengths. Passive splitters and combiners provide complete path transparency.

3.4 PON Topologies:

Logically, the first mile is a *point-to-multipoint* (P2MP) network, with a CO servicing multiple subscribers. All transmissions in a PON are performed between an *optical line terminal* (OLT) and *optical network units* (ONU) or also we can say Optical Network Terminal (ONT). The OLT resides in the CO and connects the optical access network to the metropolitan-area network or *wide-area network* (WAN), also known as the backbone or long-haul network. The ONT is located either at the end-user location (FTTH and FTTB) or at the curb, resulting in *fiber-to-the-curb* architecture.

There are several multipoint topologies suitable for the access network, including tree, ring, and bus. Using 1 × 2 optical tap couplers and 1 × *N* optical splitters, PONs can be flexibly deployed in any of these topologies. In some critical deployments, the access network may require fast protection switching. This is achieved by providing several alternative, diversely routed paths between the OLT and ONTs. Path redundancy may be added to an entire PON's topology, or to only a part of the PON, say, the trunk of the tree or the branches of the tree.

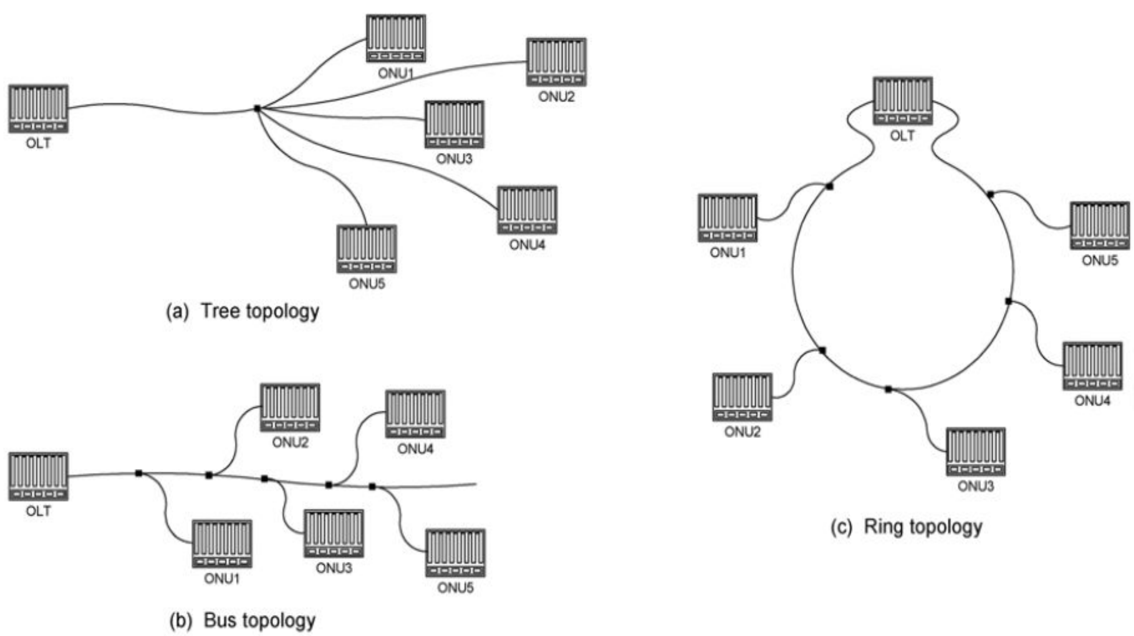


Fig. 6: PON topologies

3.5 Spectrum Sharing versus Time Sharing:

In the downstream direction (from the OLT to ONTs), a PON is a point-to-multipoint network. The OLT typically has the entire downstream bandwidth available to it at all times. In the upstream direction, a PON is a multipoint-to-point network, multiple ONTs transmit all toward one OLT. The directional properties of a passive splitter/combiner are such that an ONT transmission cannot be detected by other ONTs.

However, data streams from different ONTs transmitted simultaneously still may collide. Thus, in the upstream direction (from user to network), a PON should employ some channel separation mechanism to avoid data collisions and fairly share the trunk fiber channel capacity and resources.

3.5.1 WDMA PON:

One possible way of separating the ONTs' upstream channels is to use a *wavelength division multiple access* (WDMA), in which each ONU/ONT operates on a different wavelength. While, from a theoretical perspective, it is a simple solution, it remains cost-prohibitive for an access network.

A WDMA solution would require either a tunable receiver or a receiver array at the OLT to receive multiple channels. An even more serious problem for network operators would be wavelength specific ONT inventory. Instead of having just one type of ONT, there would be multiple types of ONTs differing in their laser wavelengths. Each ONT will have to use a laser with narrow and controlled spectral width, and thus will become more expensive. It would also be more problematic for an unqualified user to replace a defective ONT because a unit with the wrong wavelength may interfere with some other ONT in the PON. Using tunable lasers in ONTs may solve the inventory problem, but is too expensive at the current state of technology. For these reasons, a WDMA PON network is not an attractive solution in today's environment.

Several alternative solutions based on WDMA have been proposed, namely, *wavelength routed PON* (WRPON). A WRPON uses an *arrayed waveguide grating* (AWG) instead of wavelength-independent optical splitter/combiner. In one variation, ONTs use external modulators to modulate the signal received from the OLT and send it back upstream. This solution, however, is not cheap either; it requires additional amplifiers at or close to the ONTs to compensate for signal attenuation after the round-trip propagation, and it requires more expensive optics to limit the reflections, since both downstream and upstream channels use the same wavelength. Also, to allow independent (non-arbitrated) transmission from each of N ONTs, the OLT must have N receivers—one for each ONT.

In another variation, ONTs contains inexpensive *light-emitting diodes* (LEDs) whose wide spectral band is sliced by the AWG on the upstream path. This approach still requires multiple receivers at the OLT. If, however, a single tunable receiver is used at the OLT, then a data stream from only one ONT can be received at a time, which in effect makes it a *time division multiple access* (TDMA) PON.

3.5.2 TDMA PON and its advantage:

In a TDMA PON or shortly TDM-PON simultaneous transmissions from several ONTs will collide when they reach the combiner. To avoid data collisions, each ONT must transmit in its own transmission window (timeslot). One of the major advantages of a TDM PON is that all ONTs can operate on the same wavelength and be absolutely identical component wise. The OLT (CO) will also need a single receiver. A transceiver in an ONT must operate at the full line rate, even though the bandwidth available to the ONT may be lower. However, this property also allows the TDMA PON to efficiently change the bandwidth allocated to each ONT by changing the assigned time slot size, or even to employ statistical multiplexing to fully utilize the PON channel capacity.

In the subscriber access network, most of the traffic flows downstream (from network to users) and upstream (from users to the network), but not peer-to-peer (from a user to a user). Thus, it seems reasonable to separate the downstream and upstream channels. A simple channel separation can be based on space division multiplexing (SDM), in which separate PONs are provided for downstream and upstream transmissions. To save optical fiber and to reduce the cost of repair and maintenance, a single fiber may be used for bidirectional transmission. In this case, two wavelengths are used, 1 for the upstream transmission and 2 for the downstream transmission. The channel capacity on each wavelength can be flexibly divided between the ONTs by using time-sharing techniques.

Time-sharing appears to be the preferred method today for optical channel sharing in an access network, as it allows for a single upstream wavelength and a single transceiver in the OLT, resulting in a cost-effective solution.

3.5.2.1 Types of TDM PONs Technology:

Type	**APON (ATM-Based PON)**	**BPON (Broadband PON)**	**GPON (Gigabit-Capable PON)**		**EPON (Ethernet PON)**
Protocol	ATM	ATM	ATM	ATM and GEM[1]	Ethernet + FEC[2]
Standard	ITU-T G.983.1 including Amendment 1)	ITU-T G.983.3	ITU-T G.983.1 Amendment 2)	ITU-T G.984	IEEE 802.3ah
Architecture	Symmetric: FTTCab/B/C/H Asymmetric: FTTCab/B/C	Symmetric: FTTCab/B/C/H Asymmetric: FTTCab/B/C	Symmetric: FTTCab/B/C/H Asymmetric: FTTCab/B/C	Symmetric: FTTCab/C/H/B for Multidwelling Units MDU); FTTB for Business Asymmetric: FTTCab/C/H/B-MDU	1000BASE-PX10 1000BASE-PX20
Services	Telecommunication Services for Small Businesses, Teleconsulting, etc.: Symmetric FTTCab/C/H/B Digital Broadcast Services, Video-on-Demand, Internet, Distant Learning, Telemedecine, etc.: Asymmetric FTTCab/C/H/B Voice: FTTCab/C/H/B	Voice/Data/Video/ Additional Digital Services ADS)/Future Services	Voice/Data	Content Broadcast, E-mailing, File Exchange, Distant Learning, Telemedecine, Online Gaming, etc.: Symmetric FTTCab/C/H/B- MDU/Business Digital Broadcast Services, Video-on-Demand File Download, etc.: Asymmetric FTTCab/C/H/B- MDU Voice: FTTCab/C/H/B- MDU/Business Private Line: FTTB-Business xDSL: FTTCab/C	**Triple-play**
Fiber Type	ITU-T G.652 (Single or Dual Fiber)	ITU-T G.652 (Single Fiber)	ITU-T G.652 Single or Dual Fiber)	ITU-T G.652 (Single or Dual Fiber)	1000BASE-PX10: Single Fiber 1000BASE-PX20: Dual Fiber No fiber type specified)
Maximum Physical Distance (ONT-OLT)	20 km	20 km	20 km	10 km (Fabry-Perot Laser Diodes for 1244.16 Mb/s and higher) 20 km > 20 km (with different fiber types—for further study)	1000BASE-PX10: 10 km 1000BASE-PX20: 20 km
Split Ratio	Up to 32	Up to 32	Up to 32	Up to 64 (realistic) Up to 128 (considered)	1:16 Up to 32
Wavelength Band	Single fiber: Downstream: 1480-1580 nm; Upstream: 1260-1360 nm Dual fiber: 1260-1360 nm	Upstream: 1260-1360 nm (ATM-PON) Upstream and/or Downstream: Intermediate Wavelength Band: 1360-1480 nm (for future use) 1.5 μm Wavelength Band: Basic Band: 1480-1500 nm (ATM-PON Downstream) Enhancement Band: (1) 1539-1565 nm (ADS) (2) 1550-1560 nm (Video Distribution Service) Future L Band: Wavelengths not yet defined (for future use)	Single fiber: Downstream: 1480-1580 nm; Upstream: 1260-1360 nm Dual fiber: 1260-1360 nm	Single Fiber: Downstream: 1480-1500 Upstream: 1260-1360 nm Dual Fiber: Downstream/Upstream: 1260-1360 nm	1000BASE-PX10: Downstream: 1490 nm + Rx; Upstream: 1300 nm (low-cost FP optics and PIN Rx) 1000BASE-PX20: Downstream: 1490 nm + APD Rx; Upstream: 1300 nm (DFB optics + PIN Rx)
Data Rate(s)	Symmetric: 155.52/622.08 Mb/s Asymmetric: Downstream: 622.08 Mb/ Upstream: 155.52 Mb/s	Symmetric: 155.52/622.08 Mb/s Asymmetric: Downstream: 622.08 Mb/s Upstream: 155.52 Mb/s	Symmetric: 155.52/622.08 Mb/s Asymmetric: Downstream: 622.08/1244.16 Mb/s Upstream: 155.52/622.08 Mb/s	Symmetric: 1244.16/2488.32 Mb/s Asymmetric: Downstream: 1244.16/2488.32 Mb/s Upstream: 155.52/622.08/1244.16 Mb/s	Symmetric: 1.25 Gb/s

Tab. 1: PON Types

4. ETHERNET PON

4.1 EPON Standardization:

IEEE formed a study group, which had its first meeting in January 2001. EFM quickly became one of the most participated in study groups. The EFM study group focused on bringing Ethernet to the local subscriber loop, considering the requirements of both residential and business access networks. While at first glance this may appear to be a simple task, in reality the requirements of local exchange carriers are vastly different from those of private enterprise networks for which Ethernet has been designed. To "evolve" Ethernet for local subscriber networks, the EFM study group concentrated on four primary standards areas:

1. Ethernet over copper

2. Ethernet over *point-to-point* (P2P) fiber

3. Ethernet over *point-to-multipoint* (P2MP) fiber (also known as EPON)

4. *Operation, administration, and maintenance* (OAM)

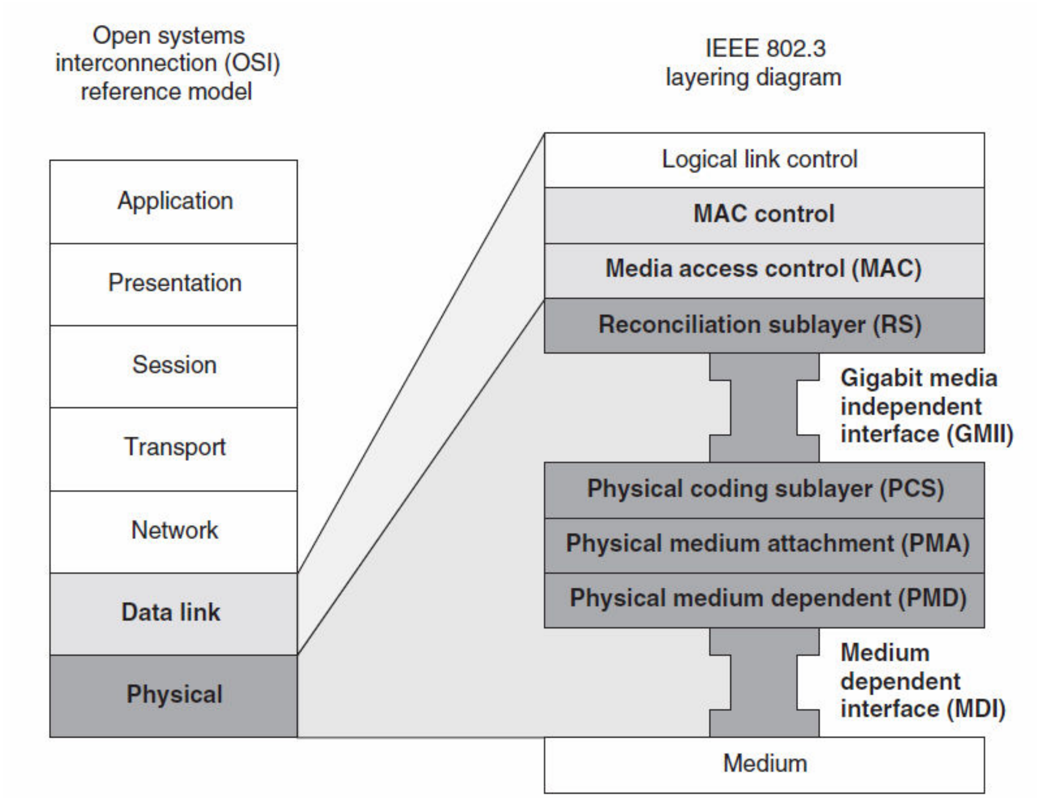
The EFM's emphasis on both copper and fiber specifications, optimized for the first mile and glued together by a common OAM system, was a particularly strong vision, as it allowed a local network operator a choice of Ethernet flavors using a common hardware and management platform. In each of these areas, new physical layer specifications were discussed and adopted to meet the requirements of service providers, while preserving the integrity of Ethernet.

To progress with the project, the study group had to demonstrate that the envisioned architectures satisfy the following five criteria:

- Broad market potential
- Compatibility with 802 architecture, including bridging and *management information bases* (MIBs)
- Distinct identity, i.e., sufficient difference from other IEEE 802 standards
- Technical feasibility
- Economic feasibility

A convincing demonstration that P2MP architecture can meet the above benchmarks has been a major milestone on EPON's road to success. The presentation outlining how and why EPONs should be part of the IEEE 802.3 standard received overwhelming support from study group participants, including representatives from the following companies: Agere, Alloptic, Atrica, Broadcom, Broadlight, Calix, Cisco, Corning, Dominet, E2O, Fiberhood, Fiberintheloop, Infineon, Intel, Lucent, Luminous, Minerva, Nokia, Nortel, OnePath, Optical Solutions, Passave, Pirelli, Quantum Bridge, Redback, Salira, Scientific Atlanta, Vitesse, and Zonu [EFM01]. As a result, the Project Authorization Request (PAR), which included P2MP architecture, was approved by the IEEE-SA Standards Board in September 2001, and consequently, EFM received a status of a task force, with a designation of 802.3ah.

Overview of Access Network Architectures



Relationship of IEEE 802.3 layering model to Open Systems Interconnection reference model

4.1.1 Scope of work:

The scope of IEEE 802.3 work is confined to two lower layers of the *Open Systems Interconnection* (OSI) reference model [OSI94]: physical layer and data link layer. Each of these layers is further divided into sub layers and interfaces. The figure above shows the sublayers and interfaces defined for Ethernet devices operating at 1 Gbps data rates. IEEE 802.3 uses the following subdivision of the physical layer (from lower sublayer to higher):

Medium dependent interface (MDI) specifies the physical medium signals and the mechanical and electrical interface between the transmission medium and physical layer devices.

Physical medium dependent (PMD) sublayer is responsible for interfacing to the transmission medium. The PMD is located just above the MDI.

Physical medium attachment (PMA) sublayer contains the functions for transmission, reception, clock recovery, and phase alignment.

Physical coding sublayer (PCS) contains the functions to encode data bits into code-groups that can be transmitted over the physical medium.

Gigabit media independent interface (GMII) specifies an interface between a gigabit capable MAC and a gigabit physical layer (PHY). The goal of this interface is to allow multiple Data Terminal Equipment (DTE) devices to be intermixed with a variety of gigabit speed physical layer implementations. *Reconciliation sublayer* (RS) provides mapping for the GMII signals to the media access control service definitions.

The data link layer consists of the following sublayers (from lower to higher):

Media access control sublayer defines a medium independent function responsible for transferring data to and from the pysical layer. In general, the MAC sublayer defines data encapsulation (such as framing, addressing, and error detection) and medium access (such as collision detection, and deferral process). *MAC control sublayer* is an optional sublayer performing real-time control and manipulation of MAC sublayer operation. The MAC control structure and specification allow new functions to be added to the standard in the future.

Logical link control (LLC) sublayer defines a medium access independent portion of the data link layer. This sublayer is outside he scope of IEEE 802.3. Correspondingly, MAC and the optional MAC control sublayer are specified in such a way that they are unaware whether LLC is located above them, or any other client, such as a bridge or a repeater.

The point-to-multipoint sub-task force concentrated on the lower layers of an EPON network. The work of defining the EPON architecture was divided into physical medium dependent sublayer specification, P2MP protocol specification, and extensions for reconciliation, physical coding, and physical medium attachment sublayers.

4.1.2 Physical medium dependent sublayer:

The EPON PMD sublayer parameters are specified in clause 60 of the IEEE 802.3ah standard. The PMD specification is based on the following set of objectives:

PMD type	1000BASE-PX10-U	1000BASE-PX10-D	1000BASE-PX20-U	1000BASE-PX20-D
Fiber type	SMF	SMF	SMF	SMF
Number of fibers	1	1	1	1
Nominal wavelength, nm	1310	1490	1310	1490
Transmit direction	Upstream (ONU to OLT)	Downstream (OLT to ONU)	Upstream (ONU to OLT)	Downstream (OLT to ONU)
Distance, km	10	10	20	20
Min. channel insertion loss, dB	5.0	5.0	10.0	10.0
Max. channel insertion loss, dB	20.0	19.5	24.0	23.5

Tab. 2: EPON PMD Types

1. Support for point-to-multipoint media using optical fiber

2. 1000 Mbps up to 10 km on one single-mode fiber supporting a fiber split ratio of 1: 16

3. 1000 Mbps up to 20 km on one single-mode fiber supporting a fiber split ratio of 1:16

To meet the above objectives, four PMD types were defined in clause 60. These types are summarized and compared in Table 2. The task of selecting PMD timing parameters, such as laser-on and laser-off times and gain control time, has generated debates lasting almost a year. Three competing parties formed in the task force, with none being able to gather 75 percent of the votes required to adopt a technical motion.

The first camp promoted a strict timing similar to BPON and GPON specs (laser-on and laser-off times of 16 ns, gain adjustment time equals or smaller than 50 ns). This group argued that increasing the compatibility with BPON and GPON specifications would result in lower component costs due to economies of scale.

The second party advertised for relaxed parameters (laser-on and laser-off times of 800 ns, gain adjustment time equals or greater than 400 ns), claiming that this would lead to higher component yields and therefore would lower the costs.

The third group lobbied for negotiable parameters, arguing that devices should be able to exploit faster PMD timing to achieve higher efficiency. In the end, after a prolonged battle, the task force settled on the following parameters: laser-on time = 512 ns, laser-off time = 512 ns, gain adjustment time greater or equals 400 ns (negotiable). The winning arguments were that the ONUs, being the mass-deployed device, must be as simple and inexpensive as possible. For this, the PMD components should have high yield and should not mandate implementation of digital interfaces which otherwise would be mandatory if ONUs were to negotiate laser on and laser-off times. The OLT device can be more expensive, as only a single device is used per

EPON. Therefore, the OLT is allowed to negotiate and adjust its receiver parameters such as AGC time.

4.1.3 Point-to-multipoint protocol

As mentioned previously that, in the upstream direction, a PON should employ some channel arbitration mechanism to share the channel capacity without data collisions.

Almost immediately upon its formation, the study group began technical discussions aimed at selecting a set of baseline technical proposals, including the EPON channel arbitration mechanism. Selecting the baseline proposals was not a consonant process as one might have hoped for. Virtually every interested equipment vendor had an idea of how to “do it right.” The reviewed proposals ranged from implementing EPON entirely in the physical layer and using PHY-based messaging, using existing IEEE 802.3 flow control mechanisms (PAUSE MAC control frames), schemes based on DOCSIS, or a unified PHY (similar to what later became GPON) to carry both ATM cells and Ethernet frames.

The study group (and later the task force) reviewed more than 40 presentations related to EPON and had countless conference calls. By November 2001, the opinions began to converge on defining a MAC control-based protocol that would allow the OLT to assign to ONUs the transmission windows. This protocol is currently known as the *multipoint control protocol* (MPCP) and is defined in clause 64 of the IEEE 802.3ah standard.

MPCP uses MAC control messages (similar to the Ethernet PAUSE message) to coordinate multipoint-to-point upstream traffic. There are two modes of operation of MPCP: *autodiscovery* (initialization) and *normal* operation. Normal mode is used to assign transmission opportunities to all discovered ONUs. A detailed description of this mode is given in Sec. 5.3.1. The autodiscovery mode is used to detect newly connected ONUs and learn their parameters such as MAC addresses and round-trip delays.

4.1.4 Extensions of the existing clauses

Several existing clauses in IEEE 802.3 require certain extensions in order to be used with P2MP architecture. All these extensions are grouped in a new clause 65.

Reconciliation sublayer (RS)

The IEEE 802 architecture makes a general assumption that all devices connected to the same media can communicate to one another directly. Relying on this assumption, bridges never forward a frame back to its ingress port. This bridge behavior has led to an interesting problem: A bridge placed in the OLT will see one PON port and will never forward upstream frames back to ONUs. However, due to the directional properties of the splitter, the ONUs are unable to directly communicate with one another. Therefore, it appears that the EPON-based network will have difficulties providing full connectivity among the attached devices. This raises a question of EPON compliance with IEEE 802 architecture, particularly with P802.1D bridging.

