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An overview of passive optical networks and components

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AN OVERVIEW OF PASSIVE OPTICAL NETWORKS AND COMPONENTS

by

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Abstract

An Overview of Passive Optical Networks and Components

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Over the past few years, telecommunication networks have experienced a dramatic shift from traditional voice-dominated traffic to data-oriented, application-based traffic.The access network or the last-mile connecting households or businesses to the internet backbone,have been recognized as a major bottleneck in todays network hierarchy.The ongoing demand for new access networks that support high-speed (greater than 100 Mb/s), symmetric, and guaranteed bandwidths for future video services has been accelerated and the search for a cost-effective optical access solution has yielded a number of possible solutions. To satisfy the required bandwidth over a 20-km transmission distance, single-mode optical fiber is a natural choice.Passive Optical Networks(PONs) are promising access solutions that will open the last-mile bottleneck bringing data rates of 100 Mb/s to 1 Gb/s to the end-users.

The goal of this work is to provide a cohesive overview of research done in the area of Fiber In The Loop (FITL) optical access technology. Specifically, it explores the area of Passive Optical Network (PON) : its history, variants, architecture, and standards. Various passive optical components which make a passive optical network work, are also discussed. Some laboratory emulations on RF over PON showing noise, distortion, and fading in the channels are then carried on using the Vector Signal Generator SMIQ03B (Rohde & Schwarz), and the Wireless Communication Analyzer WCA380 (SONY Tektronix).

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List of Acronyms

ADSL	Asymmetric Digital Subscriber Line
APON	Asynchronous Transfer Mode over Passive Optical Network.
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BPL	Broadband over Power Line
BPON	Broadband Passive Optical Network
CAPEX	CAPital EXpenditures
CATV	Cable Television.
CDMA	Code Division Multiple Access.
CO	Central Office
CODEC	Coder/Decoder
CWDM	Coarse Wavelength Division Multiplexing (20nm spacing)
DFB	Distributed Feedback Laser
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DTE	Data Terminal (or Termination) Equipment
DWDM	Dense Wavelength Division Multiplexing (less than 1nm spacing)
EML	Externally Modulated (DFB) Laser
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction.
FP	Fabry-Perot Laser
FTTB	Fiber To The Building or Business
FTTC	Fiber To The Curb
FTTD	Fiber To The Desk
FTTH	Fiber To The Home
FTTN	Fiber To The Node or Neighborhood
FTTO	Fiber To The Office
FTTP	Fiber To The Premises

FTTU	Fiber To The User
FTTZ	Fiber To The Zone
FTTx	Fiber-to-the-(generic)
GPON	Gigabit Passive Optical Network
HDSL	High bit-rate Digital Subscriber Line
HDTV	High-definition Television
HFC	Hybrid Fiber-Coax
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISI	Inter Symbol Interference
ISO	International Organization for Standards
ISP	Internet Service Provider
ITU	International Telecommunications Union
LAN	Local Area Network
LEC	Local Exchange Carrier
MMF	Multi-Mode Fiber (core $\approx$ 50mm)
MUX	Multiplexer
NAP	Network Access Provider
OLT	Optical Line Terminal
ONT	Optical Network Terminal
ONU	Optical Network Unit
OPEX	Operating Expenditures
PAM	Pulse Amplitude Modulation
PCM	Pulse Code Modulation
PIN	p-i-n Photodiode
PLC	Power Line Communication
PON	Passive optical network
POTS	Plain Old Telephone Service
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service

RF	Radio Frequency
RN	Remote Node
ROF	Radio Over Fiber
SCM	Sub-Carrier Multiplexing (e.g. Radio/TV channels)
SCMA	Sub-Carrier Multiplexing Access
SDH	Synchronous Digital Hierarchy
SDSL	Symmetric Digital Subscriber Line
SMF	Single-Mode Fiber (core $\approx$ 9mm)
SNR	Signal-to-Noise Ratio
TCP	Transport Control Protocol
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TEC	Thermo-electric Coolers
TELCO	Telephone Company
VDSL	Very high bit-rate Digital Subscriber Line
VoD	Video on Demand
VoIP	Voice over Internet Protocol
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WDMA	Wavelength Division Multiple Access
xDSL	(generic) Digital Subscriber Line