To resolve this issue and to ensure seamless integration with other Ethernet networks, devices attached to the EPON medium will use an extended reconciliation sublayer, which will emulate the point-to-point medium. This topology emulation process relies on tagging of Ethernet frames with tags unique for each ONU. These tags are called *logical link IDs* and are placed in the preamble before each frame. Subclause 65.1 of the IEEE 802.3ah standard defines the new format of frame preamble and filtering rules necessary to achieve point-to-point emulation.

Physical coding sublayer (PCS)

To avoid spontaneous emission noise from near ONUs obscuring the signal from a distant ONU, the ONUs' lasers should be turned off between their transmissions. To control the laser, the physical coding sublayer is extended (see subclause 65.2 of IEEE 802.3ah) to detect the data being transmitted by higher layers and to turn the laser on and off at the correct times.

An additional PCS extension specifies an optional *forward error correction* (FEC) mechanism, which may increase the optical link budget or the fiber distance. The FEC mechanism uses Reed-Solomon code and adds 16 parity symbols (bytes) for each block of 239 information symbols (bytes). These additional parity data are used at the receiving end of the link to correct errors that may have occurred during the data transmission. The P2MP group has adopted frame based FEC mechanism, such that each frame is encoded separately and all per-frame parity bytes are added at the end of the frame. This approach would allow devices without FEC capabilities to receive the FEC-encoded frames, albeit with a higher number of bit errors.

Physical medium attachment sublayer

The *physical medium attachment* sublayer is extended to specify a time interval required by the receiver to acquire phase and frequency lock on the incoming data stream. This interval is known as the *clock and data recovery* (CDR) time. The specification requires the PMA sublayer instantiated in an OLT to become synchronized at the bit level within 400 ns and at the code-group level within an additional 32 ns.

4.2 EPON Today: Promise and Challenges

Recently, subscriber access networks based on EPON became a hot topic in the industry as well as in academic research. Industrial interests stem from the fact that EPON is the first optical technology promising to be cost-effective enough to justify its mass deployment in an access network. The completion of the standard and the expectations that EPON architecture will enjoy the same success and proliferation as its LAN predecessor became a thrusting factor for many telecommunication operators to initiate EPON trials, or to at least study the technology.

Unlike other standards bodies, IEEE 802.3 only specifies a small portion of a communications system (only physical and data link layers). The rest is considered out of scope for IEEE 802.3. The academic research was fueled by a number of interesting challenges brought forward by EPON architecture, but left out by the standard.

One interesting research problem is related to EPON's efficiency and scalability. To support a large number of users, and to exploit multiplexing gains from serving bursty Internet traffic, the EPON scheduler should be able to allocate bandwidth dynamically. Yet, considering very significant propagation delays and the non fragmentability of Ethernet frames, developing such scheduling algorithm is a nontrivial task. In response to this challenge, the research community has generated many interesting EPON *dynamic bandwidth allocation* (DBA) proposals.

Another set of research problems is related to the fact that EPON is sought for subscriber access—an environment serving independent and non cooperative users. Users pay for service and expect to receive their service regardless of the network state or the activities of the other users. Unlike traditional, enterprise-based Ethernet, the EPON must be able to guarantee *service-level agreements* (SLAs) and enforce traffic shaping and policing per individual user. Providing dynamic bandwidth allocation, while guaranteeing performance parameters such as packet latency, packet loss, and bandwidth, is yet another rich research topic. Issues of upgradability, encryption, and authentication are also very important for EPON's success in the public access environment.

5. EPON ENGINEERING

The IEEE 802.3 standard defines two basic modes of operation for an Ethernet network. In one configuration, it can be deployed over a shared medium using the *carrier-sense multiple access with collision detection* (CSMA/CD) protocol. In the other configuration, stations may be connected through a switch using full-duplex point-to-point links. Correspondingly, Ethernet MAC can operate in one of two modes: CSMA/CD mode or full-duplex mode.

Properties of the EPON medium are such that it cannot be considered either a shared medium or a point-to-point network; rather, it is a combination of both. It has a connectivity of a shared medium in the downstream direction, and it behaves as a point-to-point medium in the upstream direction.

5.1 Downstream Transmission

In the downstream direction, Ethernet packets transmitted by the OLT pass through a 1 × N passive splitter or cascade of splitters and reach each ONU. The value of N is typically between 4 and 64 (limited by the available optical power budget). This behavior is similar to a shared medium network. Because Ethernet is broadcasting by nature, in the downstream direction (from network to user) it fits perfectly with the Ethernet PON architecture: Packets are broadcast by the OLT and selectively extracted by their destination ONU as shown in the following figure.

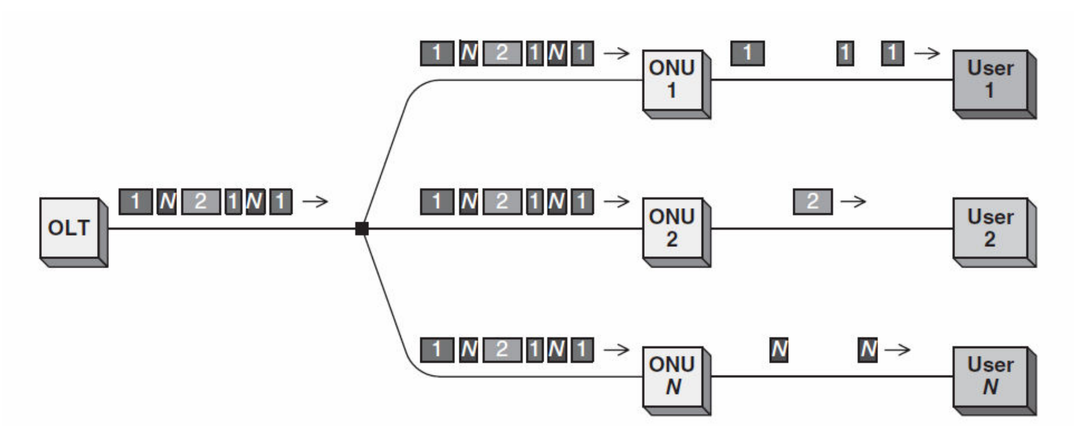


Fig. 6: Downstream transmission in EPON.

5.2 Upstream Transmission

In the upstream direction (from users to network), due to the directional properties of a passive optical combiner, data packets from any ONU will reach only the OLT, and not other ONUs. In this sense, in the upstream direction, the behavior of EPON is similar to that of a point-to-point architecture. However, unlike a true point to-point network, in EPON, all ONUs belong to a single collision domain—data packets from different ONUs transmitted simultaneously still may collide. Therefore, in the upstream direction, EPON needs to employ some arbitration mechanism to avoid data collisions and fairly share the channel capacity among ONUs.

5.2.1 Contention-based versus guaranteed media access

A contention-based media access mechanism (something similar to a CSMA/CD) is difficult to implement in EPON because ONUs cannot detect a collision due to the directional properties of optical splitter/ combiner. An OLT could detect a collision and inform ONUs by sending a jam signal; however, propagation delays in PON, which can exceed 20 km in length, can greatly reduce the efficiency of such a scheme. Contention-based schemes also have a drawback of providing a nondeterministic service; i.e., node throughput, channel utilization, and medium access delay can only be described as statistical averages. There is no guarantee of a node getting access to the medium in any small interval of time. The nondeterministic access is only a minor nuisance in CSMA/CD-based enterprise networks where links are short, typically over provisioned, and traffic predominantly consists of delay tolerant data. Subscriber access networks, however, in addition to data, must support voice and video services and thus must provide certain guarantees on timely delivery of these traffic types.

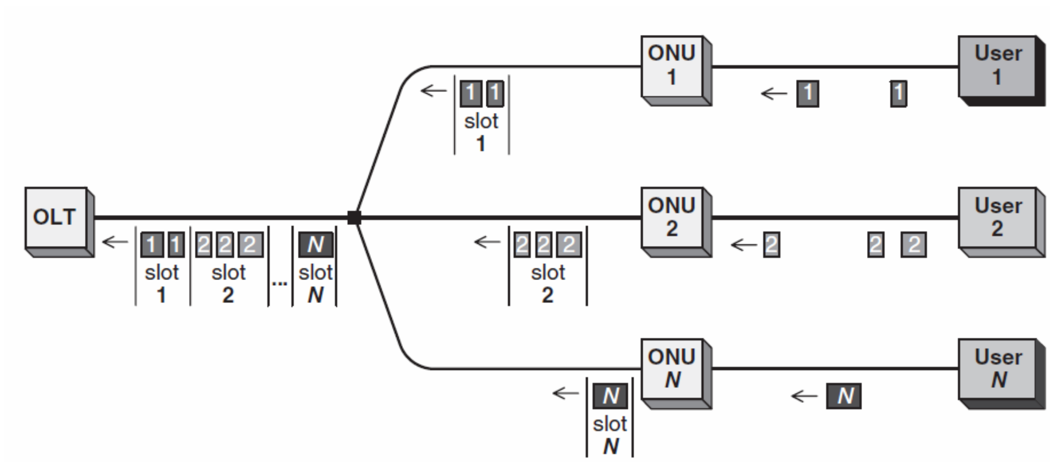


Fig. 7: Upstream transmission in EPON.

To introduce determinism in the delivery of packets, different noncontention schemes have been proposed. All such schemes grant ONUs an exclusive access to the media for a limited interval of time, commonly referred to as *transmission window* or *timeslot*. Figure 7 illustrates an upstream timeshared data flow in an EPON.

All ONUs are synchronized to a common time reference, and each ONU is allocated a timeslot. Each timeslot is capable of carrying several Ethernet packets. An ONU should buffer frames received from a subscriber until its timeslot arrives. When the timeslot arrives, the ONU "bursts" all stored frames at full channel speed which corresponds to a standard Ethernet rate of 1000 Mbps. If there are no frames in the buffer to fill the entire timeslot, 10-bit idle characters are transmitted as specified for full-duplex Ethernet MAC.

The performance of an EPON depends on a particular capacity allocation scheme. The possible timeslot allocation schemes range from static allocation (fixed TDMA) to dynamic adjustment of the slot size based on instantaneous queue load in every ONU (statistical multiplexing scheme). Choosing the best allocation scheme, however, is not a trivial task.

Fixed TDMA schemes are easier to implement. In a simplest form, each ONU would be programmed to start and stop transmission at the predetermined repeating intervals.

Fixed TDMA schemes suffer from low efficiency in the presence of bursty data or variable-size packets. If all users belonged to the same administrative domain, say a corporate or campus network, the full statistical multiplexing would make sense network administrators would like to get the most out of the available bandwidth, regardless of how much of it each particular user gets. However, subscriber access networks are not private LANs, and the objective is to ensure service-level agreement compliance for each individual user.

5.2.2 Centralized versus distributed arbitration

Noncontention (guaranteed) schemes require channel arbitration. This arbitration can be either centralized or distributed. In a distributed arbitration scheme, the ONUs themselves decide when to send data and for how long. These schemes are somewhat similar to a token-passing approach. In such a scheme, every ONU, before sending its data, will send a special message announcing how many bytes it is about to send. The ONU that is scheduled next (say, in round-robin fashion) will monitor the transmission of the previous ONU and will time its transmission such that the transmission arrives at the OLT right after the transmission from the previous ONU. Thus, there will be no collision, and no bandwidth will be wasted. However, this scheme has a major limitation: it requires connectivity (communicability) between ONUs. This imposes some constraints on the PON topology; namely, the network should be deployed as a ring or as a broadcasting star. This requirement is not desirable as (1) it may require more fiber to be deployed or (2) fiber plant with different topology might be already predeployed. In general, a preferred algorithm should support any point-to-multipoint PON topology.

In an optical access network, we can count only on the connectivity from the OLT to every ONU (downstream traffic) and from every ONU to the OLT (upstream traffic). Therefore, the OLT remains the only device that can arbitrate time-division access to the shared channel. The challenge in implementing a centralized (OLT based) dynamic arbitration scheme is the fact that the OLT does not know how many bytes of data each ONU has buffered. The burstiness of data traffic precludes a queue occupancy prediction with any reasonable accuracy. If the OLT is to make an accurate timeslot assignment, it should know the state of a given ONU exactly. One solution may be to use a polling scheme based on grant and request messages. Requests are sent from an ONU to report changes in an ONU’s state, e.g., the amount of buffered data. The OLT processes all requests and allocates different transmission windows (timeslots) to ONUs. Slot assignment information is delivered to ONUs using grant messages.

The advantage of having centralized intelligence for the slot allocation algorithm is that the OLT knows the state of the entire network and can switch to another allocation scheme based on that information; the ONUs don't need to monitor the network state or negotiate and acknowledge new parameters. This will make ONUs simpler and cheaper and the entire network more robust. In the end, the IEEE 802.3ah task force has settled on a noncontention centralized model for upstream channel access.

Given that the bandwidth allocation algorithms may depend on many parameters, such as deployment environment, supported services, and mix of SLA plans, the IEEE 802.3ah task force decided that it would be too presumptuous to select a specific *dynamic bandwidth allocation* (DBA) algorithm. Instead, the group has declared the DBA to be out of scope for the standard and has left the choice to equipment vendors. While the algorithm's decision-making process is left open, to ensure device interoperability, the message exchange protocol needed to be specified. To support dynamic capacity allocation, the IEEE 802.3ah task force has developed the multi-point control protocol. The MPCP is not concerned with a specific DBA algorithm; rather it is a supporting mechanism that facilitates implementation of various bandwidth allocation schemes in EPON.

5.3 Multi-Point Control Protocol

One of the most important conditions EPON has to comply with, in order to be part of the IEEE 802.3 standard, is the use of the existing Ethernet MAC (either CSMA/CD or full-duplex). Should EPON adopt different medium access logic, it most likely would become a new standard, separate from IEEE 802.3 Ethernet. Notwithstanding that transmission arbitration is a MAC function, the IEEE 802.3ah task force had to find a protocol which will achieve the same without any modifications to the MAC sublayer. In was decided to implement MPCP as a new function of the MAC control sublayer.

The scope of MAC control is to provide real-time control and manipulation of MAC sublayer operation. The MAC control sublayer resides between the MAC sublayer and MAC client. Before MPCP was developed by the IEEE 802.3ah task force, the only function of the MAC control sublayer was flow control an operation allowing a station to inhibit transmission from its peer for a predetermined interval of time. To achieve this, the flow control protocol uses a PAUSE MAC control message.

Transmission arbitration in EPON required a method exactly opposite to flow control an operation allowing a station to enable transmission from its peer for a predetermined interval of time. To avoid collisions, the OLT would allow only one ONU to transmit at any given time.

An important difference between MPCP and flow control is their default state, i.e., the state to which a link will eventually converge after control messages have stopped being issued. In flow control, the default state allows communication to be carried over a link; this communication may be explicitly paused by a control message. On the contrary, in MPCP, the default state inhibits the communication. Only when the control message arrives, the transmission will be enabled for a limited time. This behavior necessitated the following MPCP modes of operation:

- *Bandwidth assignment* mode. To sustain communication between OLT and ONUs, the MPCP should provide periodic granting for each ONU.

- *Autodiscovery* mode. To discover newly activated ONUs, the MPCP should initiate the discovery procedure periodically.

While the MAC control sublayer is optional for other configurations, in EPON it is mandatory, because EPON cannot operate without MPCP.

5.3.1 Bandwidth assignment

The bandwidth assignment mechanism relies on grant and request messages, or GATE and REPORT, in IEEE 802.3ah terminology. Both GATE and REPORT messages are MAC control frames, which are identified by a predefined type value of 88-0816.

A GATE message is sent from the OLT to an individual ONU and is used to assign a transmission timeslot to this ONU. A timeslot is identified by a pair of values {*startTime, length*}. The values for *startTime* and *length* are decided upon by a *DBA agent* or *scheduler*, located in MAC control client, a sublayer outside the scope of IEEE 802.3ah. The values of *startTime* and *length* are passed to the gating process at the OLT. The gating process, formally specified in the standard, forms a GATE message and transmits it to the ONU. In the ONU, the received GATE message is parsed and demultiplexed to the ONU's gating process, which is responsible for allowing the transmission to begin within the timeslot assigned by the received message. Additionally, an indication of the received GATE message is passed to the DBA agent at the ONU to allow it to perform any necessary DBA specific functions, e.g., select the order of frames to be sent out. Indeed, in some scheduling algorithms, such as those based on packet deadlines, the order of frames may depend on the time when the timeslot starts or on the size of the timeslot.

A REPORT message is a feedback mechanism used by an ONU to convey its local conditions (such as buffer occupancy) to the OLT to help the OLT make intelligent allocation decisions. Such information as number of egress queues and their status is not available to the MPCP, and so the REPORT message, similarly to the GATE, is initiated by the DBA agent (as shown in the following figure). It is then passed to the reporting process at the ONU, which forms and transmits the REPORT frame. REPORT frames can be sent only in previously assigned timeslots. At the OLT, the received REPORT frame is parsed and demultiplexed to the OLT's reporting process, which, in turn, passes it to the DBA agent. The DBA agent may use this information to make timeslot allocations for the next round.

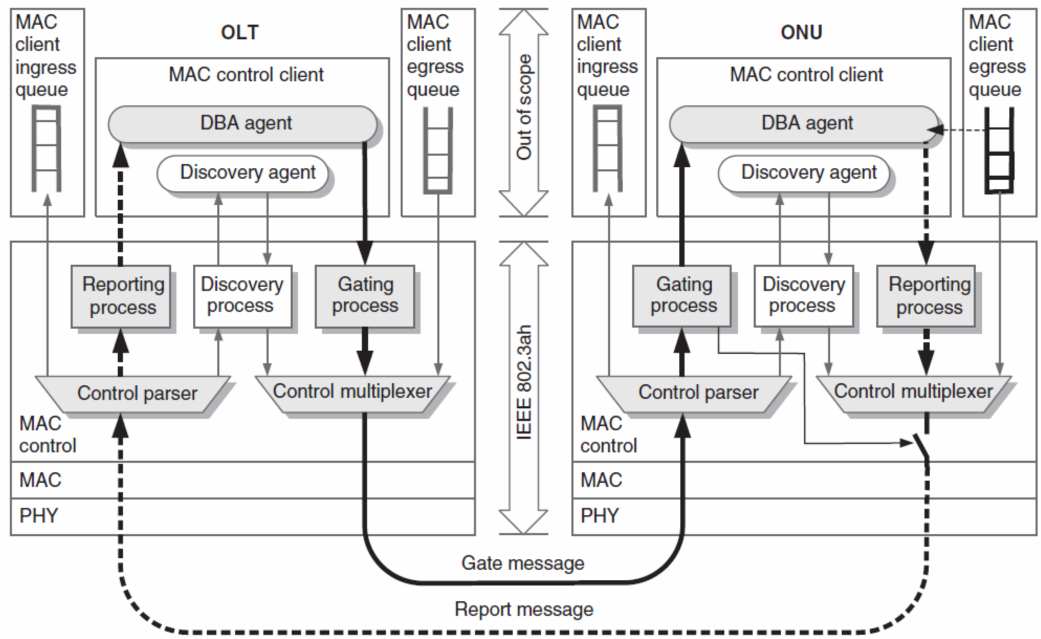


Fig. 8: Processes and agents involved in bandwidth assignment.

5.3.1.1 Pipelined timeslot assignment

An interesting question is how the OLT can make sure that timeslots assigned to different ONUs do not overlap. In a *sequential* timeslot assignment mode, the OLT assigns a timeslot to ONU *i* only after the data from ONU *i* - 1 have been received (see Fig. 9). As simple as the timeslot assignment may be, this scheme is very inefficient, because after a GATE has been sent, the channel would remain idle for the entire round-trip time. This idle time is often called *walk-time*. In EPON, the distance between the OLT and an ONU can reach 20 km, so the walk-time could be as high as 200 µs. To eliminate the walk-time overhead, MPCP allows a *pipelined* timeslot assignment. In this mode, the OLT may send a GATE to ONU *i* before data from ONU *i* - 1 have arrived (see Fig. 10). The pipelined mode requires the OLT to know the round-trip time to each ONU. Having this knowledge, the OLT is able to calculate future time when all pending transmissions will complete and the upstream channel will become idle, and to schedule the following timeslot to start at that time. The measurement of the round-trip time for a newly connected ONU is one of the main tasks of the autodiscovery procedure.

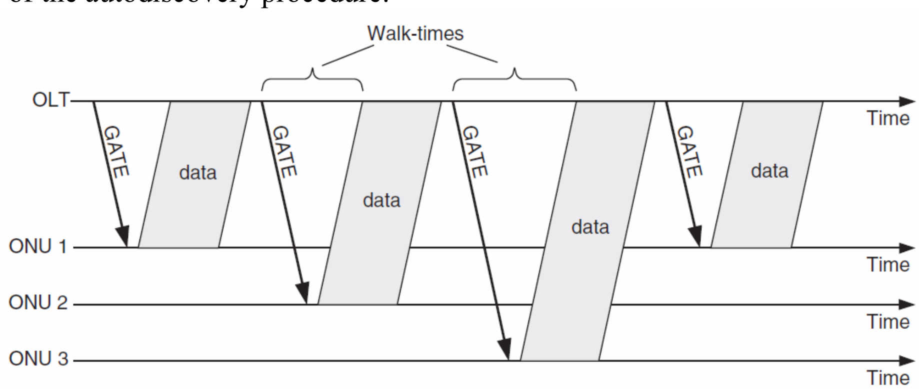


Fig. 9: Sequential timeslot assignment

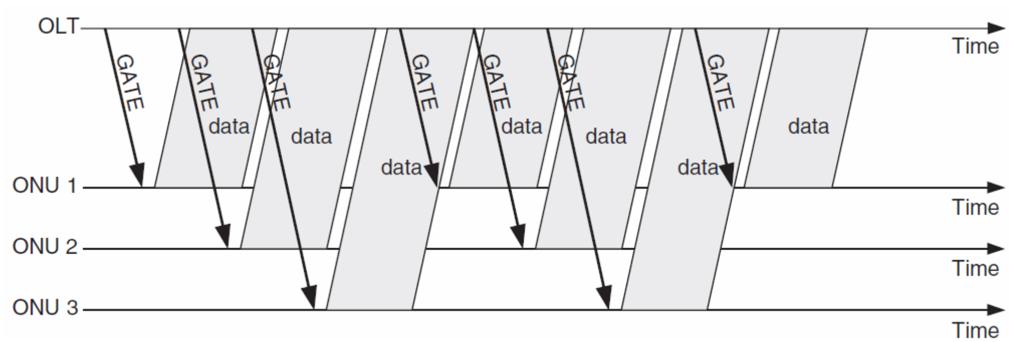


Fig. 10: Pipelined timeslot assignment

5.3.1.2 Decoupled downstream and upstream timing

In several schemes considered by the EFM task force, timeslots were represented in the GATE messages only by *length* instead of by a {*startTime*, *length*} pair. Proponents of these schemes argued that the GATE message arrival time can explicitly serve as the timeslot start time. If the DBA agent in the OLT desires to receive data from ONU *k* at time *t*, the GATE message should be sent to this ONU exactly at time *t* - *RTTk*, where *RTTk* is the round-trip time to ONU *k* (including any message parsing and processing delays). This idea of "just-in-time" GATE transmission hit a snag, because Ethernet frames cannot be preempted or fragmented. Very conceivably, a GATE message could be blocked behind a long data frame that started its transmission a moment before the GATE message was to be transmitted. In addition, GATE messages could be blocked behind other GATE messages. A blocked GATE message will be transmitted with some delay, and will cause a corresponding delay in the upstream transmission from an ONU, degrading the upstream channel utilization. A more serious problem may arise if a GATE message to ONU *k* is scheduled for transmission after the GATE message to ONU *k* + 1 as shown bellow.