Chapter 1

Introduction

1.1 Background

Over the last decade the world has seen a great transformation in the telecom industry. Prior to the widespread use of the internet, telecommunication service customers used only standard telephones, fax machines, or dial-up modems to communicate on a world-wide basis. To connect to the outside world, these applications typically used the public switched telephone network (PSTN), which consists of twisted-pair copper wire links that run from customer premises to local telecommunication switching centers. The telecom companies then, concentrated on building high-capacity networks up to a local distribution point. Beyond that point, connections to the customers' premises were by lower-speed copper wire.

This situation changed with the advent of powerful personal computers, which created a demand for new band-width hungry applications and services, each of which could consume several megabits per second. Among these high-rate applications were video-on-demand, streaming media, virtual private circuits, high-resolution image transfers, and online entertainment in addition to traditional phone, data, and fax services. This required a new look at the capabilities of the access network.

To date, the most widely deployed technologies to provide services in the last mile have been DSL (Digital Subscriber Loop) and CM (Cable Modems). However, although these technologies provide much more bandwidth than 56 Kbps dial-up lines, they are incapable of delivering enough bandwidth to the emerging bandwidth-intensive services such as Video-on-Demand (VoD), interactive gaming, and two-way video conferencing.Neither DSL nor CMs can keep up with such demand. Both technologies are built on top of existing copper communication infrastructure not optimized for data traffic. A new technology is required; one that is inexpensive, simple, scalable, and capable of delivering bundled voice, data, and video services to an end-user subscriber over a single network. To satisfy the required bandwidth over a 20-km transmission distance, single-mode optical fiber is a natural choice. Passive Optical Networks(PONs) are promising access solutions that will open the last-mile bottleneck bringing data rates of 100 Mb/s to 1 Gb/s to the end-users. Let us now define some standard terminologies used in the optical access networks.

1.1.1 Core network and Access network

Core network is a combination of Switching Centers and Transmission Systems connecting the Switching Centers. Core network includes a radio access network, terminals and applications. It is also referred to as the backbone network. In contrast, an access network is that part of a communications network which connects subscribers to their immediate service provider. It is the only part of the fixed telecommunications plant that has not already evolved completely to fiber. Access Network is also referred to as the *local drop*, *local loop*, *first mile* or *last mile*. It is the final leg of delivering connectivity from a service provider to a customer. A perfect example of a traditional access network is a telcos twisted-pair network connecting individual telephones to a central office.

Table 1.1: Categorization of optical networks

Category	Users	Span	Bit Rate(bps)	Multiplexing	Fiber	Laser	Receiver
Core/Long Haul	Phone Company, Government	$10^3 km$	10^{11} (100's of Gbps)	DWDM TDM	SMF DCF	EML DFB	APD
Metro/Regional	Phone Company, Big Business	$10^2 km$	10^{10}(10's of Gbps)	DWDM CWDM TDM	SMF LWPF	DFB	APD PIN
Access/Local Loop	Small Business, Consumer	10km	10^9(56kbps - 1Gbps)	TDM SCM	SMF MMF	DFB FP	PIN

1.1.2 Categorizing Optical Networks

Telecommunications networks are normally segmented in a three-tier hierarchy depending upon the type of users and amount of bit-rates required. These are-Core/Long Haul/Backbone, Metropolitan/Regional, and Local Loop/Access Networks. The definitions are clear from table 1.1 above.