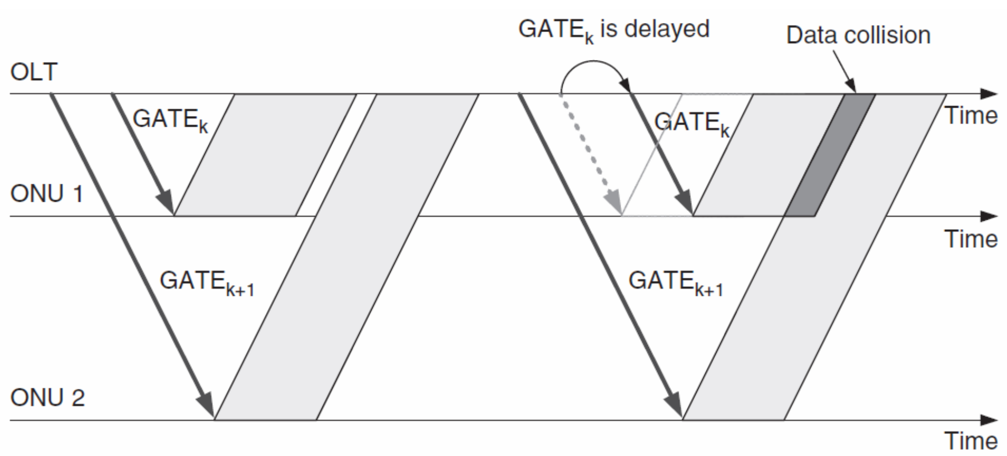


Fig. 11: In "just-in-time" granting schemes, data collisions are possible due to delayed GATE message.

If GATE *k* + 1 was transmitted on time but GATE *k* was delayed, the transmission from ONU *k* will be delayed and some data frames may collide with transmission from ONU *k* + 1.

To resolve the difficulties associated with just-in-time granting, it was deemed very desirable to decouple GATE transmission timing from the upstream transmission timing. Such decoupling is achieved by explicitly specifying the timeslot start time in each GATE message (Fig. 12). Rather than using the GATE message arrival as the base time, the ONU would start transmission when its local clock became equal to the *startTime* value conveyed in the GATE message. The delay experienced by the GATE message itself will not affect the upstream transmission timing, as long as GATE message arrives before the intended timeslot start time. Since there may be a significant time lag between the GATE message arrival and the timeslot start time, this scheme requires clocks in the OLT and ONUs to be well synchronized.

5.3.1.3 MPCP clock synchronization.

To allow decoupling of GATE transmission time from the timeslot start time, the OLT and each ONU should maintain a local clock, called the *MPCP clock*. The MPCP clock is a 32-bit counter which counts time in units of *time quanta* (TQ). The TQ is defined to be a 16-ns interval, or the time required to transmit 2 bytes of data at 1 Gbps line rate. Correspondingly, the timeslot start times and lengths in GATE messages, as well as queue lengths in REPORT messages, are expressed in TQ. To synchronize ONU's MPCP clock to the OLT's clock, each MPCP message defines a field called *timestamp*. The OLT's control multiplexer, writes the value of the MPCP clock into the timestamp field of an outgoing GATE message. When a GATE message arrives to an ONU, the control parser sets its local MPCP clock to the value received in the timestamp field.

This clock synchronization scheme is based on the assumption that frame propagation delay between the control multiplexer at the transmitting device and the control parser at the receiving device is nearly constant. In other words, frames cannot be blocked or delayed in the MAC and PHY sublayers.

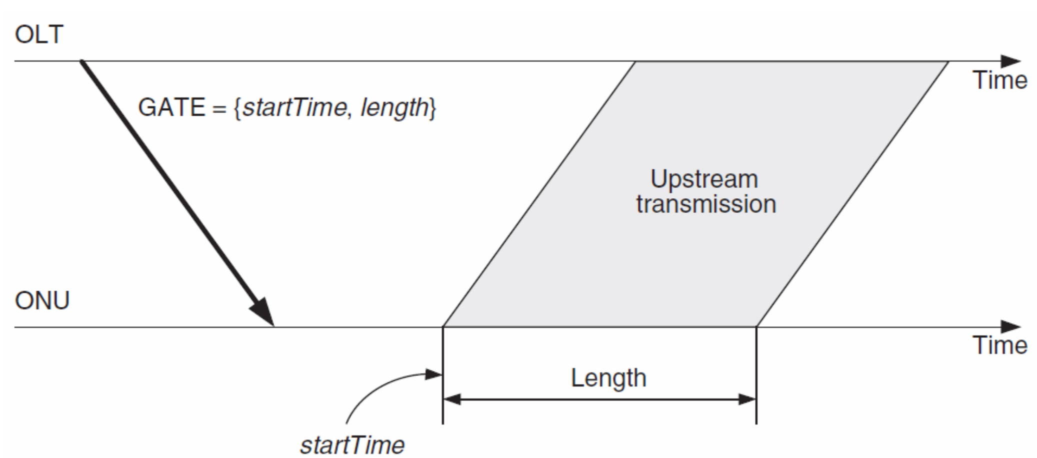


Fig. 12: Decoupled GATE arrival time and timeslot start time.

5.3.1.4 Loop timing

In traditional Ethernet, clocks were allowed to deviate from the nominal frequency by 100 *parts per million* (ppm). Such clock tolerance was a great asset of Ethernet specification, allowing very inexpensive devices to be built. But in EPON, it becomes a handicap. Consider a situation where the time interval between the GATE message arrival and the start of timeslot is large, say 20 ms. ONU will synchronize the MPCP clock to the received timestamp when the GATE message arrives. If the MPCP clocks in the OLT and ONU are free-running, the OLT clock runs at frequency f + 100 ppm, and the ONU clock runs at f - 100 ppm, then the ONU will initiate its upstream transmission late by 4 µs, which equals the clock drift during the 20 ms interval since the last synchronization.

To remedy this situation, MPCP mandates loop timing for the ONU, which means that the ONU's MPCP clock should track the receive clock, recovered from the data transmitted by the OLT. The OLT's clock is still allowed to be ±100 ppm from the nominal frequency. Since the OLT constantly transmits data or idle characters, ONUs are able to recover the clock and remain synchronized at all times.

5.3.2 Auto discovery

Recall that in the default state the MPCP does not allow transmission from an ONU. An ONU cannot transmit any data (cannot even turn its laser on) unless it is granted by the OLT. Thus, after boot-up, an ONU would silently wait for a grant from the OLT. This grant, however, will never arrive because the OLT doesn't know and cannot know that a new ONU has joined, since the ONU has to remain silent. To resolve this sort of chicken-and-egg situation, MPCP defines an autodiscovery mode.

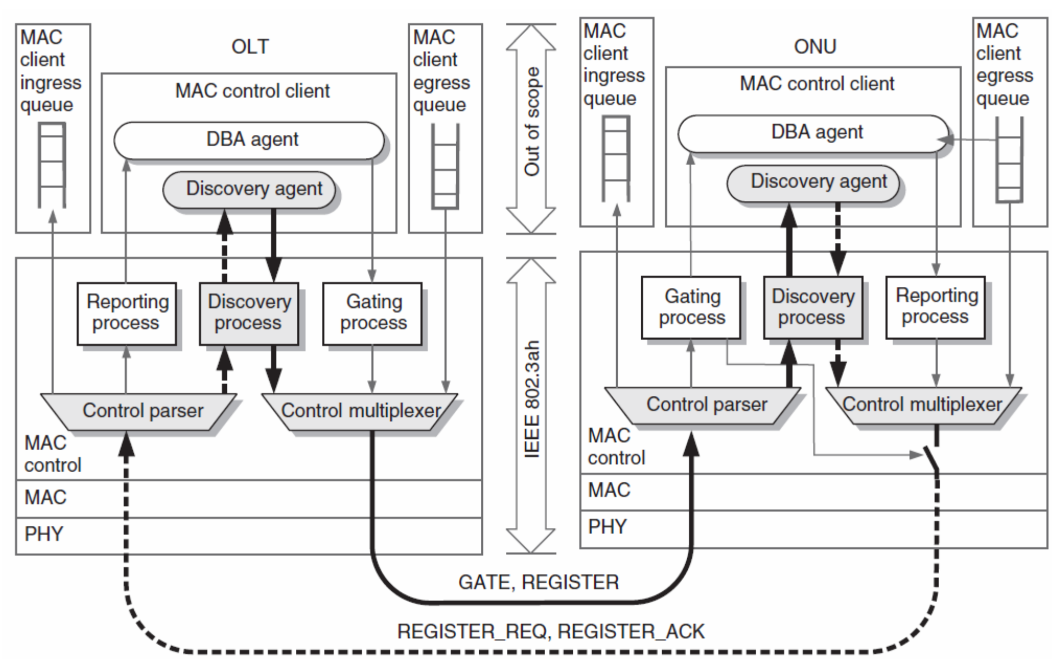


Fig. 13: Processes and agents involved in autodiscovery.

The autodiscovery mechanism is used to detect newly connected ONUs and learn the round-trip delays and MAC addresses of these ONUs. Both the OLT and ONUs implement the discovery process, which is driven by the *discovery agent* (Fig 13).

Autodiscovery employs four MPCP messages: GATE, REGISTER_ REQ, REGISTER, and REGISTER_ACK. These messages are carried in MAC control frames, which are distinguished by a predefined type value of 88-0816. At a high level, the autodiscovery is a four-step procedure, and it works as follows.

Step 1.

The discovery agent at the OLT decides to initiate a discovery roun and allocates a *discovery window* an interval of time when no previously initialized ONUs are allowed to transmit. It is assumed that the discovery agent may freely communicate with the DBA agent and that both agents will agree on the discovery window size and its start time. The DBA agent ensures that no active ONUs are scheduled to transmit during the discovery window. The discovery agent instructs the discovery process to send a special GATE message, called *discovery GATE*, advertising the start time of the *discovery slot* and its *length*. Further the relationship between the discovery slot size and the discovery window size will be explained. While relaying the discovery GATE message from the discovery agent to the MAC sublayer, the MPCP will timestamp it with the OLT's local time.

Step 2.

Only uninitialized ONUs will respond to the discovery GATE message. Upon receiving the discovery GATE message, an ONU will set its local time to the timestamp that it received in the discovery GATE message. When the local clock located in the ONU reaches the start time of the discovery slot (also delivered in the discovery GATE message), the ONU will wait an additional *random delay* and then transmit the REGISTER_REQ message. The random delay is applied to avoid persistent collisions when REGISTER_REQ messages from multiple uninitialized ONUs consistently collide. The REGISTER_REQ message contains the ONU's source address and a timestamp representing the local ONU's time when the REGISTER_REQ message was sent. When the OLT receives the REGISTER_REQ from an uninitialized ONU, it learns its MAC address and round-trip time.

Step 3.

Upon parsing and verifying the REGISTER_REQ message, the OLT issues the REGISTER message sent directly to an initializing ONU using the MAC address received during the previous step. The REGISTER message contains a unique identification value called the *logical link* ID (LLID) that the OLT assigns to each ONU. Following the REGISTER message, the OLT sends a normal GATE (nondiscovery or unicast GATE) to the same ONU.

Step 4.

Finally, after receiving both the REGISTER and the normal GATE messages, the ONU sends the REGISTER_ACK message to acknowledge to the OLT that it has successfully parsed the REGISTER message. The

REGISTER_ACK should be sent in the timeslot granted by the previously received GATE message.

Since multiple uninitialized ONUs may respond to the same discovery GATE message, the REGISTER_REQ messages may collide. In that case, the ONUs whose REGISTER_REQ messages have collided will not get the REGISTER message. If an ONU does not receive the REGISTER message before it receives another discovery GATE, it will infer that a collision has occurred and will attempt to initialize again.

5.3.2.1 Discovery slot and discovery window

Discovery slot is a length of the grant advertised to all uninitialized ONUs in the discovery GATE. The discovery window is an interval reserved by the discovery agent. No data traffic should be scheduled during the discovery window. as shown in (Fig. 14) the discovery window size and discovery slot size are related. The discovery window should be at least as large as the discovery slot. In addition, since the distance to an uninitialized ONU is not known yet, the discovery window should accommodate the entire range of possible round-trip times (RTTs). Thus, the relationship between discovery slot and discovery window can be expressed as

$$discoveryWindow \geq discoverySlot + maxRTT - minRTT$$

Often, either for simplicity or because it is not known, *minRTT* is taken as 0. Considering the maximum PON distance of 20 km (per IEEE 802.3ah specification), the following relationship should hold:

$$discoveryWindow \geq discoverySlot + 200\ \mu s$$

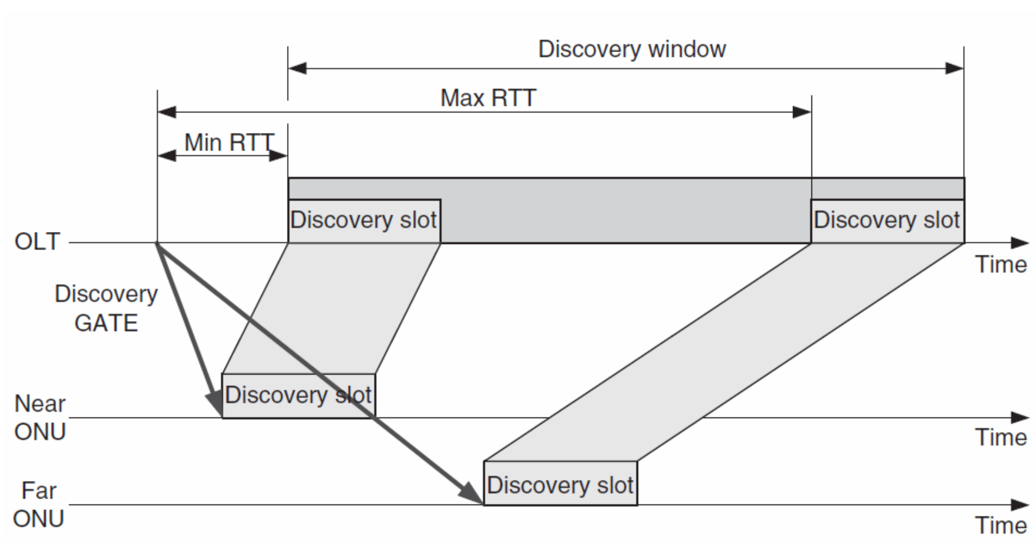


Fig. 14: Relationship of discovery slot and discovery window.

5.3.2.2 Avoiding persistent collisions.

Since more than one ONU may attempt initialization at the same time, autodiscovery is a contentionbased procedure. If two or more uninitialized ONUs happen to be at the same distance from the OLT, their REGISTER_REQ messages will persistently collide and such ONUs will never be discovered by the OLT. To avoid the persistent collisions, the OLT allocates the discovery slot larger than the necessary time to transmit a single REGISTER_REQ message.

Each uninitialized ONU will apply some random delay to offset the transmission of the REGISTER_REQ message within the discovery slot (Fig 15).

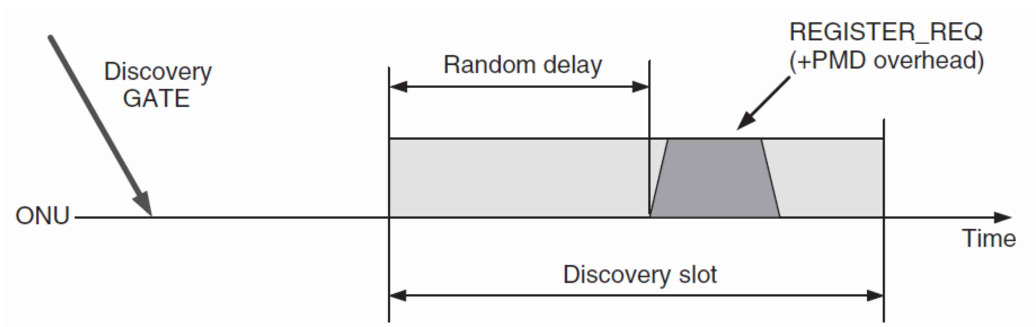


Fig. 15: Applying random delay during discovery process to avoid persistent collisions.

Two or more REGISTER_REQ messages still may collide in this configuration: however, given a sufficiently large discovery slot, such collisions will not be persistent. During the next discovery opportunity, the ONUs will choose different random delays, possibly avoiding the collision (Fig 16).

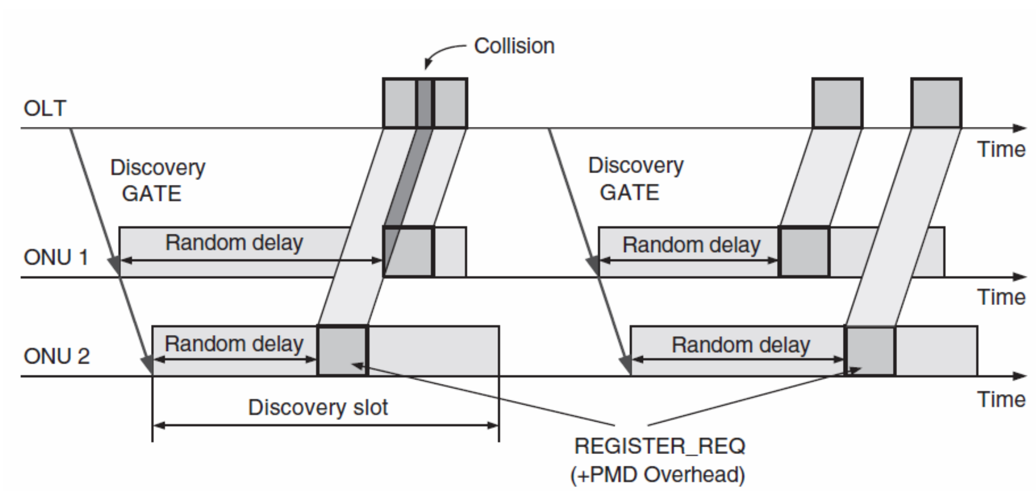


Fig. 16: Discovery attempt with and without REGISTER_REQ collision.

Clearly, the discovery is an invasive process, since no normal traffic can be carried upstream by EPON during the discovery window allocation. It is interesting to note that the IEEE 802.3ah task force has also considered an alternative method for avoiding the persistent collisions, namely, a back-off mechanism. Using this method, an ONU, whose REGISTER_REQ message has collided, will skip a random number of discovery attempts. This random number could be chosen from a range that doubles in size after each collision, resulting in a *binary exponential back-off* (BEB) algorithm, akin to the method used in CSMA/CD.

Even though in the BEB method the discovery slot may be smaller (only long enough to transmit one REGISTER_REQ message), the number of required discovery attempts will be significantly higher than in the *random delay* (RD) method described above. This is so because, in the BEB method, there is a significant probability that all collided ONUs will back off by more than one and that none of them will respond during the next discovery opportunity. This will consume EPON bandwidth without any reduction in the number of undiscovered ONUs. In the RD method, all undiscovered ONUs transmit the REGISTER_REQ message in every discovery slot until they succeed. The group has also considered a combination of BEB and RD, called BEB+RD, in which the ONUs would apply random delay to the REGISTER_REQ messages and would back off in case these messages collided. Intuitively, the efficiency of the BEB+RD method was between those of the BEB and RD methods. In the end, the efficiency argument prevailed, and the task force voted against the BEB and BEB+RD methods.

5.3.3 Round-trip time measurement

Probably, a simplest way to measure RTT is to send a message from the OLT to an ONU and request an ONU to echo it back right away. Then the RTT is simply the time difference between sending the message and receiving the response at the OLT. However, this simple scheme suffers from three issues:

1. Possibly the varying time to generate a response at the ONU is counted as part of RTT.
2. Downstream and upstream transmission timing is coupled.
3. If two ONUs happen to be at the same distance from the OLT, they would receive discovery GATE messages simultaneously and generate REGISTER_REQ messages at the same time. Without the possibility of applying random delay, these messages would persistently collide.

To resolve the above issues, the IEEE 802.3ah standard defines a more sophisticated RTT measurement scheme. The timing diagram of RTT measurement mechanisms is shown in (Fig. 16).

When the discovery GATE is passed through the control multiplexer at the OLT, it is times tamped with OLT's MPCP clock (*t*0). The timestamp reference point is the first byte of the discovery GATE message. In other words, the timestamp value should be equal to the MPCP clock value at the moment when the first byte of *destination address* (DA) is transmitted, i.e., passed from MAC control to MAC.

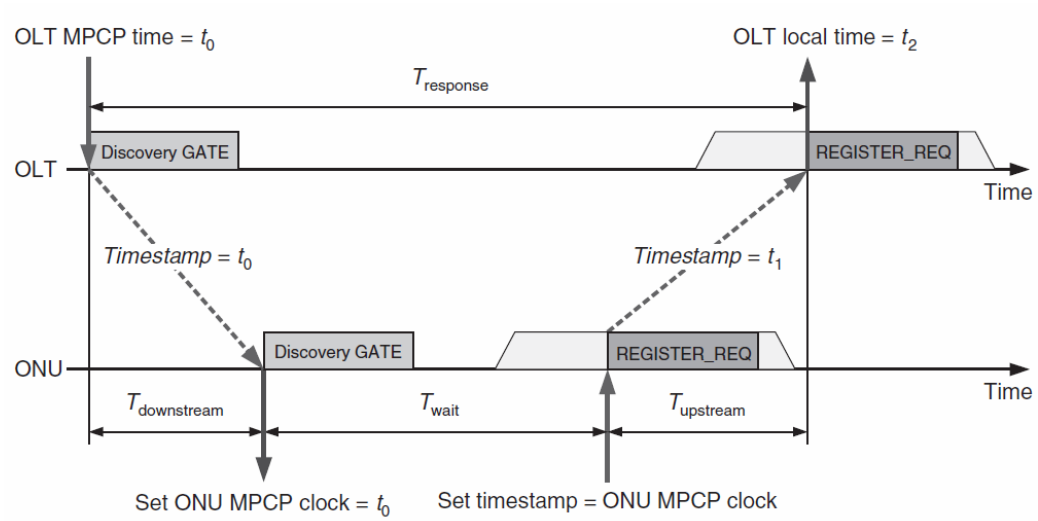


Fig. 16: Round-trip time measurement.

When this discovery GATE arrives at the ONU, the ONU sets its local MPCP counter to the value of the received timestamp. Here as well, the reference point should be the first byte of DA, as received by the ONU. After the initial value of the local MPCP clock is set, this clock continues running synchronously with the clock recovered from the received data stream.