1.1.3 Last-mile Bottleneck

Much of the emphasis over the past few years has been on developing high capacity backbone networks. Backbone network operators currently provide high capacity links. Copper cannot suffice to bridge the enormous and growing capacity gap between our desktop, laptops, or TVS and the equally enormous and growing capacity that this very medium, fiber, has brought to metro and long-haul interoffice facilities. Cable companies are beginning to offer voice over cable; a number of IP telephony trials are currently underway. This last-mile[1] bottleneck can be seen clearly in Fig.1.1. In the interoffice environment of both telcos and cable providers, raw bit rates of 2.5 up to 10 Gb/s per wavelength have been standard for 5 years or more. At the user end, 2 to 8 Gb/s data transfer rates within the ubiquitous laptops and desktops are common and this number is growing.

1.1.4 Triple Play

In order to remain competitive as the broadband market evolves, the favored service offering for broadband today, (whether DSL, cable, or FTTx) is a standard mix of traffic types referred to as triple play. The three traffic components are bidirectional voice bit streams, unidirectional video and bidirectional high-speed data. Of these three, video service is the most challenging as it requires the most bandwidth.

Different countries have responded differently to this. While triple play may be the standard emerging broadband offering in the North America, in some other parts of the world, regulatory restrictions mean that not all three components can be carried out by the same facilities.

[1]last mile and first mile are often used as interchangeable terms both indicating that part of a communications network which connects subscribers to their immediate service provider.

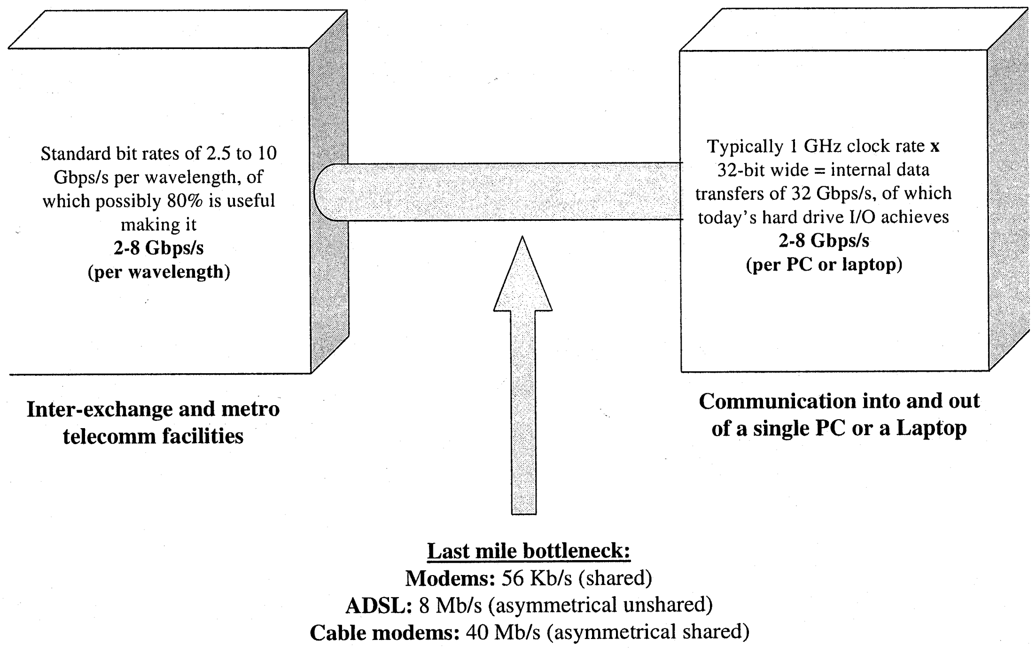

Figure 1.1: "Last-mile bottleneck" between a user's computer and the metro and long-haul facilities [1]

1.2 Existing Wired Access Network Technologies

Many of the high-speed access technologies have been emerged during the last decade; triggered by the need for faster and cheaper internet access, and the next generation TV and video services. Access networks fall into two broad categories : wired and wireless. Wired networks can further be divided into copper, Hybrid Fiber Coaxial (HFC) , Broadband over Power Line (BPL), and fiber. The passive optical network (PON) is just one of several access technologies used by service providers, but it enjoys a dominant position in the access market. Before discussing the specific details of the PON, it is worthwhile to survey the alternate access technologies in order to understand the reasons for the PONs success. However, in this report we will review only the wired access solutions and not touch the wireless solutions.