When the value of the MPCP clock reaches the timeslot start time, the ONU applies an additional random delay, after which it starts transmitting the REGISTER_REQ message. When the REGISTER_REQ is passed through control multiplexer at the ONU, it is timestamped with the ONU's MPCP clock ($t1$). The timestamp reference point is the first byte of the REGISTER_REQ message. In (Fig 16), the interval of time between receiving the discovery GATE message and transmitting the REGISTER_REQ is denoted Twait and is equal $t1$ - $t0$.

This interval provides sufficient time for the ONU to generate the REGISTER_REQ message.

Finally, when the REGISTER_REQ message arrives at the OLT, the OLT notes the value of its MPCP clock corresponding to the first byte of the DA field. In (Fig 16), this value is denoted $t2$. The time elapsed at the OLT between sending the discovery GATE and receiving the REGISTER_REQ is denoted Tresponse and is equal to $t2$ - $t0$. From the timing diagram it is clear that Tresponse is equal to Tdownstream + Twait + Tupstream. Thus, we have

$$RTT = T\,downstream + T\,upstream = T\,response - T\,wait = (t\,2 - t\,0) - (t\,1 - t\,0) = t\,2 - t\,1 \qquad (5.1)$$

Equation (5.1) shows that the RTT equals exactly the difference between the REGISTER_REQ arrival time and the timestamp contained in the REGISTER_REQ message. Of course, this equation is only valid if Tresponse and Twait are measured in the same time domain, i.e., if the ONU's MPCP clock is synchronized to the OLT's clock.

5.3.3.1 Timestamp reference

Interestingly enough, the timestamp reference point being the first byte of the DA is not listed in the IEEE 802.3ah standard as a *mandatory* requirement. That means that standard-compliant devices are allowed to use different timestamp reference points.

Below we consider several examples of RTT measurement in the EPON system where the OLT and an ONU assume different timestamp reference points. Recall that the RTT is measured only to enable pipelined granting (see Sec. 5.3.1.1). In pipelined granting, the OLT must be able to precalculate the arrival time of the data burst from a given ONU. In the following examples, we will analyze how the choice of a reference point may affect the OLT's ability to precalculate the burst arrival time.

We first consider a case when the OLT and an ONU choose distinct reference points for the GATE message (Fig. 17). For example, the OLT will read MPCP clock Δ_{OLT} TQ ahead of transmitting the first byte of DA, and the ONU will set its MPCP clock to the received timestamp value Δ_{ONU} TQ after receiving the first byte of DA. As shown in (Fig. 5.17a) in this situation, the calculated RTT value will be

$$RTT = T\,\text{downstream} + T\,\text{upstream} + \Delta_{OLT} + \Delta_{ONU} \qquad (5.2)$$

Figure 17b illustrates a cycle of bandwidth assignment performed after the autodiscovery completes. In pipelined granting mode, if the OLT expects to receive ONU's data at time S, it will send to this ONU a GATE message with timeslot start time equal to $S - RTT$. As can be seen from the diagram, the actual arrival time A is equal to

$$A = t\,0 + \Delta_{OLT} + T\,\text{downstream} + \Delta_{ONU} + S - RTT - t\,0 + T\,\text{upstream} \qquad (5.3)$$

Expanding RTT per Eq. (5.2), we get $A = S$; that is, the actual data arrival time A exactly corresponds to the expected arrival time S. This example demonstrated that any time delta between actual GATE timestamp reference points used by the OLT and an ONU is indistinguishable from a downstream propagation delay. *The actual timestamp reference points for downstream MPCP messages do not need to coincide for the OLT and ONUs. The location of reference points is irrelevant as long as these points remain the same during autodiscovery and during the normal granting process.*

In our next example we consider a case when the OLT and an ONU use different reference points for the REGISTER_REQ message (Fig. 18). As before, we assume that the timestamp value is prepared before a frame transmission begins, and that the receiving device gets the timestamp value after the entire message is received and parsed. Therefore, in this example, the ONU will read MPCP clock Δ_{ONU} TQ ahead of transmitting the first byte of DA, and the OLT will latch message arrival time Δ_{OLT} TQ after receiving the first byte of DA.

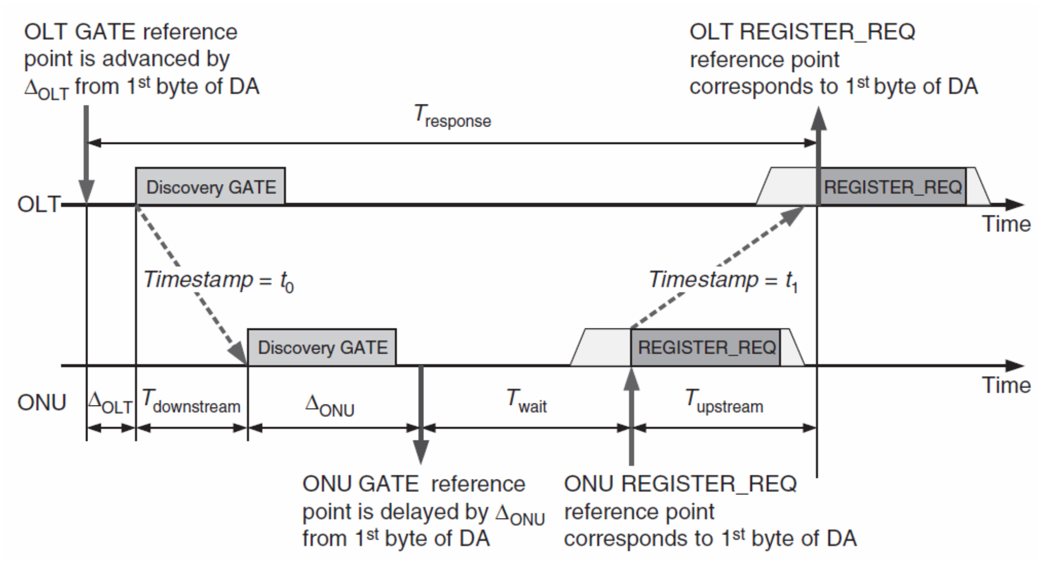


Fig. 17a: Measured RTT: RTT = Tresponse–Twait = Tdownstream + Tupstream + ΔOLT + ΔONU

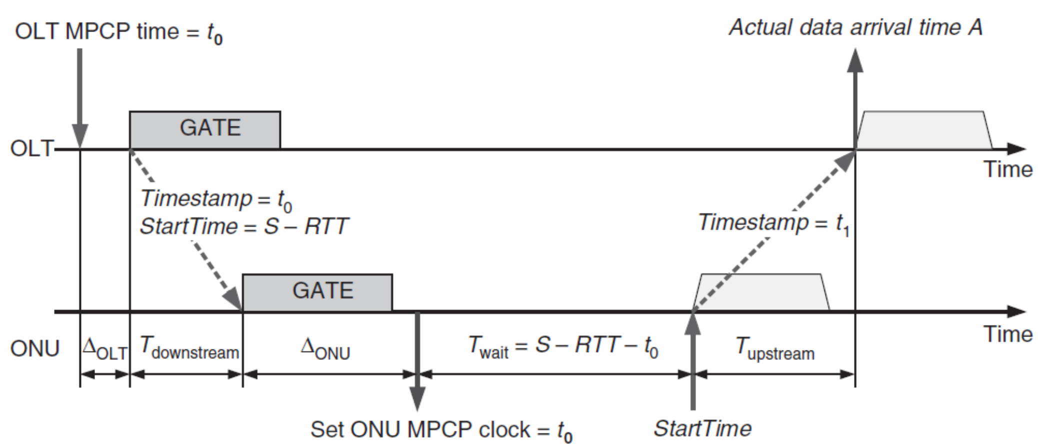


Fig. 17b: Data Arrival: A = t0 + ΔOLT + Tdownstream + S – RTT – t0 + ΔONU + Tupstream = S

Fig. 17: *Precalculation of arrival time when the OLT and ONUs use different GATE timestamp reference points.*

As shown in Fig. 5.18a, the calculated RTT value will be

$$RTT = T\,\text{downstream} + T\,\text{upstream} + \Delta_{OLT} + \Delta_{ONU} \qquad (5.4)$$

Fig. 18b illustrates a cycle of bandwidth assignment performed after the autodiscovery completes. As can be seen from the diagram, the actual arrival time A is

$$\begin{aligned} A &= t\,0 + T\,downstream + S - RTT - t\,0 + T\,upstream \\ &= t\,0 + T\,downstream + S - T\,downstream - T\,upstream - \Delta_{OLT} - \Delta_{ONU} \\ &\quad - t\,0 + T\,upstream \\ &= S - \Delta_{OLT} - \Delta_{ONU} \qquad (5.5) \end{aligned}$$

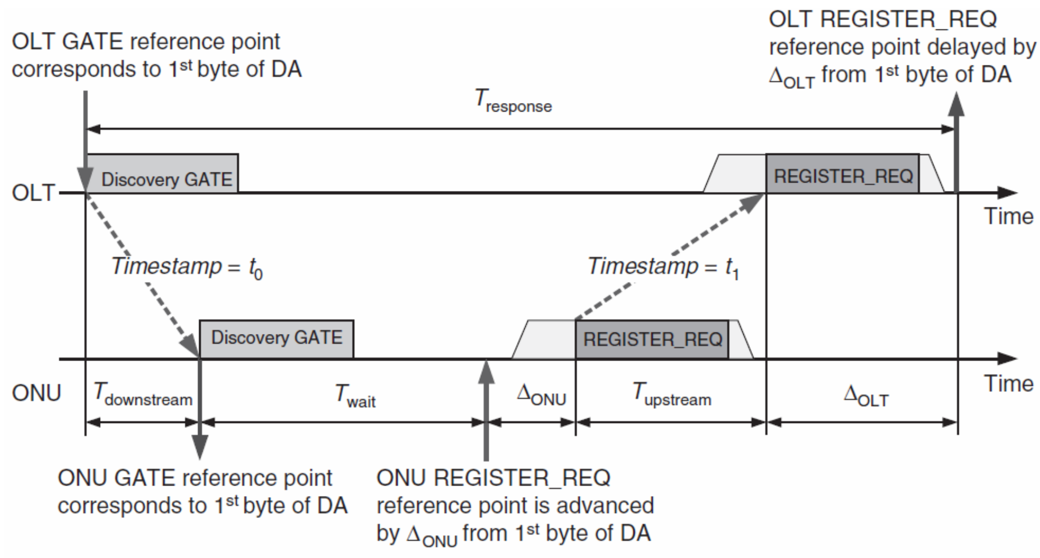


Fig. 18a: Measured RTT: RTT = Tresponse–Twait = Tdownstream + Tupstream + ΔOLT + ΔONU

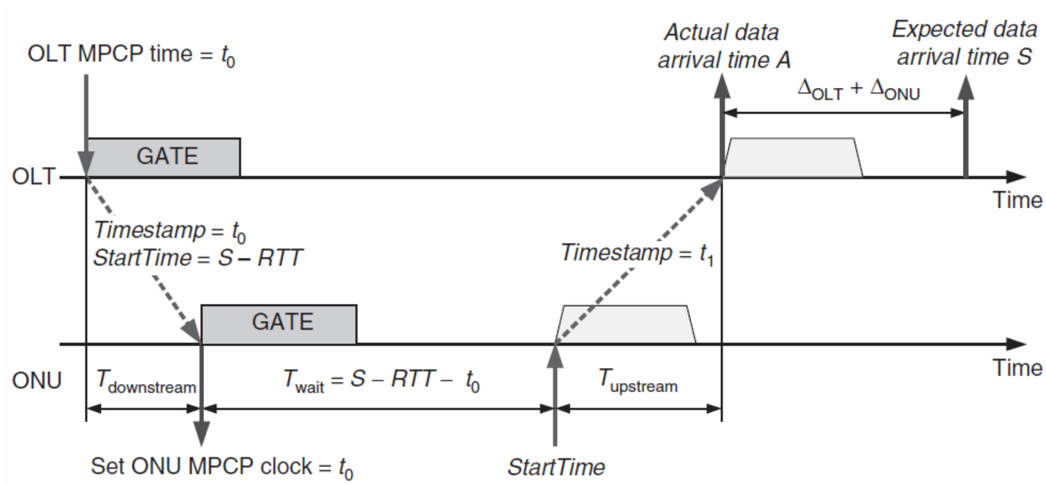


Fig. 18b: Data Arrival: A = t0 + Tdownstream + S – RTT – t0 + Tupstream = S – ΔOLT – ΔONU

Fig. 18: Precalculation of arrival time when the OLT and ONUs use different REGISTER_REQ timestamp reference points.

The actual data arrival time *A* is earlier than the expected arrival time *S* by *ΔOLT* + *ΔONU*. During the autodiscovery, the time delta between REGISTER_REQ timestamp reference points used by the OLT and an ONU is accounted for as part of the upstream propagation delay. However, during normal operation, the upstream propagation delay is simply a propagation time of the signal. This discrepancy results in incorrectly measured RTT and OLT's inability to precalculate the exact data arrival times. *For proper MPCP operation, the actual timestamp reference points for upstream MPCP messages should exactly coincide for the OLT and ONUs.* The fact that the reference points for upstream MPCP messages are not required to coincide appears to be an oversight in the IEEE 802.3ah standard specification.

6. EPON ARCHITECTURE TOPOLOGY EMULATION

The IEEE 802 architecture [802] assumes all communicating stations in a LAN segment to be connected to a shared medium. In a shared medium, all stations are considered as belonging to a single *access domain*, where at most one station can transmit at a time and all stations can receive all the time.

Multiple access domains can be interconnected by a device called a *bridge*. Bridges selectively forward packets to create an appearance of a LAN consisting of all access domains. The selective forwarding prevents transmitting a packet into the domains that do not include any destination stations for this packet. Bridging of multiple LANs is widely used to provide administrative isolation of access domains, to increase the number of stations or the physical reach of the network beyond the limitations of individual LAN segments, and to improve the throughput.

In an extreme case, an access domain may consist of just one station. Typically, many such single-station domains are connected by *point-topoint* (P2P) links to a bridge, forming a *switched LAN*.

Relying on the notion of access domains, bridges never forward a frame back to its ingress port. In case the access domain consists of multiple stations, it is assumed that all the stations connected to the same port on the bridge can communicate with one another without the bridge's help. In the case of a switched LAN, there can be no recipients in the access domain of the sender, so no frames are ever forwarded back. This bridge behavior has led to an interesting problem: Users connected to different ONUs in the same PON cannot belong to the same LAN and are unable to communicate with one another at layer 2 (data link layer). The reason is that the PON medium does not allow ONUs to communicate with one another directly, due to the directivity of passive splitters/combiners. Yet, the OLT has only a single port connecting to all ONUs, and a bridge located in the OLT would never forward a data frame back to its ingress port. In IEEE 802.3ah task force, this issue raised a question of EPON compliance with IEEE 802 architecture, particularly with P802.1D bridging. The above example is illustrative of the conflict endured by EPON throughout its entire development cycle in the IEEE 802.3ah work group. On one hand, to be part of the IEEE 802.3 Ethernet standard, EPON specification must comply with all the requirements put forward by the 802 architectural model. Specifically, all stations interconnected by a shared medium should form an access domain and be able to communicate with one another. On the other hand, EPON was being developed for subscriber access networks with requirements drastically different from those of private LANs. Subscriber access networks serve non cooperating, independent users who, for various security, regulatory, and economical reasons, may not be allowed to communicate to one another, except when provisioned by a network operator to do so.

To resolve this issue and to ensure seamless integration with other Ethernet networks, devices attached to the PON medium implement a *logical topology emulation* (LTE) function that, based on its configuration, may emulate either a shared medium or a point-to-point medium.

To preserve the existing Ethernet MAC operation defined in the IEEE 802.3 standard, the LTE function should reside below the MAC sublayer. Operation of this function relies on tagging of Ethernet frames with tags unique for each ONU. These tags are called *logical link identifiers* (LLIDs) and are placed in the preamble at the beginning of each frame. To guarantee uniqueness of LLIDs, each ONU is assigned one or more tags by the OLT during the initial registration (autodiscovery) phase.

6.1 Point-to-Point Emulation (P2PE)

The objective of P2P emulation mode is to achieve the same physical connectivity as in switched LAN, where all the stations are connected to a central switch using point-to-point links.

In P2P emulation mode, the OLT must have *N* MAC ports (interfaces), one for each ONU (Fig. 19). During ONUs registration, a unique LLID value will be assigned to each ONU. Each MAC port at the OLT will be assigned the same LLID as its corresponding ONU.

When sending a frame downstream (from the OLT to an ONU) the emulation function in the OLT inserts the LLID associated with a particular MAC port that the frame arrived from (Fig. 19a). Even though the frame will pass through a splitter and reach each ONU, only one P2PE function will match that frame's LLID with the value assigned to the ONU and will accept the frame and pass it to its MAC layer for further verification. LTE functions in all other ONUs will discard this frame, so the MAC sublayers will never see that frame. In this sense, from the MAC sublayer perspective, it appears as if the frame was sent on a point-to-point link to only one ONU.

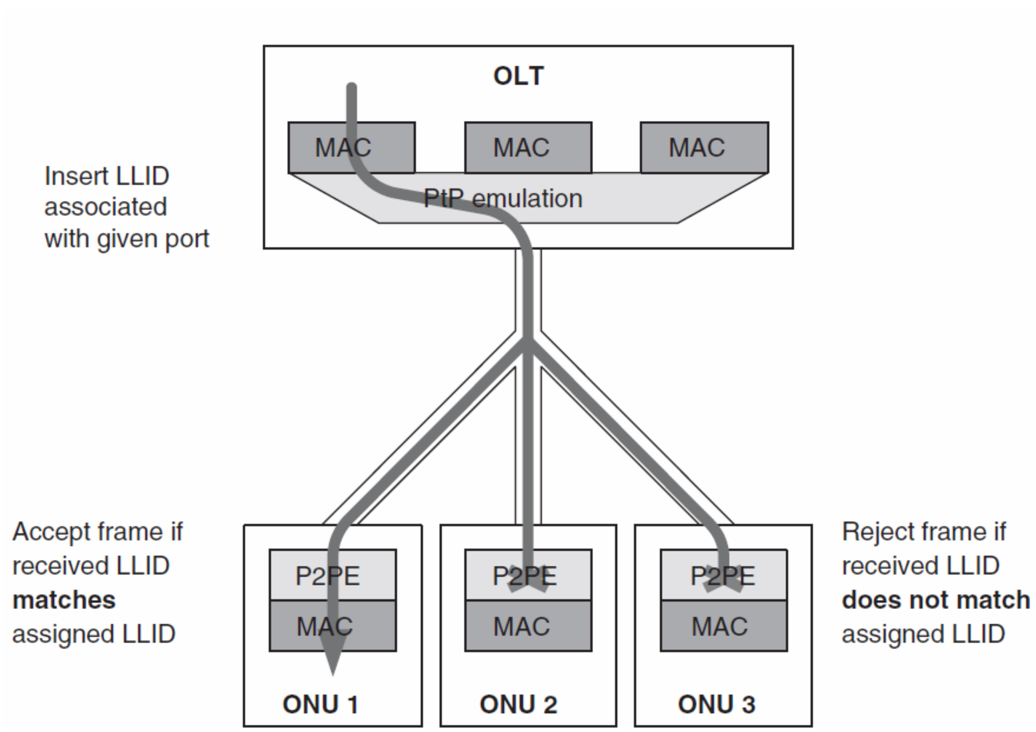


Fig. 19a: Downstream transmissions

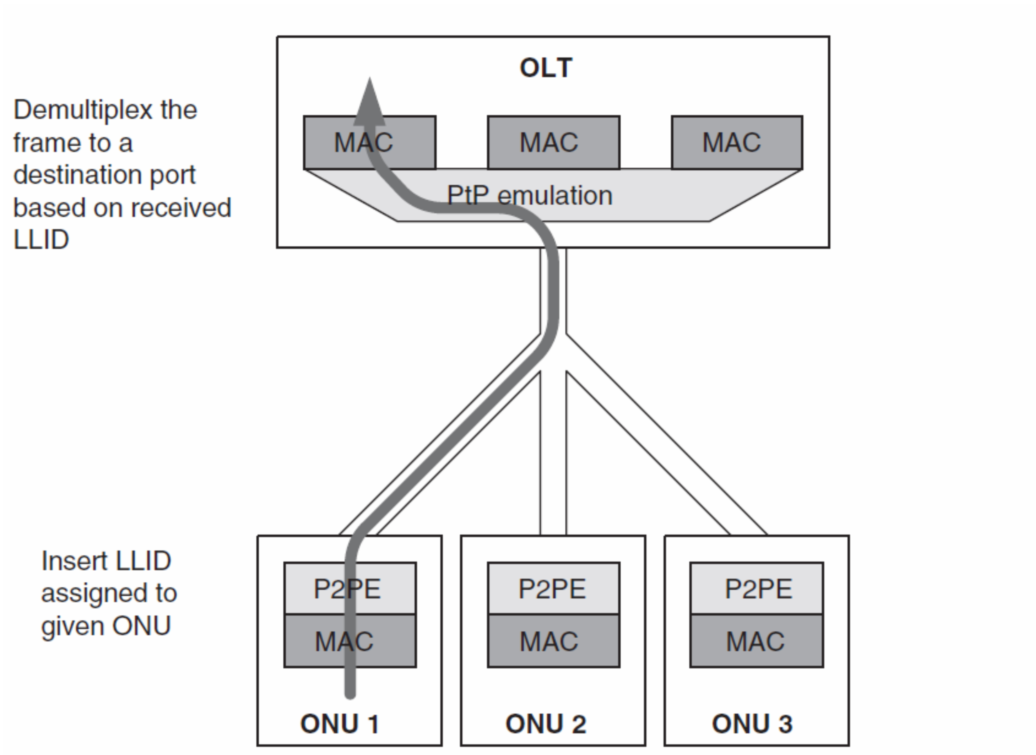


Fig. 19b: Upstream transmissions

Fig. 19:Point-to-point virtual topology emulation.

In the upstream direction, the ONU will insert its assigned LLID in the preamble of each transmitted frame. The P2PE function in the OLT will demultiplex the frame to the proper MAC port based on this unique LLID (Fig. 19*b*).

The P2PE configuration is clearly compatible with bridging, as each ONU is virtually connected to an independent bridge port. The bridge placed in the OLT (Fig. 20) will relay inter-ONU traffic between its ports.

6.2 Shared-Medium Emulation (SME)

In shared-medium emulation, frames transmitted by *any* node (OLT or any ONU) should be received by *ever*y node (OLT and every ONU), except the sender. In the downstream direction, the OLT inserts a *broadcast* LLID, which will be accepted by every ONU (Fig. 21*a*).

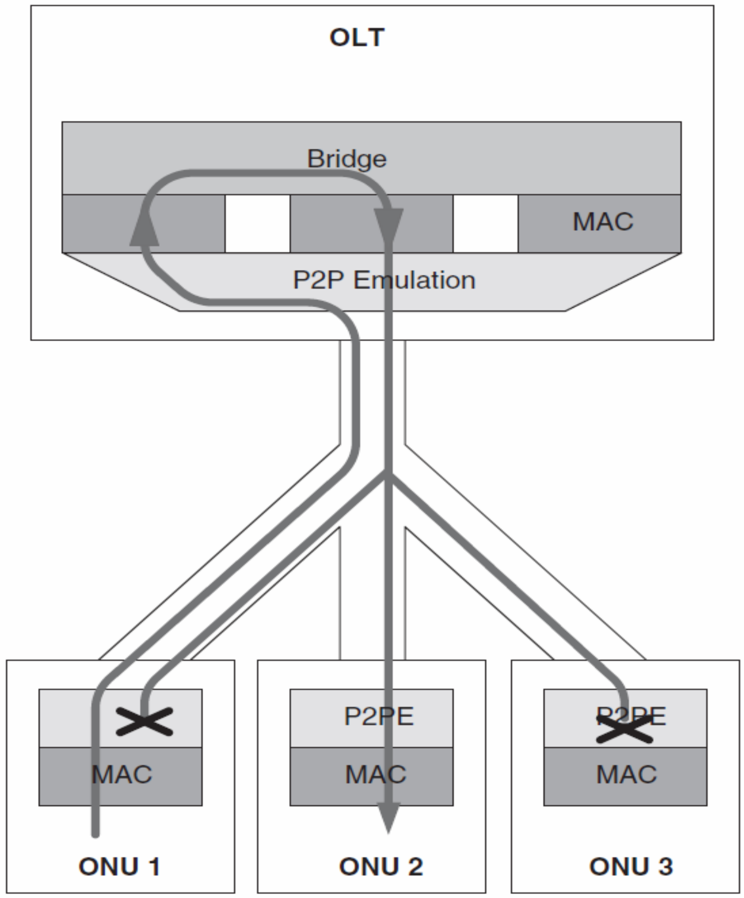


Fig. 20: Bridging between ONU 1 and ONU 2 using the point-to-point emulation.

To ensure shared-medium operation for upstream data (frames sent by ONUs) the LTE function in the OLT must mirror all frames back downstream to be received by all other ONUs (Fig. 21*b*). To avoid frame duplication, when an ONU receives its own frame, the LTE function in an ONU accepts a frame only if the frame's LLID is different from the LLID assigned to that ONU. Thus, in SME mode, the ONU's filtering rules are opposite to those of P2PE mode. While in P2PE mode an ONU only accepts frames whose LLIDs match ONU's own LLID, in the SME mode an ONU accepts frames whose LLIDs are different from the ONU's assigned LLID.

The shared-medium emulation requires only one MAC port in the OLT and presents PON to a bridge as a single access domain. Physicallayer functionality (LTE function) provides the ONU-to-ONU communicability, eliminating the need for a bridge.

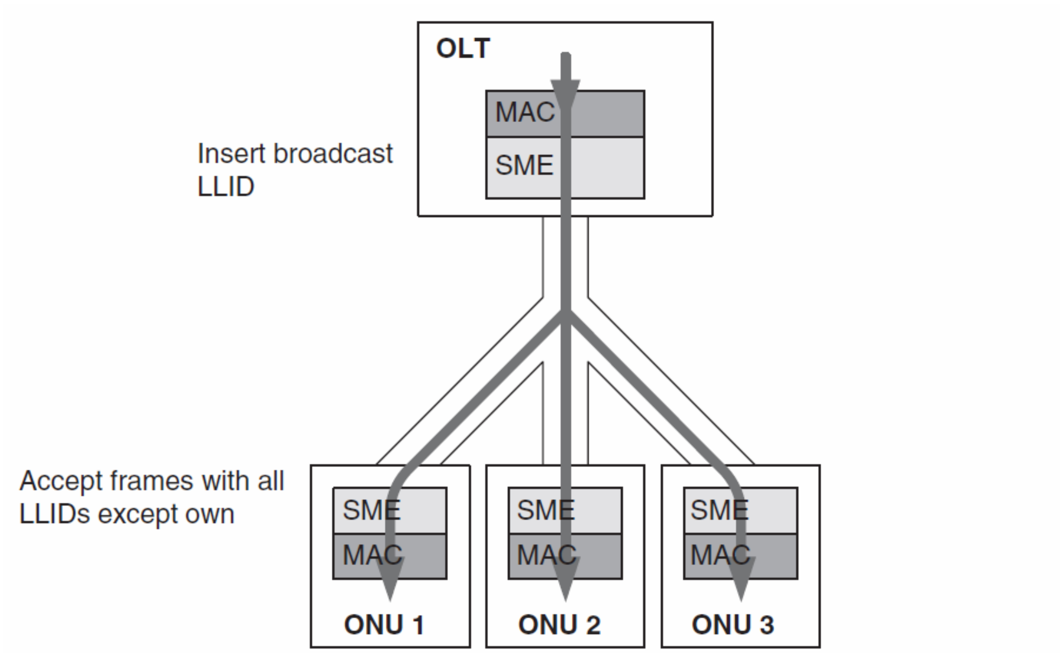


Fig. 21a: Downstream transmission

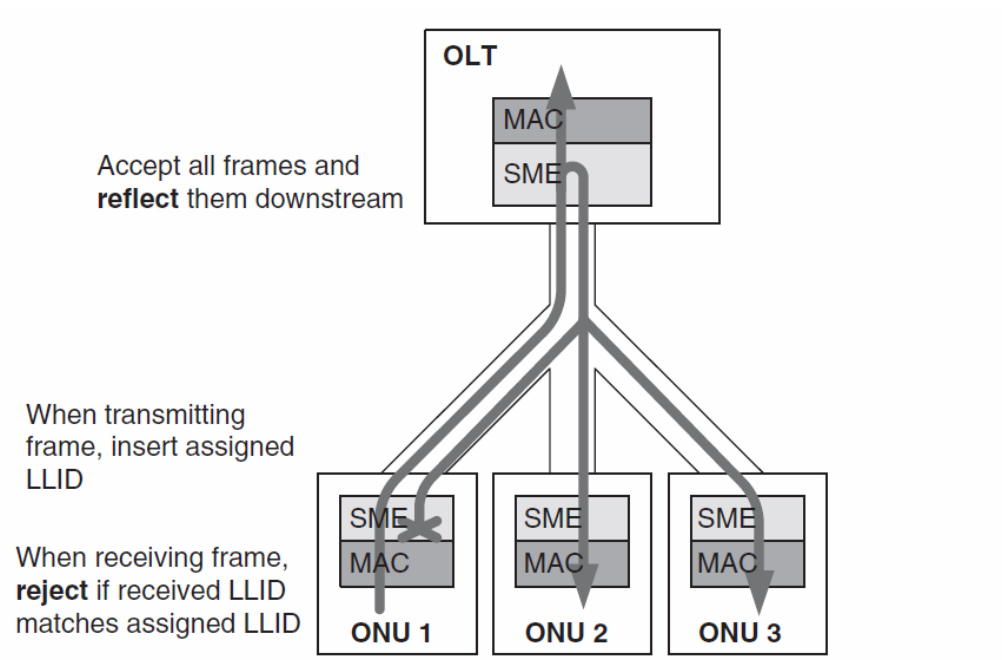


Fig. 21b: Upstream transmission

Fig. 21: Shared-medium emulation

6.3 Combined P2PE and SME Mode

While both P2PE and SME options provide solutions for P802.1 standards compliance issues, both also have drawbacks, specifically when considered for an application in a subscriber access network. The P2PE mode precludes a single-copy multicast/broadcast when a single frame sent by the OLT is received by several ONUs. This feature is very important for services such as video broadcast or any real time broadcast services. To support such services, the OLT operating in the P2PE mode must duplicate broadcast packets, each time with a different LLID.

Shared-medium emulation, on the other hand, provides broadcast capabilities. However, because *every* upstream frame is reflected downstream, it wastes a large portion of downstream bandwidth.

To achieve optimal operation, the IEEE 802.3ah task force has considered the possibility of using both point-to-point and shared medium emulation modes simultaneously. To identify which mode is to be used with each particular data frame, the 16-bit-wide LLID field was divided into a *mode bit* and 15-bit *logicalLinkId*. The mode bit represents the emulation mode with a 0 indicating the point-to-point emulation and a value of 1 indicating the shared-medium emulation. The basic idea was that if the received mode bit is 0, the LTE function at the ONU will accept the frame only if *logicalLinkId* matches itsassigned *logicalLinkId*. If, however, the received mode bit is 1, the LTE function will accept the frame only if the received *logicalLinkId* does not match the assigned value.

The idea of combining different emulation modes did not work out quite well. The SME mode only allowed a single access domain per EPON, which means that a data frame sent by any ONU will reach every ONU. Yet, it was recognized that broadcasting user's frames to all other ONUs is not a desirable feature in subscriber access networks. What is needed is the ability to specify any number of access domains between 1 (SME mode) and *N* (P2PE mode). Such flexibility would allow some access domains, representing individual subscribers, to contain only a single ONU each and other access domains, representing, for example, campuses or distributed corporate LANs, to contain several ONUs.

At various times, the task force considered different ideas to achieve this. One proposal called for the LLID to be a bitmap with every bit mapped to a particular ONU. This would allow 2*N* access domains with any combination of ONUs being able to form an access domain. Clearly, because only a limited number of bits are available in the preamble, this solution is not scalable with the number of ONUs.

A more flexible solution proposed splitting LLID into three fields: mode bit, *logicalGroupId*, and *logicalLinkId*. The *logical-GroupId* essentially identified an access domain. An ONU would only accept frames belonging to the same access domain, i.e., having a matching *logicalGroupId*. Should this proposal be accepted, the ONU's filtering rules would look like the following:

Accept frame only if:

1. *logicalLinkId* is equal to broadcast LLID, or

2. Mode bit is 0 and the received *logicalGroupId* is equal to the assigned *logicalGroupId* and the received *logicalLinkId* is equal to the assigned *logicalLinkId*, or

3. Mode bit is 1 and the received *logicalGroupId* is equal to the assigned *logicalGroupId* and the received *logicalLinkId* is not equal to the assigned *logicalLinkId*.

This solution, as proposed, was limited to only 8 access domains and only 2047 logical links, which was a point of concern. And while technically this solution could be improved, it was proposed too late to be included in the standard.

6.4 Final Solution

Whether it was due to lack of interest or its uselessness in the access environment, the idea of shared emulation died and was buried without a ceremony. The compromise was to retain only the point-to-point emulation and add an auxiliary *single-copy broadcast* (SCB) port at the OLT. In such a configuration, in an EPON with N ONUs, the OLT will contain $N + 1$ MACs: one for each ONU (P2PE) and one for broadcasting to all ONUs (Fig. 22). To optimally separate the traffic, higher layers (above MAC) will decide which port to send the data to.

If the SCB and unicast ports are connected to a 802.1D bridge, it is possible that the *spanning tree protocol* (STP) will detect a loop, since the same ONU will be reachable through virtual P2P link and through virtual broadcast channel. To avoid STP disabling one of the ports that formed the loop, the standard recommends that the SCB port not be connected to a 802.1D bridge. The SCB channel is to be used for

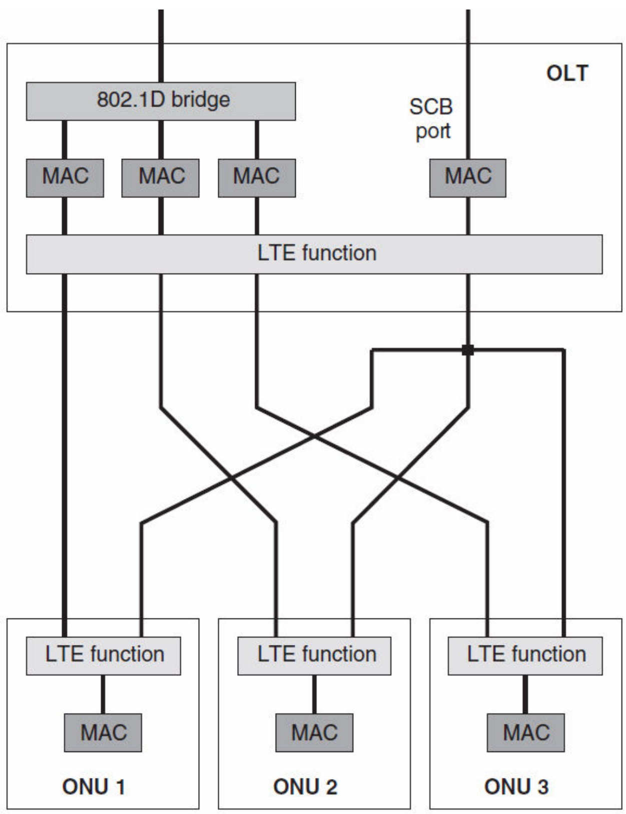


Fig. 22: Combined point-to-point and shared-medium emulation mode.

downstream broadcast only. ONUs are not allowed to send upstream frames with broadcast LLID. The exceptions are several special control frames used for ONU's autodiscovery and registration.

6.4.1. LLID filtering rules

The following LLID filtering rules for the ONU are specified in the standard:

1. If the received mode bit is 0 and the received *logicalLinkId* value matches the assigned *logicalLinkId*, then the frame is accepted.
2. If the received mode bit is 1 and the received *logicalLinkId* value doesn't match the assigned *logicalLinkId*, then the frame is accepted.
3. If the received *logicalLinkId* is a broadcast *logicalLinkId* (has value 0x7FFF), then the frame is accepted.
4. All other frames are discarded by the LTE function.

At the OLT, the filtering rules are the following:

1. If the received *logicalLinkId* is a broadcast *logicalLinkId* (has value 0x7FFF) and a virtual port exists with an assigned broadcast *logicalLinkId*, then the frame is accepted and is transferred to this port.
2. If the received *logicalLinkId* is any value other than the broadcast *logicalLinkId* and a virtual port exists with an assigned mode bit 0 and an assigned *logicalLinkId* matching the received *logicalLinkId*, then the frame is accepted and is transferred to this port.
3. All other frames are discarded by the LTE function. Even though the shared emulation mode died, its legacy in the form of the mode bit lived on. One may reasonably argue that the final specification is awkward, as neither is the mode bit necessary nor is its usage well defined. For example, if the OLT transmits a frame with a mode bit set to 1 and the *logicalLinkId* different from any assigned *logicalLinkId*, such frame will be accepted by every ONU. The same effect will be achieved if the frame is transmitted with the broadcast *logicalLinkId*. In effect, the mode bit simply reduces the available LLID address space almost by one half.

7. FTTH PROJECT MODEL OF THE PON NETWORK

7.1 Design of Project model solution for 90 houses

Choosing FTTH as the project for building a network of 90 private houses is the best and most practical solution, to deliver high quality service and delivering Triply-Play to every house, provided and Centrally controlled by the Central Office of the telecom company, Based on GEPON Technology.

- Because of undefined locations of the houses in the project I virtualized 3 location division areas and other 3 subdivision areas, resulting of 6 allocations, all set in one small geographical given area presenting the 90 private house distant 20km from the Central office.

7.1.1 The Network Project design model

The connection design will be set as follows:

- Each end user private house is connected over one fiber.
- The fiber is terminated with an Optical Network Unit ONU in the subscriber's private house.
- Whole network is based on GEPON Technology.
- With choosing of GEPON its possible to connect up to 32 subscribers to 1 port of the OLT.
- 1 Optical Line Terminal (OLT) in the central office, which is 20km distant for the given area, for Centralized, controlling of all the network connection links.
- 3 feeder fiber will root from the same OLT using 3 ports of the OLT unit which is capable of centralized connection for up to 256 end users, the OLT contains 8 ports that we could use for connecting several other networks, and future proof solution model for further increase of end users in the future.
- 3 ports will be used from our OLT providing us with 3 feeder fibers.
- The 3 feeder fiber will measure 20km long for each.
- On the other side each feeder fiber will be split in the ratio of 1:2, by one 1:2 splitter, and then met with 2 splitters each of 1:16 for each line. This will result of total number of 3 splitters, connecting 32 subscribers to one port.
- Same scenario is repeated for the other 2 feeder fiber.

- This will result of a total number of 9 splitters provident network connections for 96 ONUs, which will cover for us all 90 houses and will also leave us with spare 6 lines to use.

This allocation and choice of the number of splitters is based on providing each house with optimal service, we would have been able to use different numbering of splitters that will not much affect the whole network quality, such as directly connecting each feeder fiber with a 1:32 splitter, using 3 splitters in total, But I tried to provide optimal solution, have taken into consideration the density of connecting points and the geographical allocation of each house, giving us the flexibility to better navigate through 6 division areas and root connection closer to location divisions of the given area.

7.1.2 The Network Project design model diagram

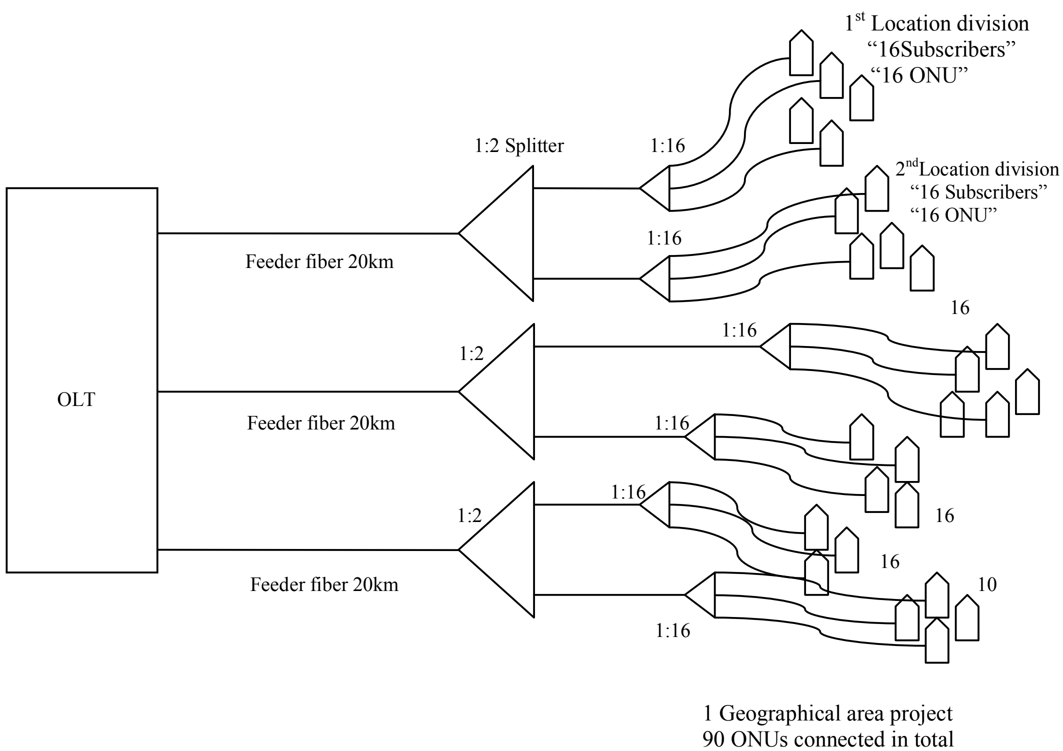


Fig. 23: The network design model diagram of the Project

The diagram illustrates the network project design model as was described above in *7.1.1 The Network Project design model*

OLT is a central element and the heart of FTTH-PON network. This element communicates with all the ONU unit clients, assigns them their defined profiles, advance QoS politics. This communication is bilateral and in the direction of ONUs communicates with the broadcast. And in the reverse direction received from client units, it defines for each unit the time the communication will take.

7.1.3 Monitoring solution for the Project

The development of the optical networks has led to the problem of checking individual fibers and the whole network. Operation outage can be monitored in the electrical layer of transmission. To insure security and continuous operation of our design project, the fibers can simply be monitored as follows:

- Optical supervision is run on the 1625 nm wavelength.

- The principle may be based on the direct transmission method or on the application of OTDR.

- The drop interruption of transmission is detected and failure state can be transmitted to the dispatching center.

- Suggesting of a solution for our network design model is to use MLS (Monitoring Line System) which is a registered and most elaborated system in the market the moment.

Benefits of the MLS system

- Can save money to the user of leased fiber networks in claiming downtimes.
- Administration of the software can be done through a web interface.
- In case of alarm, MLS immediately send a warning via e-mail and/or SMS messages.
- Fast and efficient detection of a problem in the network.
- Localization in short-time and temporary changes in optical routes

7.2 Choosing Ethernet PON:

In the previous chapters 4, 5 and 6 I have given in depth study analysis and research of EPON which explains why I went for choosing EPON, here I will briefly summarize the reason of choosing Ethernet PON for my FTTH model design solution.

In 1995, when the FSAN initiative was started, there were high hopes of the ATM becoming the prevalent technology in the LAN, MAN, and WAN. However, since that time, Ethernet technology has leapfrogged ATM. Ethernet has become a universally accepted standard, with over 320 million ports deployed worldwide, offering staggering economies of scale.

High-speed gigabit Ethernet deployment is widely accelerating, and 10-Gigabit Ethernet products are becoming available. Ethernet, which is easy to scale and manage, is gaining new ground in MAN and WAN. Given that more than 95 percent of enterprise LANs and home networks use Ethernet, it becomes clear that ATM PON may not be the best choice to interconnect two Ethernet networks.

One of the shortcomings of the ATM is its high overhead for carrying variable-length IP packets, which are the predominant component of the Internet traffic. And perhaps most importantly, the ATM did not live up to its promise of becoming an inexpensive technology—vendors are in decline and manufacturing volumes are relatively low. ATM switches and network cards are significantly more expensive than Ethernet switches and network cards.

Ethernet is a logical choice for an IP data optimized access network. Newly adopted *quality-of-service* (QoS) techniques have made Ethernet networks capable of supporting voice, data, and video (Triple-Play).

These techniques include full-duplex transmission mode, prioritization, and *virtual LAN* (VLAN) tagging. Ethernet is an inexpensive technology, which is ubiquitous and interoperable with a variety of legacy equipment. It is not surprising that Ethernet is poised to become the architecture of choice for next-generation subscriber access networks.

Both BPON and GPON architectures were conceived by the ITU-T group, which is driven by major incumbent telecommunications operators. Most of the operators are heavily invested in providing legacy TDM services. Accordingly, both BPON and GPON are optimized for TDM traffic and rely on framing structures with a very strict timing and synchronization requirements.

In BPON, an upstream frame consists of 53 timeslots, where each timeslot is comprised of one ATM cell and 3 bytes of overhead. When two consecutive timeslots are given to different ONTs, these 3 bytes or approximately 154 ns of the overhead should be sufficient to shut down the laser in the first ONT, turn it on in the second ONT, and perform gain adjustment and clock synchronization at the OLT.

Similarly, very tight timing is specified for GPON. For example, in GPON with a 1.244 Gbps line rate, only 16-bit times (less than 13 ns) are allocated for the laser-on and laser-off times. Such short intervals require more expensive, higher-speed laser drivers at the ONT. A very tight bound of 44-bit times (less than 36 ns) is allotted for the gain control and clock recovery. In many cases, the dynamic range of the signal arrived from different ONTs will require a longer AGC time than the allotted overhead (guard interval). To reduce the range of necessary gain adjustment, BPON and GPON perform a power-leveling operation, in which the OLT instructs individual ONTs to adjust their transmitting power, so that the levels of signals received at the OLT from different ONTs are approximately equal.

The IEEE 802 work group has traditionally focused on enterprise data communication technologies. In EPON, the main emphasis was placed on preserving the architectural model of Ethernet. No explicit framing structure exists in EPON, the Ethernet frames are transmitted in bursts with a standard inter-frame spacing. The burst sizes and physical layer overhead are large in EPON. For example, the maximum AGC interval is set to 400 ns, which provides enough time to the OLT to adjust gain without ONTs performing the power-leveling operation.