1.2.1 Digital Subscriber Line (xDSL)

A family of technology that have transformed the narrow-band copper access network into broadband network is the xDSL family of technologies. The letter 'x' indicates that there are many variants of the DSL technology and the term DSL refers to the modulation/demodulation technology which uses the existing coper telephone infrastructure to facilitate high speed data connections. It uses a DSL modem at the customer premises, and a DSL Access Multiplexer (DSLAM) in the local exchange/Central Office or at nodes in the access network to transmit and receive the data signals.There are a number of different DSL technologies, the key ones are Asymmetric DSL (ADSL),Symmetric DSL (SDSL),High bit-rate DSL (HDSL), and Very high speed DSL (VDSL). Extensive literature exists on DSL and its variant technologies [2, 3, 4, 5, 6].The International Telecommunications Union Technical standards group (ITU-T) has standardized HDSL as G.991.1 [7], ADSL as G.992.1 [8] and VDSL as G.993.1[9] standard. xDSL frequency band ranges from 1.1 MHz for ADSL, to 2.2 MHz for ADSL2+ and could reach to a maximum of 12 MHz for VDSL by using complex data modulation techniques.

ADSL, as an extension of HDSL, is the most popular access technology due to the low cost and high penetration of the telephone infrastructure [2]. ADSL deals with asymmetrical traffic for which the downstream flow is assumed to be greater than the upstream one. This is typically the case for multimedia interactive services (VoD, teleshopping, entertainment, etc.) for which the end user accesses a server through the public network. Currently acceptable ADSL standards use the discrete multi-tone (DMT) modulation scheme for data transmission. Enhanced versions of the ADSL like ADSL2 and ADSL2+ were developed later [3, 4]. Most recently, ADSL2++, has been introduced.

For business applications it is possible to get Symmetric DSL (SDSL) [6] which allows high speed download and uploads, but the max. available bandwidth is around 3 Mb/s.

The VDSL [6] technique is an extension of ADSL and which unlike the ADSL, may operate either symmetrically or asymmetrically over either a single POTS subscriber line or a basic ISDN access line. It operates at higher data rates than ADSL but over very short distances. Therefore, in order to offer VDSL to a significant proportion of the population, it need to work in conjunction with optical fiber access networks. The DSLAMs need to be relocated to street cabinets (closer to the subscriber) and fiber feeds installed to the street cabinets. ADSL2+ allows transmission of sufficient bandwidth for some video services, over greater distances than VDSL, without the need of DSLAMs relocation [10]. As a result

Table 1.2: **xDSL bandwidth versus distance capability.**

Technology	Maximum Upstream Capacity	Max Downstream Capacity	Maximum Distance	**Downstream Capacity @ Maximum Distance**	Frequency Range
ADSL	640 kb/s	12 Mb/s(0.3km)	5.4 km	**1.5 Mb/s**	Up to 1.1 MHz
SDSL	3 Mb/s	3 Mb/s	2.7 km	**2 Mb/s**	Up to 1.1 MHz
ADSL2+	1 Mb/s	26 Mb/s(0.3km)	3.6 km	**4 Mb/s**	Up to 2.2 MHz
VDSL	16 Mb/s	52 Mb/s(0.3km)	1.3 km	**13 Mb/s**	Up to 12 MHz

ADSL2+ is becoming the upgrade path for operators wishing to improve upon their standard ADSL service offerings.