As a result, ONTs do not need any protocol and circuitry to adjust the laser power. Also, the laser-on and laser-off times are capped at 512 ns, a significantly higher bound than that of GPON. The relaxed physical overhead values are just a few of many cost-cutting steps taken by EPON.

Another cost-cutting step of EPON is the preservation of the Ethernet framing format, which carries variable-length packets without fragmentation. In contrast, both BPON and GPON break the packets into multiple fragments. GPON employs the *GPON encapsulation method* (GEM) to enable packet fragmentation. This method uses a complicated algorithm to delineate variable-size GEM segments and reconstruct the packets at the receiving device. Given the level of complexity of the GPON or tight specification for various physical-layer parameters, it is very doubtful that the cost of GPON equipment can match that of an EPON.

Where EPON fulfills the requirement and being able to provide good Triple-Play services for each home in a network with a splitter of 1:32, with this EPON 1Gbps of symmetrical bandwidth in both directions, where also it is a real investment and a future proof solution with EPON 10Gbits for even more advanced Triple-Play services.

First let us analyze Triple-Play by understanding its requirements.

7.2.1 Triple-Play service requirements:

For advanced Triple-Play, the transmission of voice, data and video to the home services, has a total required downstream bandwidth that could vary between 28 and 44 Mbits/s, when factoring in multiple channels of high definition IPTV, high-speed Internet access, and voice over Internet protocol (VoIP).

Besides the massive amounts of data that will be flowing to the user home, the network should handle the flow of content being generated by users. Using digital video and still cameras, personal computers, and the software to edit and produce content, consumers are generating and distributing large amounts of content that are uploaded from the user premises (witness the popularity of YouTube and Google Video), To ensure good quality of service and a favorable experience, users need much symmetric high upstream bandwidth as well.

Downstream Service	**Downstream Bandwidth(Mbits/s)**
HDTV (Two per household, 9-12 Mbits/s per H.264 channel)	18-24
High-speed Internet	10-20
IP Voice (four channels)	0.25
Total required downstream bandwidth	28-44 Mbits/s

Tab. 3: Triple-Play Bandwidth Requirements

From these requirements and from previous table of PONs technologies and TDM overview, it’s clear that FTTH TDM-PON is the best answer at the present state, and EPON is the optimal protocol technology and my choice as an analytical answer of the design and the used technology in FTTH for Triple-Play service, and we should keep in mind that it is the future proof solution with EPON 10Gbits for even a more advanced Triple-Play service.

7.3 Network general design architecture

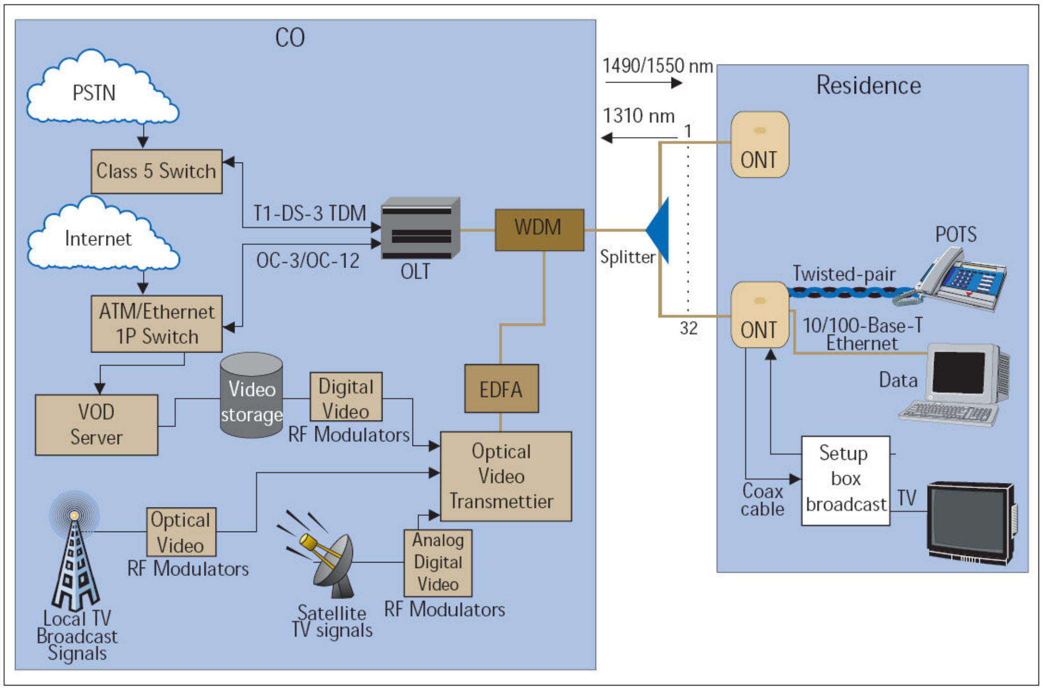


Fig. 24: Network General Design

The general architecture of an FTTH network, where at the central office (CO), also called the headend, the public switched telephone network (PSTN) and Internet services are interfaced with the optical distribution network (ODN) via the optical line terminal (OLT).

The downstream 1490 nm and upstream 1310 nm wavelengths are used to transmit data and voice. Video services are converted to optical format at the 1550 nm wavelength by the optical video transmitter. The 1550-nm and 1490-nm wavelengths are combined by the WDM coupler and transmitted downstream together. At present, there are no plans for upstream video transmission.

In total, the three wavelengths (1310, 1490 and 1550 nm) carry different information simultaneously and in various directions over the same fiber through the FTTH Network. The feeder cable carries the optical signals between the CO and the splitter, which allows a number of ONTs to be connected to the same feeder fiber. An ONT is required for each subscriber and provides connections for the different services (POTS, Ethernet, and video). Mainly one FTTH network typically provides service to up to 32 homes (subscribers), many such networks (originating from the same CO) are usually required in order to serve a community. There are different architectures for connecting subscribers to the PON. The simplest uses a single passive splitter, but multiple splitters can also be used but the total sum wont exceeding 32 unless we use EPON 10G which is sufficient enough for up to 64 end terminals.

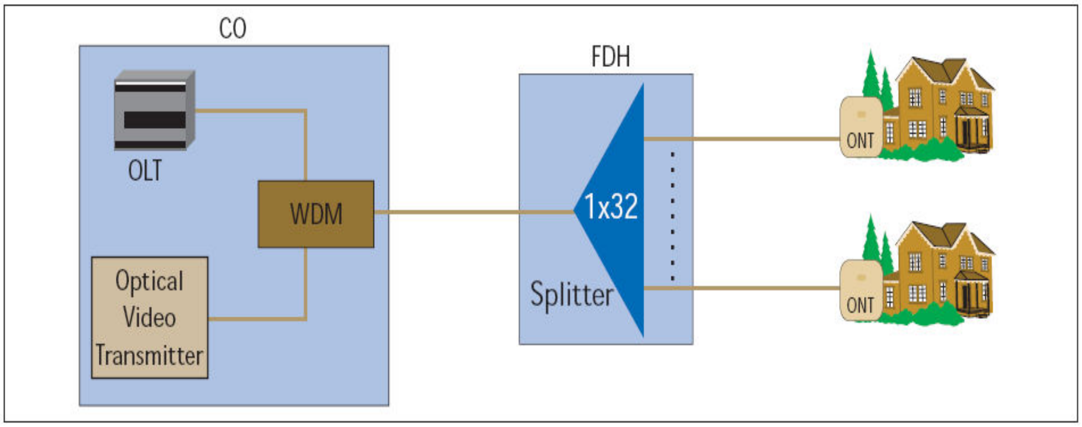


Fig. 25: Single 1:32 splitter FTTH network

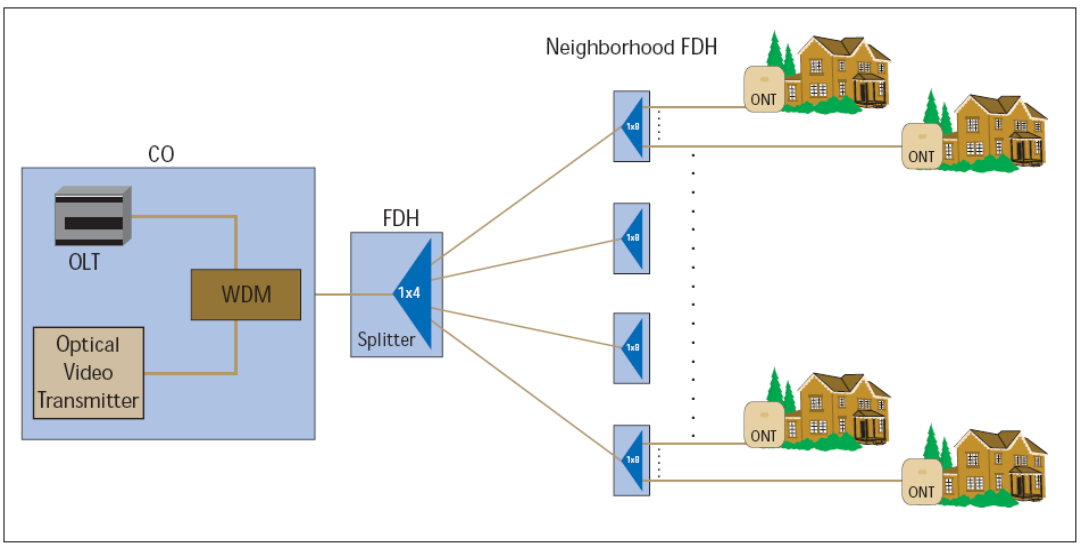


Fig. 26: FTTH network with multiple splitters

WDM couplers are used to multiplex the downstream voice/data signal at 1490 nm with the downstream video signal at 1550 nm and the upstream voice/data signal at 1310 nm. Because of their wide wavelength range and low-coupling-loss, thin-film filter technology, WDM couplers are typically the preferred devices to perform this task.

7.3.1 Collision avoidance in upstream transmissions:

In the upstream direction (towards the OLT), a PON is a multipoint-to-point network. This may cause the data to collide.

So to prevent collisions of data from different ONT signals arriving at the splitter at the same time, we should use time-division multiple access (TDMA). TDMA can send burst data from each ONT back to the OLT, at a specific time. Each ONT transmission time slot is granted by the OLT so that the packets from various ONTs do not collide with each other.

7.3.2 OSP equipment:

Outside plant (OSP) equipment consists of equipment and components located between the CO and the customer premises. This includes both optical and non-optical components of the network. The optical components make up the optical distribution network (ODN) and include fiber-optic cables, WDM coupler patch cords, splices, connectors, splitters and drop terminals. The non-optical components include pedestals, splice closures, vaults, patch panels, and miscellaneous hardware.

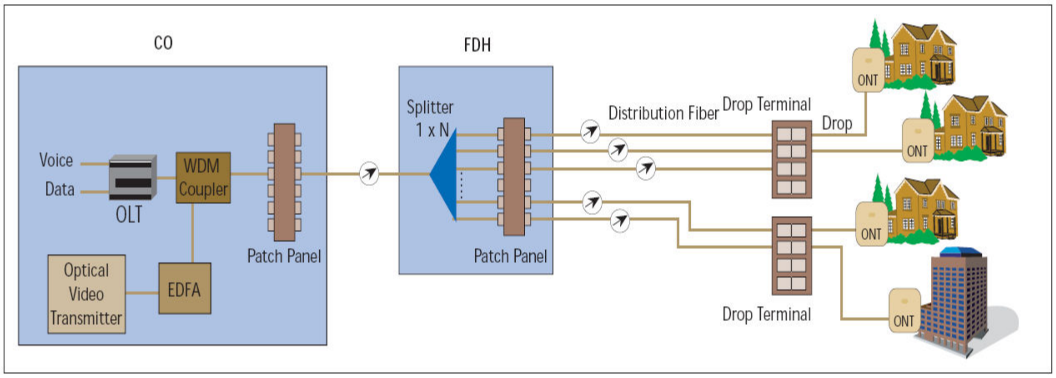


Fig. 27: OSP equipment

The OSP includes:

- CO fiber distribution units (or patch panels).
  - Fiber-optic cables. The feeder cables form the segment between the CO and the first splitter. Distribution fibers link the splitter to the drop terminals near the subscribers. Drop cables connect the individual ONTs to the drop terminal.
  - Fiber distribution hub(s) include:
    - Cabinets, pedestals, splice enclosures (aerial or buried)
    - Splitter(s)
    - Patch panel(s)
    - Fiber management elements

- Drop terminals.
- Connectors: SC/APC (8° slope on ferrule reduces reflections, typical loss ≤ 0.5 dB)

And we should note that On account of Rayleigh scattering, macro bending, and the like, fiber-optic cables introduce signal loss (attenuation) that is proportional to their length.

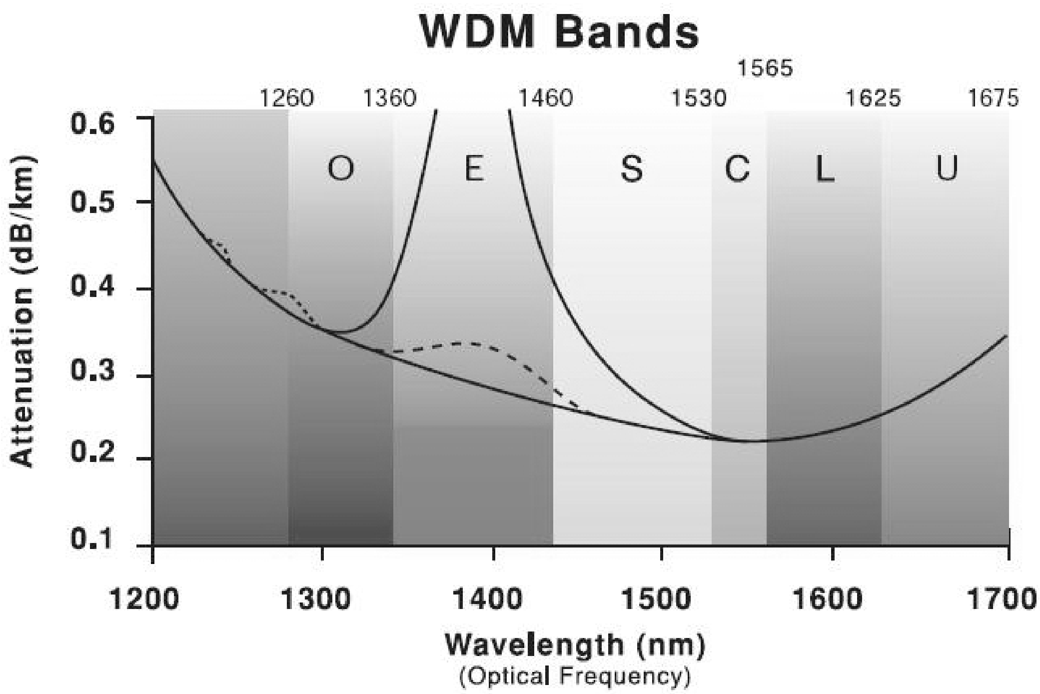


Fig. 28: Spectral attenuation

O = Original band E = Extended band S = Short band C = Conventional band L = Long band U = Ultra-long band.

7.3.3 Splitters:

The bidirectional optical branching device used in the PON is called a splitter, which has one input port and multiple output ports. The input (downstream) optical signal is divided among the output ports, allowing multiple users to share a single optical fiber and consequently a shared bandwidth. In the upstream direction, optical signals are combined from a number of ONTs into the single fiber.

Splitters are passive devices because they require no external energy source other than the incident light beam. They are broadband and only add loss, mostly due to the fact that they divide up the input (downstream) power. This loss, called splitter loss or splitting ratio, is usually expressed in dB and depends mainly on the number of output ports, as I show it in the table below. It should be noted that, contrary to what one might expect, the splitter adds approximately the same loss even for light traveling in the upstream direction.

Splitters and patch panels are installed in cabinets or pedestals. There may be one splitter or several cascaded splitters in the FTTH network, depending on the network topology. ITU-T recommendation G.983 currently allows split ratios up to 32 as well as IEEE 802.3ah, while recommendation G.984 extends this to up to 64 splits. Regardless of the topology, the splitter must accommodate the allowed optical loss budget (Class A, B or C).

Number of Ports	**Splitter Loss (dB) (excluding connectors an excess splitter loss)**
2	3
4	7
8	10
16	13
32	17
64	21

Tab. 4: Splitter loss

Splitters can be packaged in different shapes and sizes depending on the basic technology used. The most common types are the planar waveguide (typically for high split counts) and the fused-biconic taper (FBT) fiber coupler (typically for low counts). Both types are all manufactured for mounting in closure tray assemblies.

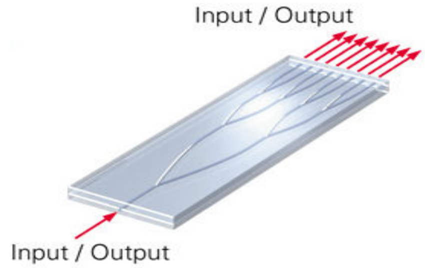


Fig. 29: Planar waveguide 1:8 splitter

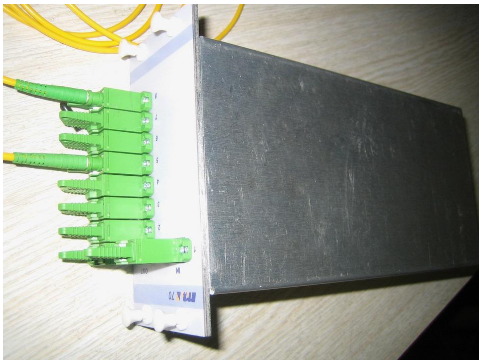


Fig. 30: Real world picture of planar waveguide 1:8 splitter

Active equipment:

The active equipment includes:

- The OLT (voice/data transmitter/receiver), located at the CO.
- Video equipment (transmitter) and the erbium-doped fiber amplifier (EDFA) used to amplify the video signal before transmission through the WDM coupler.
- The ONT, its power supply and battery backup, located at the customer premises.

PON OSP Installation:

Installation of outside plant (OSP) equipment in an FTTH network can be carried out in many ways and each installation may be different, depending, for example, on the distance from the CO, residential density and distribution, etc. Fiber-optic cables can be installed using the most appropriate aerial or underground installation techniques. The placement of splitters and other passive components, and the types of pedestals or cabinets used will depend on geographical factors and on the PON topology.

7.3.4 Fibers:

Fiber-optic cable installation is one of the most costly elements in PON deployment, as it is in other fiber-optic network technologies. Several methods are available. The choice of method depends on various factors including cost, right-of-way, local codes, aesthetics, etc, and on whether the installation is being performed in a new development (Greenfield installation) or in an existing development over existing routes (overlay/overbuild).

Three basic cable-installation methods:

- The direct burial method places the cable underground in direct contact with the soil. This is done by trenching, plowing or boring.
- A duct installation involves placing the optical cable inside an underground duct network. Although the initial duct installation is more expensive than a direct burial installation, the use of ducts makes it much easier to add or remove cables.
- Aerial installations involve the placement of the cable on poles or towers above the ground. This type of installation, commonly used for overbuilding, is usually more affordable than underground installation and does not require heavy machinery. The optical cable can be lashed to a supporting messenger cable, or self-supporting optical cables can be used. For densely populated areas with particular right-of-way challenges, several alternative methods are available, such as installing

the cable in grooves cut into the pavement, inside drainpipes, inside sewer pipes, and inside natural gas pipelines.

7.3.5 Splices:

Splices can be mechanical or fused. Mechanical splices are the least expensive but have higher insertion losses (0.2 dB) and back reflections. Fused splices have very little loss (0.02 dB) and almost no back reflection but require typically expensive fusion splicing equipment. The number of splices depends on the cable section lengths used (typical sections lengths are ≤ 2 km, 4 km and 6 km). Splices are protected from the environment by splice closures.

7.3.6 Drop terminals:

Drop terminals can be aerial, underground or located in apartment buildings, depending on the installation field. Cable drops between splitter and premises are sometimes pre-connectorized and can be buried or aerial-mounted.

8. TESTING AND MODEL MEASURMENT

Here I will clarify the testing procedures that could be applied during the PON installation and the testing after activating the service, but I will start this chapter with the testing procedure of after activating the service, since I will go deeper describing the PON installation testing methods and practical tests and measurements later on.

8.1 Service Activation Testing:

8.1.1 OLT (initial service activation only)

Optical power measurement at the OLT is required to ensure that sufficient power is delivered to the ONTs. This is done only during the initial activation because it cannot be repeated without interrupting service for the entire network. To perform this measurement, we should disconnect the feeder fiber and measure the power directly at the output of the WDM (combining video and OLT power).

Two methods can be used:

- An OPM measures the total optical power. Optical filters can be used to measure the power at each individual wavelength, one wavelength at a time.

- A wavelength-separating PON power meter measures the power of each wavelength simultaneously. Power thresholds can be set in order to provide Pass, Warning or Fail status for each wavelength.

After reconnecting the feeder fiber, perform a similar test at the FDH, measuring the power at each splitter output.

8.1.2. Optical network terminals (ONT)

Each time a new ONT is added to the PON, the downstream and upstream optical power at the drop should be measured. The preferred method is to use a wavelength separating PON power meter that can be connected as a pass-through device.

Another method is to use an OPM and filters; however, this method does not allow measurement of the upstream signal, nor pass-through operation.

Fig. 31: EXFO's PPM-350 PON Power Meter

A PON power meter should be connected as a pass-through device between the drop and the ONT. This type of instrument simultaneously measures the downstream power at 1550 and 1490 nm, and the upstream power at 1310 nm. Unlike an OPM, which measures the average power of an optical signal, the PON power meter detects the power of the ATM traffic bursts in order to provide accurate measurement.

The downstream power at 1550 and 1490 nm must meet the minimum ONT receiver sensitivity (depending on the PON class). The upstream power should correspond to the ONT specifications.

Similarly, the upstream power at 1310 nm must meet minimum criteria to be properly detected at the OLT. Knowing the worst-case optical power budget, it is simple to define a minimum optical power value that the 1310 nm signal must have right at the ONT output.

When all problems have been corrected and the measured power level at the drop is sufficient, we connect the drop directly to the ONT.

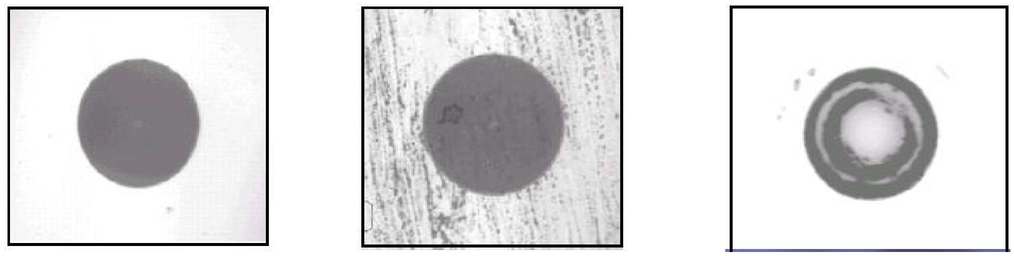
8.2. PON Installation Testing:

Before going in to testing methods, we should properly inspect the connector as it's a main step of the whole testing process.