One major disadvantage of xDSL is that it is a distance-sensitive technology. As the connection length from the user to the DSLAM increases, the signal quality decreases and the connection speed goes down. Table 1.2 shows this. The maximum data capacities shown are not available at the max distance. There is always a trade-off between distance and bandwidth.

1.2.2 Hybrid Fiber Coax (HFC) : CATV and Cable Modems

Digital cable TV networks offer bi-directional data transfer bandwidth in addition to voice and digital TV services. To facilitate the digital data transmission over deployed CATV networks, a manufacturing standard for cable modems has been developed and approved by the ITU-T as the Data Over Cable Service Interface Specification (DOCSIS). ITU-T has adopted two DOCSIS versions as international standards : DOCSIS 1.1 (Recommendation J.112 [11])and DOCSIS 2.0 (Recommendation J.122 [12]). Recently, a DOCSIS 3.0 version has also been proposed. A DOCSIS architecture includes two primary components: a cable modem (CM) located at the customer premises, and a cable modem termination system (CMTS) located at the CATV headend. A typical CMTS is a device which hosts downstream and upstream ports (it is functionally similar to the DSLAM used in DSL systems).

The dominant architecture for North American cable systems is downstream transmission from 50 to 750 MHz, though a few systems go to a maximum of 860 or 870 MHz [13] out of which the spectrum from 50 to 450/550 MHz [2, 13] is filled with analog TV channels, and the spectrum above 450/550 MHz usually reserved for digital video shared with data and voice downstream. The digital data is modulated and then placed on a typical 6 MHz television channel (8 MHz in Europe). Fig.1.2 shows the typical spectrum utilization of of an HFC network in the coaxial section. Currently, 64 or 256 QAM are the preferred modulation techniques, offering upto 30-40 Mb/s per 6 MHz channel. Typical implementations in the upstream transmissions use the QPSK or 16 QAM techniques.

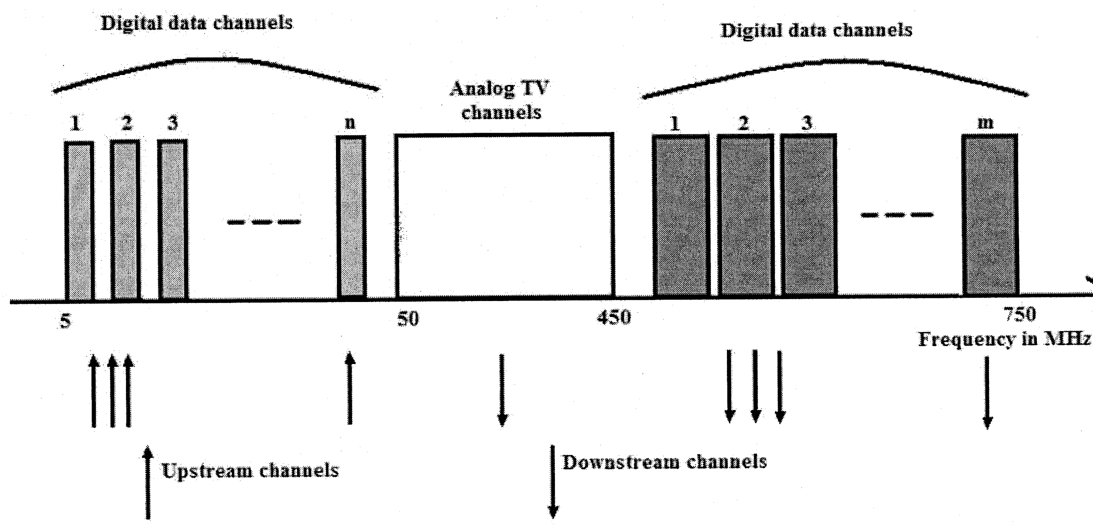

Figure 1.2: Spectrum utilization of the coaxial cable in an HFC network

Data transmission over Cable TV network has the advantage that where the coaxial cable is in good condition and RF amplifier exist (or can be installed) to extend the network reach, relatively high bandwidths can be provided to the end-user without distance limitations. However, a CATV broadband service relies on a shared network architecture, resulting in slow speeds during peak hours.