Connector Care:

Proper cleaning and inspection must be performed using a high magnification fiber inspection probe (minimum 400X) on each patch panel, test jumper and cable connector. All the connectors should be inspected and, if necessary, cleaned before testing, includes new factory-delivered jumpers and cables.

Connector Inspection



View of a clean connector View of a clean connector Damaged connector

Fig. 32: Connector Conditions

Inspection Instructions

1. Connect the probe to the connector that will be inspected.
2. Adjust magnification.
3. Inspect and clean the connectors:

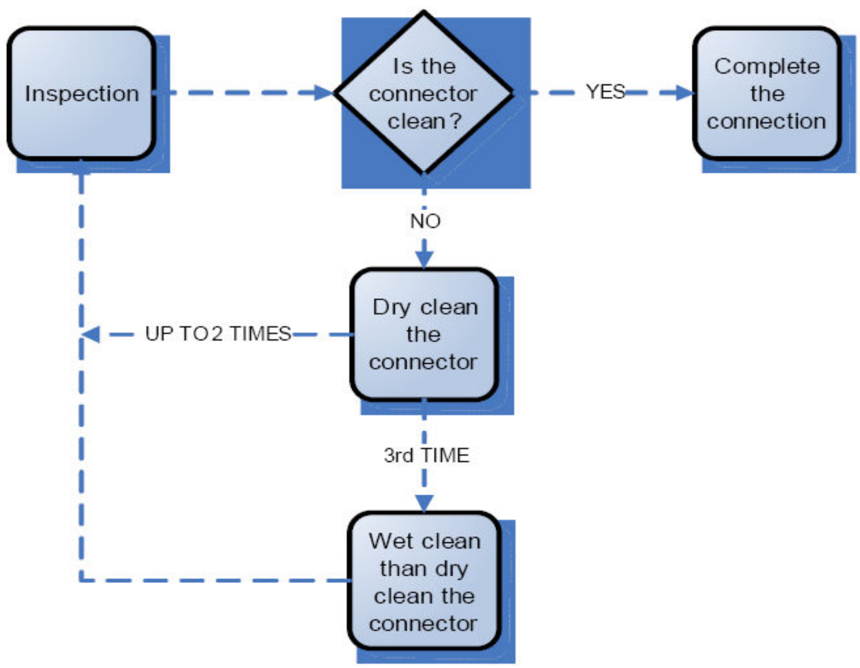


Fig. 33: Inspection procedure

. When testing in a patch panel, only the port corresponding to the fiber under test should be uncapped—protective caps should be replaced immediately after testing.

. If a launch cord is used for OTDR testing, we should not use a test jumper in between the OTDR and launch cord or in between the launch cord and the patch panel.

. Different tips for fiber inspection probe are available to match the connector type: angle-polished connectors (APC) and flat-polished connectors (PC, SPC or UPC).

The purpose of any fiber-optic network is to perform high-speed, error-free data transmission. Adequate testing during network installation will minimize costly and time-consuming troubleshooting efforts by locating questionable splices, dirty or damaged connectors, and other faulty components before they disrupt service.

One of the most important factors in ensuring proper transmission is controlling the power losses in the network against the link loss budget specifications. This is done first by establishing a total end-to-end loss budget with sufficient margin. In addition, back reflections must be reduced to a minimum. This is particularly true for high power analog video signals from very narrowband lasers because strong backreflections will degrade the quality of the video transmission.

Adequate loss and backreflection testing is important to ensure that at each transmission wavelength:

- End-to-end loss and back reflection meet the specifications; and
- Upon questionable results, each segment meets or exceeds the requirements. These tests are critical, especially when the network includes older cables, because fibers designed for use at 1550 nm, for instance, may not have been previously qualified for use at 1490 nm and may show higher attenuation than expected.

I should note that ratio of the output power to the input power of a device is called the attenuation and has a positive value. When a device is inserted in an assembly, the attenuation is called the insertion loss and has a positive value.

Installation tests:

The three main optical tests to be performed during installation are:

- Bidirectional optical return loss (ORL) measurement
- Bidirectional end-to-end optical loss measurement
- Bidirectional end-to-end link characterization

Useful test instruments may include an ORL meter, optical loss test set (OLTS), visual fault locator (VFL), live fiber detector (LFD), optical time-domain reflectometer (OTDR), and a wavelength-separating PON power meter. The PON power meter should be capable of measuring the burst power of the ATM or Ethernet traffic. A VFL injects a bright red laser light into the fiber to find faults, bad splices, breaks and macrobends visible to the naked eye. An LFD is used to detect fibers transmitting traffic.

Test setup for ORL and optical loss measurement

Because communication over the fiber is bidirectional, the ORL must be measured in both directions. Using an ORL meter or compatible optical loss test set (OLTS) at each end of the link, the ORL should be measured first in one direction, then in the opposite direction. The OLTS can be used for measuring both ORL and optical loss at the same time.

8.2.1 Test 1: ORL Testing:

ORL is defined as the ratio of reflected power to incident power and is measured at the input of a device under test (DUT), such as a fiber-optic segment or link. ORL is given in dB units and is a positive number. Reflectance, on the other hand, is a negative number and is defined as the reflection from a single interface or event, such as a transition from a fiber end (glass) to air.

Link ORL is made up of Rayleigh backscattering from the fiber core and the reflectance from all the interfaces found along the link. ORL can be a problem in digital DWDM and high-speed transmission systems such as OC-48 and OC-192 systems, but is particularly critical for analog transmission, such as the 1550 nm CATV signals used in FTTH systems (e.g., analog video in a PON).

Fig. 34: the test meter FOT-930 measuring ORL in the laboratory.

While Rayleigh backscattering is intrinsic to the fiber and cannot be completely eliminated, reflectance is caused by different network elements (mainly connectors and components) with air/glass or glass/glass interfaces and can always be improved by special care or better designs. To optimize transmission quality, backreflection effects (e.g., light-source signal interference or output power instability) must be kept under control. Therefore, attention must be focused on ensuring quality network connections through highly accurate ORL measurements.

The main effects of ORL include the following:

- Causes strong fluctuations in the laser output power
- Causes interference at the receiver end
- Lower carrier-to-noise ratio in analog systems which leads to distortions on video signals
- Higher bit error rate (BER) in digital systems
- Can permanently damage the laser

Needed Equipment

Test setup for measuring the ORL and the optical loss. ORL is measured using an ORL meter (or ORL test set). The ORL meter includes a source and an optical power meter (OPM) to measure reflected power. Some OLTSs can perform this test, making a dedicated ORL meter unnecessary. Either one can provide a total end-to-end ORL of the system.

The Procedure

The ORL meter should be calibrated before use, and before connecting or splicing cables, we should measure the ORL for each section and each splitter branch separately. We should perform the ORL test in both directions and check for uniformity at the different splitter ports.

Once all connections are made, we measure ORL end-to-end between each drop and the OLT, So the higher the ORL reading, the better.

8.2.2. Test 2: Bidirectional Loss Testing:

Optical loss is defined as the difference in power level between the transmitting source and the receiving power meter. The total optical system/link loss is the sum of the insertion loss (IL) of the OLT connector, WDM coupler, splices, fiber attenuation, splitter, ONT connector and any bad connector matings. IL is the loss of optical energy resulting from the insertion of a component or device in an optical path.

When the network is designed, a loss budget is established. This is a detailed analysis designed to ensure that the receiver will receive the level of power required for error free transmission. The loss budget takes into account the transmitter power and the receiver sensitivity, as well as the expected loss of every optical component in the network. The loss budget requirement for the PON, based on ITU Rec. G.983 is shown in the following table.

Class	ITU-T Rec.	Loss (dB)	
		Min	Max
A	983.3	5	20
B	983.3	10	25
B	984.2	10	22
C	983.3	15	30
C	984.2	15	27

Tab. 5: PON Power Budget Requirements for single-fiber topology

The splitters in a PON cause an inherent loss because the input power is divided between several outputs. Splitter loss depends on the split ratio and is approximately 3 dB for a 1:2 splitter, increasing by 3 dB each time the number of outputs is doubled. A 1:32 splitter has a splitter loss of at least 15 dB. This loss is seen for both downstream and upstream signals. Splices or connectors at the splitter ports create an additional loss.

An example of a PON loss budget is shown in the following table. In this example, no loss from dispersion or any non-linear effects are taken into account (only 1 dB loss would be expected for very high-bit-rate systems at 1550/1490 nm). Based on the worst-case total loss of 25 dB (at 1310 nm), this system would meet a class B loss budget but with no margin. The worst loss comes from the splitter (68%) and its loss would need to be improved, otherwise class C transmission would be required to guarantee the loss margin.

	Loss (dB)	Number/Length	Total Loss (dB)
Splitter (1:32)	~ 16 - 17	1	17
WDM Coupler (1:2)	~ 0.7-1.0	1	1
Splice (fused)	~ 0.02-0.05	4	0.2
Connector (APC)	~ 0.2	2	0.4
Fiber G.652C			
1310nm	~ 0.35/km	18.2 km	6.4
1490nm	~ 0.27/km		4.9
1550nm	~ 0.22/km		4.0
Total Loss (dB)			
1310nm			25.0
1490nm			23.5
1550nm			22.6

Tab. 6: Loss budget scenario (worst case: 18.2 km maximum)

Needed equipment

Loss can be measured using a separate source and an OPM. A basic OLTS consists of a light source and an OPM, while an advanced OLTS consists of a light source and OPM combined into one unit and is particularly useful for bidirectional testing, automatic referencing and results analysis. Some of the more advanced OLTSs can perform automatic bidirectional end-to-end loss and ORL tests together, also providing an estimate of the link distance and chromatic dispersion.

Testing Procedure

Before connecting or splicing cable fibers, we measure the optical loss for each cable section and each splitter branch separately.
We perform the loss test in both directions, and we check for uniformity at the different splitter ports.

Once all connections are made, we measure the end-to-end loss between each drop and the OLT. Total loss should not exceed the loss budget; otherwise, error-free transmission may not be possible.

Measurement should always be performed at the output of the patch panel to ensure that the connector mating is taken into account.

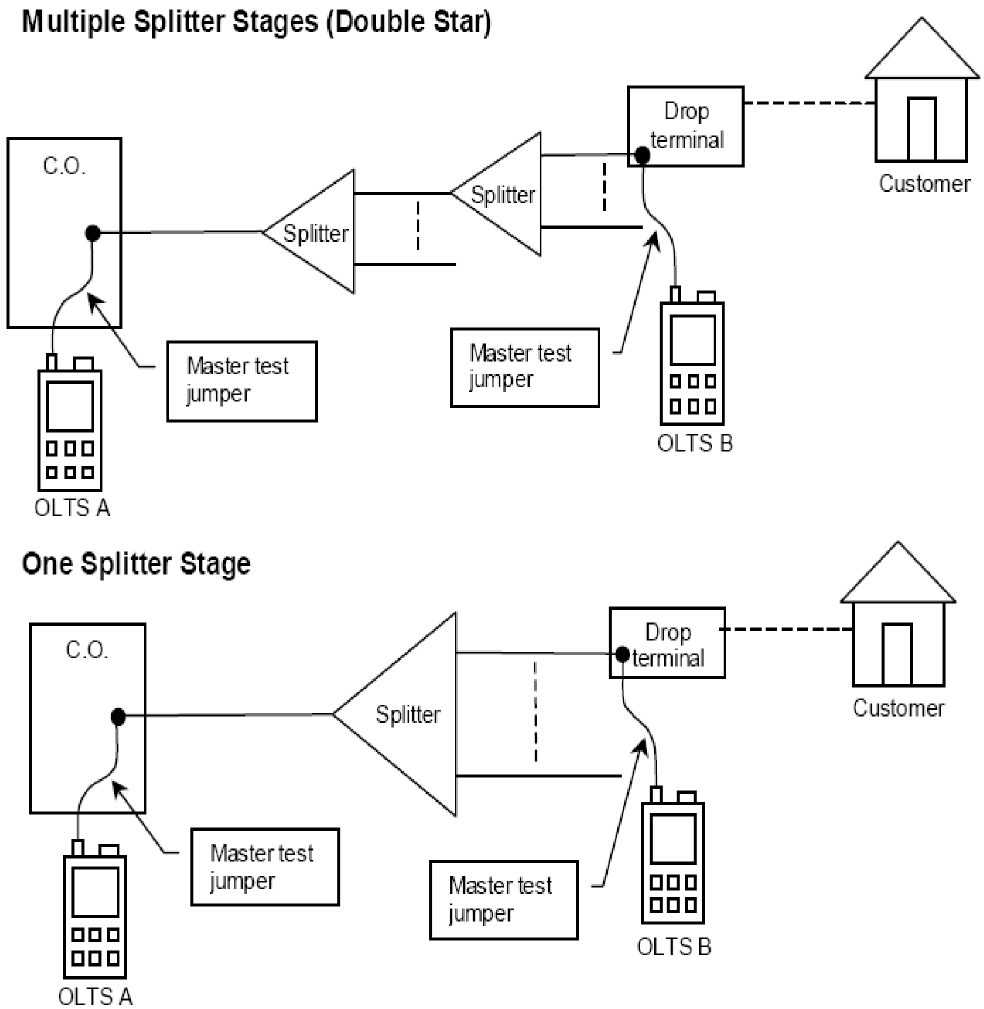


Fig. 35: Bidirectional loss testing

8.2.3 Test 3: Link Characterization Using an OTDR

Tests carried out at the BUT Telecommunications department laboratory, during PON installation, it is important to ensure that each cable section meets or exceeds the cable specifications. This can best be accomplished by using an optical time-domain reflectometer (OTDR).

While applying this test personally in BUT Telecommunication Department Laboratory this test is different than the OLTS, which characterizes the overall loss of an entire link using two instruments, an OTDR provides a detailed map of all of the section losses, allowing the users to locate and characterize every individual element in the link, including connectors, splices, splitters, couplers, and faults.

An OTDR operates by sending a high-power pulse of light down the fiber and measuring the light reflected back. Every event in the link (that is, every optical component and optical fault) causes a reflection or an optical loss, or both. Fiber ends and breaks, as well as connectors and other components each reflect a small part of the pulse back to the OTDR. The OTDR uses the time it takes the individual reflections to return to determine the distance of each event.

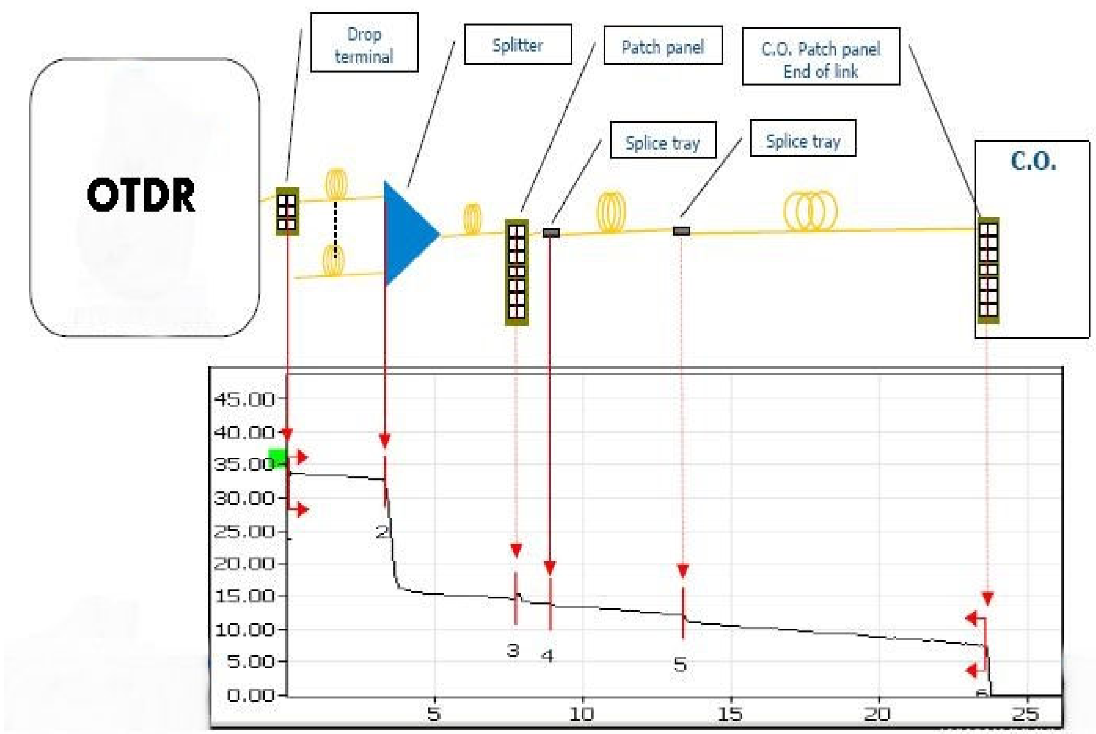


Fig. 36: Upstream complete link characterization including splitter

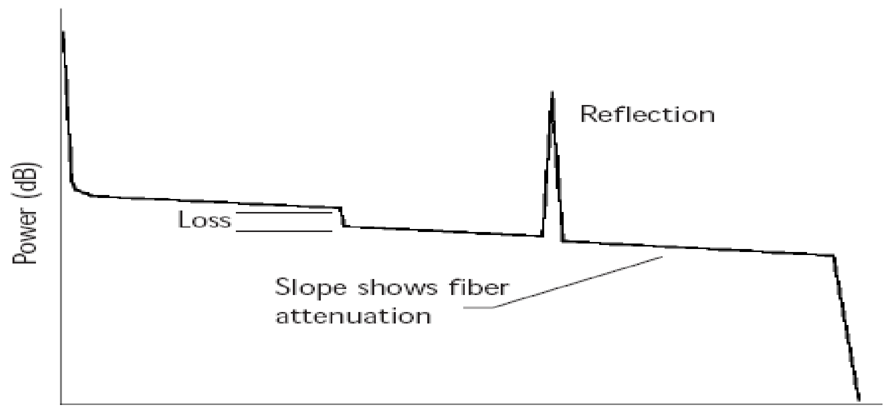


Fig. 37: Cable section mapping from splitter input to WDM coupler output

Optical fibers uniformly backscatter a small portion of the light over their entire length. The OTDR measures this backscattered light to determine the attenuation of the fiber. Sudden reductions in the level of backscattered light correspond to optical losses due to splices or other events. For instance, the fiber attenuation for new G.652.C fibers can be measured over the ranges of wavelengths used in the PON, typically:

• 0.33 dB/km at 1310 nm (0.35 dB/km for worst case)

• 0.21 dB/km at 1490 nm (0.27 dB/km for worst case)

• 0.19 dB/km at 1550 nm (0.25 dB/km for worst case)

The faults that can be detected by the OTDR include misalignments and mismatches, angular faults, dirt on connector ferrules, fiber breaks and macrobends. Macrobends are unwanted events that are caused when a fiber is bent tighter than its minimum bend radius (tie-wrap too tight, etc.), and can easily be detected by comparing the loss at 1310, 1490 and 1550 nm. This is because macrobends have more significant losses at higher wavelengths (1550 nm) than at lower ones (1310 nm). The best available OTDR wavelength for macrobending detection is 1625 nm (the longer the wavelength, the better).

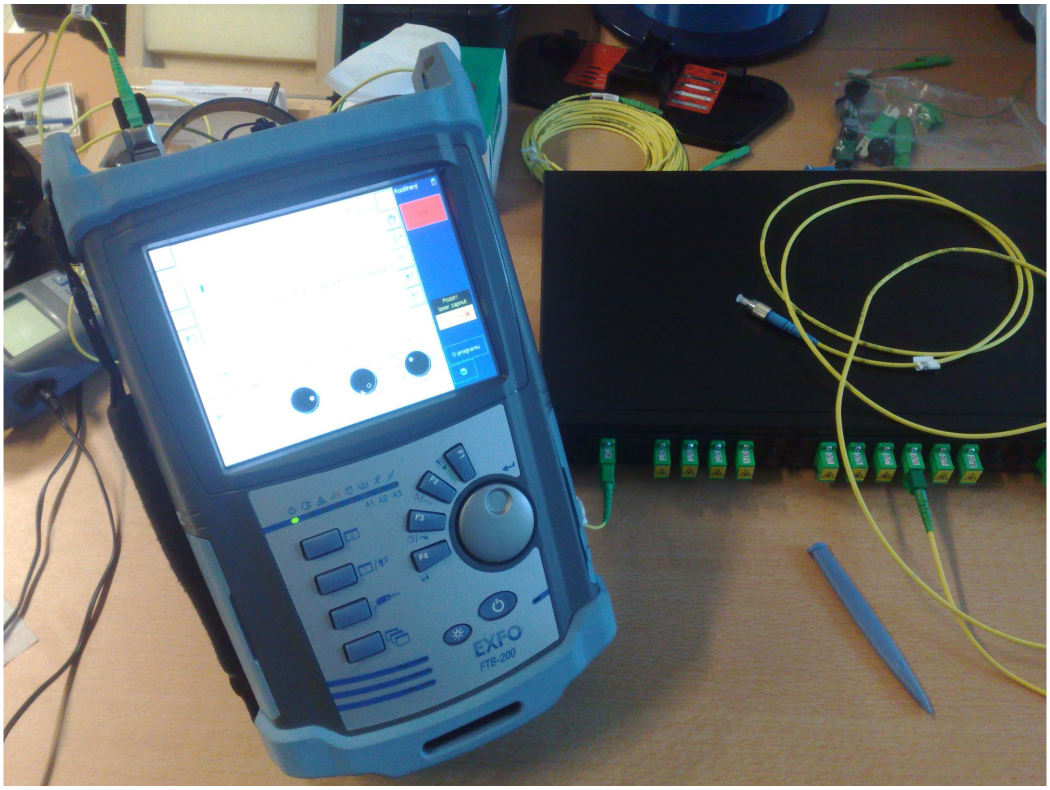


Fig. 38: OTDR connected to the 1:16 planner waveguide splitter

Each fiber should be tested from the OLT at the CO to the splitter, as well as from the splitter to the ONTs, bidirectionally if possible. Several types of events, such as mismatched core size, generate different levels (gainers vs. losses) depending on whether the light comes from one direction or the other. Bidirectional testing provides more accurate results because the loss values measured in each direction can be averaged.

Another important consideration when using an OTDR is the dead-zone phenomenon. Because the detector in the OTDR is very sensitive, it may become saturated by strong reflections, such as from the OTDR output connector and from the first event (connector) in the network. Often, the longest dead zone occurs at the first connection (the OTDR bulkhead connector). Since it is impossible to measure loss within a dead zone, loss due to splices and connectors close to the OTDR launch point cannot be determined under ordinary circumstances. However, the use of a pulse suppressor box (PSB) between the OTDR and the FUT can work around this problem. The PSB contains a length of fiber-optic cable that allows the first connector, as well as events hidden by the dead zone. to be included in the link loss measurement. Loss from the last connector of the FUT can be measured in the same way, by connecting the PSB to the last connector. The PSB enables the OTDR to compare backscattering levels before and after the event to calculate the connector loss.

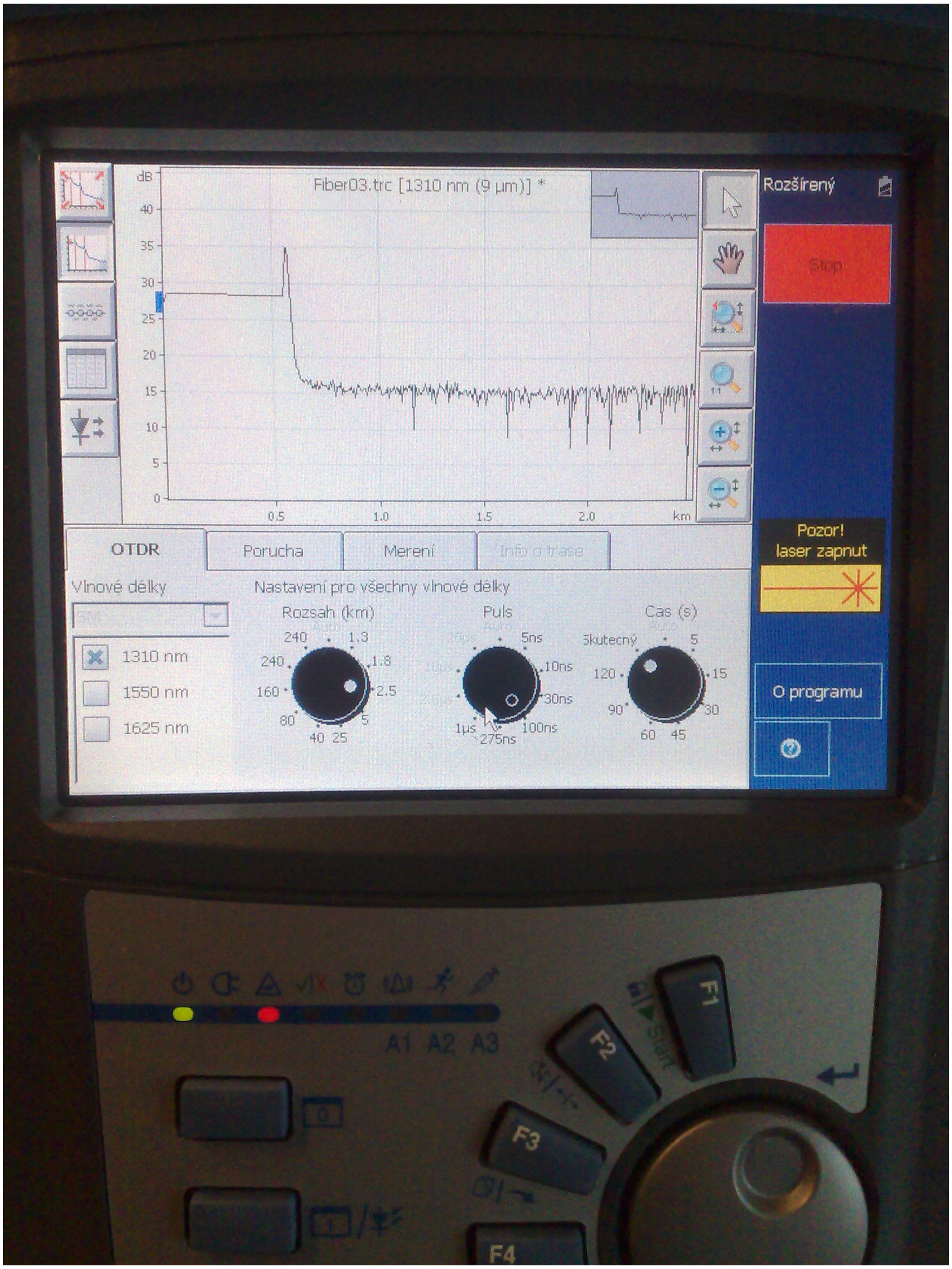


Fig. 39: Using the FTB-200 OTDR for testing in the Laboratory

The end-to-end OTDR measurement enables the characterization of the splitter loss and the total link loss. The OTDR measurement must be conducted upstream (i.e., from the customer premise to the central office (CO)) virtually applying it in the laboratory. Depending on the split ratio, a relatively large pulse must be used. And we should make sure that the last fiber section (feeder fiber) is tested up to the CO.

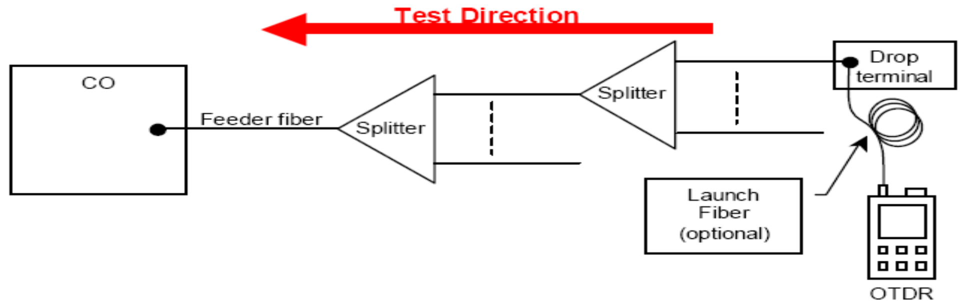


Fig. 40: Test Direction from Drop Terminal to CO

For PON testing, the OTDR should be able to test at three wavelengths (1310, 1490 and 1550 nm). In many cases, however, testing at 1550 nm is considered adequate to cover the 1490-nm region at the same time. It is generally agreed that the fiber attenuation at 1490 nm is approximately 0.02 dB greater than at 1550 nm.

The OTDR analysis software must be well-designed to thoroughly locate all possible types of events, such as reflections, caused by connectors, fiber breaks or ends; losses, caused by splices or macrobends, and gains, caused by imperfect core alignments or diameter differences (delta variations in mode-field diameter). A good-quality OTDR should be able to clearly point out all types of events on the trace to make them easily identifiable to the user, and list the events in an event table.

It is important to select an option that provides a well-designed, easy-to-use interface and features such as signal averaging, report generation and printing, as well as an automatic mode of operation which was all available and provided from the laboratory equipments.

Fig. 41: PON network devices and 1:8 passive splitter

Setting the OTDR

Although many OTDRs have an Auto mode like here in the department laboratory in which the instrument attempts to determine the optimal settings for the link under test, in some situations, it may be necessary to set the parameters manually in order to obtain the desired results. When testing at several different wavelengths, the same settings for all wavelengths, or different settings for each individual wavelength, may be used. In addition, there are usually options for storing test results in a database and for printing reports. The main test parameters are described below.

- **Distance range:** determines the maximum distance at which the OTDR will detect an event and should normally be set to cover the entire length of the link, unless you wish to test only part of the link at high resolution (short pulse width).

- **Pulse width:** determines the time width (duration) of the pulse that is sent into the link by the OTDR. A longer pulse travels further down the fiber and improves the signal-to-noise ratio (SNR), but results in less resolution, making it more difficult to separate closely spaced events. A longer pulse also results in longer dead zones. In contrast, a shorter pulse width provides higher resolution and shorter dead zones, but less distance and lower SNR. Generally, it is preferable to select the shortest possible pulse width that allows you to see everything in the link, and then make further adjustments for optimization. When testing downstream in an FTTH network, the optical power of the OTDR pulse must be large enough to go through the splitter(s), and the dynamic range must be high.

- **Acquisition time:** Sets the acquisition duration (time period during which test results will be averaged). In general, longer acquisition times produce cleaner traces (especially with long-distance traces) because as the acquisition time increases, more of the noise is averaged out. This averaging increases the SNR and the OTDR's ability to detect small and closely spaced events. When performing a quick test in order to locate a major fault, such as a break, a short acquisition time (e.g., 10 s) should be used. To fully characterize a link with optimal precision and to make sure the end-to-end loss budget is respected, a longer acquisition time (45 s to 3 min.) is preferable.

- **Pass/Warning/Fail criteria:** Some OTDRs can display a message at the end of an analysis to inform the user if one or more events exceed a preset threshold. Separate Warning and Fail thresholds can be set for each type of measurement (splice loss, connector loss, reflectance, fiber section attenuation, total span loss, total span length, and ORL). This feature can be used to ensure that each optical component in the link meets its acquired values.

Procedure

During installation, OTDR testing should be performed after each segment of the network is installed, Including:

- *Testing the feeder and distribution fibers from the CO to the drop terminal*
- *Testing from the splitter output to the CO*
- *Testing from an ONT or drop terminal to the CO*

The total loss, including the splice and the splitter, is measured at the splitter point.

The following table indicates the values for splitter loss:

Splitter Loss Values					
Split ratio	1:4	1:8	1:16	1:32	1:64
Insertion loss (typical)	7.4 dB	10.5 dB	13.7 dB	17.1 dB	21.1 dB
Splice values two splices)	0.2 dB	0.2 dB	0.2 dB	0.2 dB	0.2 dB
Total loss	7.6 dB	10.8 dB	14.3 dB	17.6 dB	21.4 dB

Tab. 7: General passive splitters loss values with splices

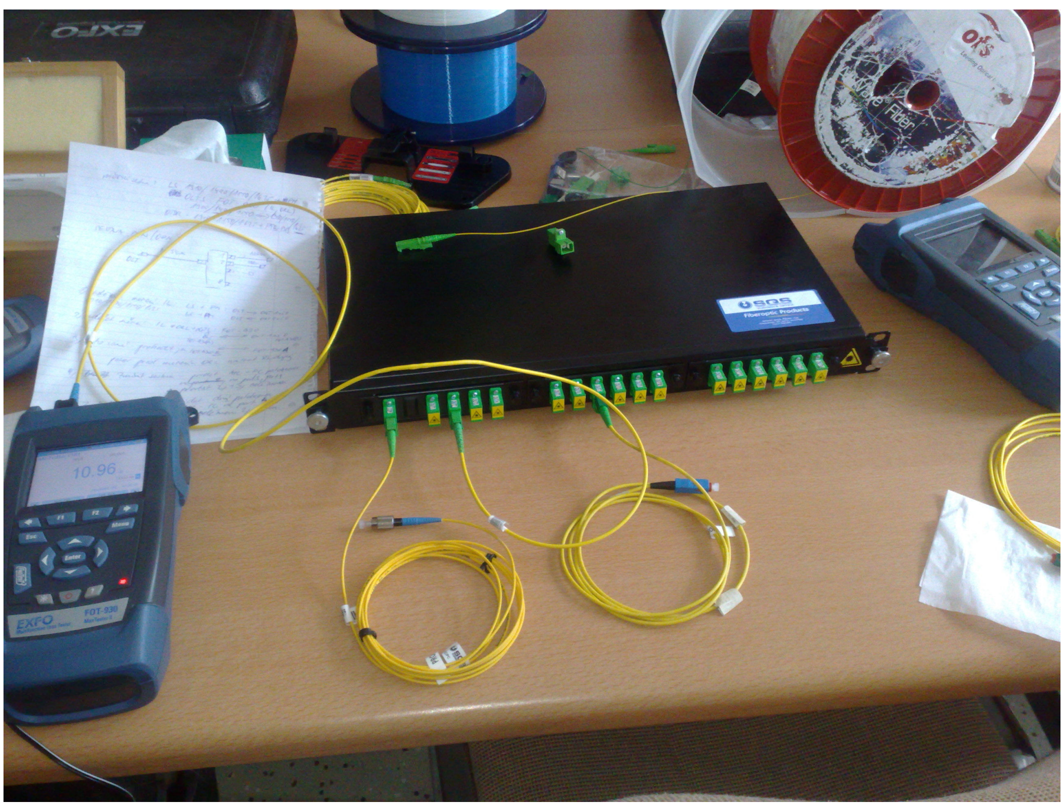


Fig. 42: Planar waveguide 1:16 splitter that I used in the laboratory

And so I used 1:16 splitters in the experiment measuring the splitter loss value of three ports, port 16, 10 and 4. I have included the OTDR trace graph and the measurement values, set ups as follows:

20km cable
9.12 dB – 1310 nm 5.98 dB – 1490 nm 5.35 dB – 1550 nm

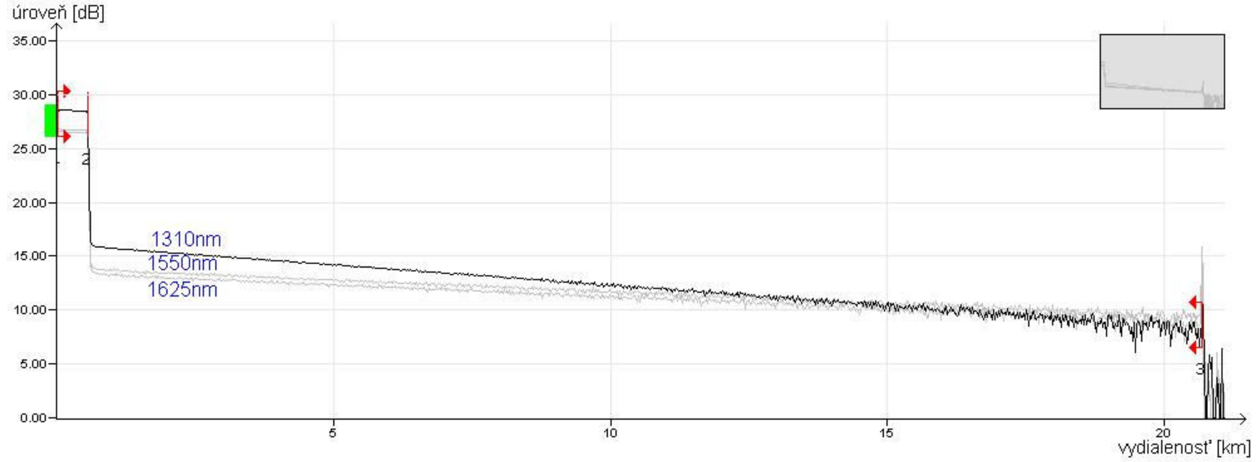
Splitter 1:16	CO➔ONT	ONT➔CO
Output port 16	12.89 dB – 1310 nm 13.04 dB – 1490 nm 13.12 dB – 1550 nm	13.03 dB – 1310 nm 13.23 dB – 1490 nm 13.29 dB – 1550 nm
Output port 10	13.30 dB – 1310 nm 13.63 dB – 1490 nm 13.20 dB – 1550 nm	13.23 dB – 1310 nm 13.64 dB – 1490 nm 13.14 dB – 1550 nm
Output port 4	13.70 dB – 1310 nm 14.39 dB – 1490 nm 14.45 dB – 1550 nm	14.15 dB – 1310 nm 14.25 dB – 1490 nm 14.33 dB – 1550 nm

Splitter 1:16	CO 20km ➔ 1:16 ➔ 2m ONT
Output port 16	22.20 dB – 1310 nm 19.22 dB – 1490 nm 19.10 dB – 1550 nm
Output port 10	22.22 dB – 1310 nm 19.58 dB – 1490 nm 18.90 dB – 1550 nm
Output port 4	22.42 dB – 1310 nm 19.65 dB – 1490 nm 19.61 dB – 1550 nm

Splitter 1:16	CO 2m ➔ 1:16 ➔ 2m ➔ 20km ONT	CO 2m 🡐 1:16 🡐 2m 🡐 20km ONT	Avg.
Output port 16	21.24 dB – 1310nm 18.09 dB – 1490nm 19.39 dB – 1550nm	21.27 dB – 1310nm 18.23 dB – 1490nm 19.51 dB – 1550nm	21.25 dB – 1310nm 18.16 dB – 1490nm 19.45 dB – 1550nm

Tab. 8: Measurement tests

OTDR Trace



General Info

Job ID:	zxx2	Reason:	Test measurement
Contractor:	---	Operator A:	---
Customer:	---	File:	zxx2.trc

Link Measurements

Link Loss:	0.113 dB	Avg. Splice Loss:	---
Link Length:	0.5537 km	Max. Splice Loss:	---
Average Loss:	0.204 dB/km	Total ORL:	45.26 dB

Events Table

No.	Loc. (km)	Event Type	Loss (dB)	Refl. (dB)	Att. (dB/km)	Cumul. (dB)
1	0.0000	Lunch Level	---	-70.8		0.000
		Fiber Section (0.5637 km)	0.113		0.204	0.113
2	0.5537	Reflective Fault	---			0.113
		Fiber Section (20.1208 km)	4.554		0.226	- - -
	20.6744	Reflective Fault	---	-44.8		- - -

Marker Info

A:	0.0000 km, 25.080 dB	B:	0.0000 km, 25.080 dB
A:	N/A	B:	N/A
A to B Distance:	0.0000 km	A to B LSA Att.:	0.000 dB/km
A to B LSA Loss:	0.000 dB		

Test and Cable Setup

Wavelength:	1625 nm	Acq. Time:	5 s
Filename:	zxx2.trc	Pulse Width:	100 ns
Hardware:	FTB-7400E-0234B-EA-VFL	Helix Factor:	0.00 %
Serial Number:	464254	Splice Loss Threshold:	0.020 dB
Software:	N/A	Reflectance Threshold:	-72.0 dB
Range:	25.0 km	End-of-Fiber Threshold:	5.000 dB
IOR:	1.46873		
RBS:	-82.85		

Tab. 9: OTDR trace

6. CONCLUSION

Advantage of optical system communications and system networks was studied and represented by illustrating its use and benefits understanding the huge information capacity that could be carried.

By analyzing the current state and methodology of Passive Optical Network PON we have it was clear that Time-sharing TDM for PON appears to be the preferred method today for optical channel sharing in an access network, as it allows for a single upstream wavelength and a single transceiver in the OLT, resulting in a cost-effective solution.

ATM-PON and Ethernet PON (EPON) where researched, which are based on common network architecture, but adopt different transfer technologies to support integrated services and multiple protocols, where we studied and reasoned on why choosing EPON as the preferred technology that we used for our project design model, We also can conclude that EPON is the first public network architecture that traces its ancestry not to telephony or cable communications, but to private enterprise data networks. While trying to analyze EPON taking into consideration all the factors of future proof bandwidth and capability of EPON 10G after studying the requirements of Triple-Play service, I concluded that FTTH TDM-PON is the best answer at the present state for my project design model, while EPON is the optimal protocol technology and my choice as an analytical answer of the design and the technology used in FTTH for the Triple-Play service, and we should keep in mind that it is the future proof solution for even more advanced Triple-Play, so we used three wavelengths (1310, 1490 and 1550 nm) so that the downstream 1490 nm and upstream 1310 nm wavelengths are used to transmit data and voice. While the optical video transmitter converts the video services to optical format at the 1550-nm wavelength. And the 1550-nm and 1490-nm wavelengths are combined by the WDM coupler and transmitted downstream together.

In the given project model I virtualized 3 location division areas and other 3 subdivision areas, resulting of 6 allocations, all set in one small geographical given area presenting the 90 private house distant 20km from the Central office, that resulted of a total number of 9 splitters provident network connections for 96 ONUs, which will cover for us all 90 houses and will also leave us with spare 6 lines to use. The allocation and choice of the number of splitters was based on the concept optimal overall solutions taking in consideration, the divisions, cost, and distribution, for 1 geographical area of 90 private houses.

As explained OLT was used which is the central element and the heart of FTTH-PON network, the element communicates with all the ONU unit clients, assigns them their defined profiles, advance QoS politics. This communication is bilateral and in the direction of ONUs communicates with the broadcast. And in the reverse direction received from client units, it defines for each unit the time the communication will take.

Maintenance of then network, troubleshooting, and testing is not expensive, testing could be concluded or defined as three main methods for activating the service, those are Bidirectional optical return loss (ORL), Bidirectional end-to-end optical loss, and Bidirectional end-to-end link characterization using OTDR, while the OTDR test is different than the OLTS, which characterizes the overall loss of an entire link using two instruments, an OTDR provides a detailed map of all of the section losses, allowing the users to locate and characterize every individual element in the link, including connectors, splices, splitters, couplers, and faults. And the best available OTDR wavelength for macrobending detection is 1625 nm (while the longer the wavelength, the better), so as fibers can be measured over the ranges of wavelengths used in the PON, typically: 33 dB/km at 1310 nm (0.35 dB/km as for worst case), 21 dB/km at 1490 nm (0.27 dB/km for worst case), and 0.19 dB/km at 1550 nm (0.25 dB/km for worst case), while 1:8 splitter loss value keeps ranging around 10.5 dB for insertion loss, 0.2 dB for two splices, 10.9 db in total loss. And again, each fiber should be tested from the OLT at the CO to the splitter, as well as from the splitter to the ONTs, Bidirectional testing provides more accurate results because the loss values measured in each direction can be averaged.

For monitoring of the given project design model, the operation outage can be monitored in the electrical layer of transmission and to insure security and continuous operation of our design project, is can simply solved by using MLS (Monitoring Line System) which is a registered and most elaborated system in the market for fast and efficient detection of a problem in the network and localization in short-time and temporary changes in optical routes.

Last thing I would like to mention, is the same statement I mentioned Two years ago on my Bachelor's Thesis, the idea did not change yet. Is that no matter how much pros and cons are there in PON (EPON) solution versus other PON matching technology and even other architectures like active Ethernet point to point, or WDM, the debate will continue and overall no clear winner, Dependent on many factors, Telecoms, Density, Residential vs. Business, Network Engineering.

References

[1] M. Filka, Optoelectronic for Telecommunications and Informatics © OPTOKON Co., LTD. Texas, USA 2009. ISBN 978-0-615-33185-0

[2] Anas O. Dallal, FTTH-Network Design and Testing, Bachelor's thesis, BUT FEEC, Telecommunications Dept. Czech Rep. Brno. 2008.

[3] Glen Kramer, *Ethernet Passive Optical Networks* © by The McGraw-Hill Companies, Inc. USA. 2005. 0-07-144562-5

[4] Harry J. R. Dutton, *IBM Understanding Optical Communications* © International Business Machines Corporation USA. 1998. *SG24-5230-00*

[5] GIRARD. A. *FTTX PON Technology and Testing. EXFO,* Quebec. 2005.

[6] Tim Kearby, Robert Beiderbeck*, IBM 9729 Optical Wavelength Division Multiplexer* © International Business Machines Corporation USA. 1998. SG24-2138-00

[7] G. Kramer, B. Mukherjee, G. Pesavento. *Ethernet PON (ePon) © Kluwer Academic Publishers. 2001. The Netherlands. 3:3, 307-319*

[8] Teresa Mastrangelo, *Global FTTH Deployment Trends* © 2007 The Windsor Oaks Group LLC. www.broadbandtrends.com

[9] Literature from EXFO. *Mario Simard*, *Optical Business Unit.* www.exfo.com

[10] Kyeong Soo Kim, *On the evolution of PON-based FTTH solutions.* USA. 2002.

[11] P.P. Mitra and J.B. Stark , *Nonlinear limits to the information capacity of optical fibre communications. Nature* 411. 2001.

Internet Pages:

[12] http://www.sqs-fiber.cz MLS

[13] http://www.omron.com/ecb/products/opt/1-4.html (Optical splitter module P1C).

[14] http://www.fujikura.co.uk/fujikura.htm Fujikara Europe limted Ltd, (Fibre to the Home: Thoughts from Japan).

[15] http://www.ieee.org/ IEEE official website.

[16] http://www.itu.int ITU official website.

[17] http://www.ftthcouncil.org/ FTTH Council website

[15] http://www.fiberevolution.com Benoit Felten, The point of PON. 2007

[16] http://www.networkcomputing.com/ Study: Global Fiber-to-the-Home Use To Surge.