1.2.3 Broadband over Powerline (BPL)

Broadband over Power Line (BPL) (termed as Power line communication (PLC),in Europe) refers to a technology which uses electric power lines to carry information over the power line. BPL systems allow for high speed data transmission on existing power lines, and do not need a network overlay as they have direct access to the ubiquitous power utility service areas. BPL systems are being promoted as cost-effective way to service a large number of subscribers with broadband. Several competing standards are evolving including the HomePlug Powerline Alliance, Universal Powerline Association, ETSI, and the IEEE. It is unclear which standard will come out ahead. The U.S Federal Communications Commission (FCC), the IEEE BPL Study Group, Universal Powerline Association (UPA) are some of the promoters of BPL in the U.S and worldwide. In a BPL system, the data is transmitted over the existing power line as a low voltage, high frequency signal which is coupled to the high voltage, low frequency power signal. Typical data rates in current trials are 2-3 Mb/s, but vendors have indicated that commercially systems offering upto 200 Mb/s could eventually become available.

However, there is no clear upgrade path to higher data rates. Most BPL systems at present are limited to a range of 1 km within the low voltage grid, but some operators are extending this reach into the medium voltage grid. BPL requires a high investment cost to upgrade the power transmission network and bypass transformers, to support high speed and reliable broad-band services. In addition, the frequencies used for BPL often interfere with amateur radio transmission and some BPL trials have consequently suffered considerable opposition. In February 2004, as part of its ongoing effort to promote access to broadband services for all Americans and to encourage new facilities-based broadband platforms, the FCC proposed changes to certain technical rules that will foster broadband deployment using the significantly untapped capabilities of the nation's power grid, while safeguarding existing services against harmful interference. At present, given the cost and lack of an upgrade path, it seems unlikely that BPL will emerge as a leading broadband technology, but will remain as a niche fixed line broadband option.

1.3 Challenges in Access Network : The need of Fiber

There have always been things that copper and radio cannot do but fiber can. They just have not been important for the access environment until now. They have to do with bandwidth capacity certainly (e.g. the capacity to carry multiple HDTV channels), but there is more to it than just the bandwidth. There are matters of signal attenuation, first cost, life time serviceability costs, convenience to the user, and the business advantages of combining all the communication services into one bundle, one management process, and one monthly customer bill. We have seen that access network is truly the bottleneck for providing broadband services such as video-on-demand, interactive games, video conference etc., to end users. The predominant broadband access solutions deployed today are the Digital subscriber Line (DSL) and cable TV (CATV) based networks. However, both of these technologies have limitations because they are based on infrastructure that was originally built for carrying voice and analog TV signals respectively; but their retrofitted versions to carry data are not optimal. In addition DSL and its variations like ADSL and VDSL have severe distance limitations because of signal distortions. For example, the maximum distance which VDSL can be supported is limited to 1500 feet. CATV networks provide internet services by dedicating some RF channels in co-axial cable for data. Cable networks are mainly built for delivering broadcast services, so they don't fit well for distributing access bandwidth.

Faster access-network technologies are clearly desired for next-generations broadband applications. The next wave of access networks promises to bring fiber closer to the home. The FTTx model - Fiber-to-the-Home (FTTH), Fiber-to-the-Curb (FTTC), Fiber-to-the-Building (FTTB), etc. offers the potential for unbelievable access bandwidth to end users. FTTx networks provide much, much better data, voice, and video performance than HFC and DSL networks. These technologies aim at providing fiber directly to the home, or very near to the home, from where technologies such as VDSL can take over.

1.4 Structure of an Optical Access Network

An optical access network is generally integrated by an OLT (Optical Line Termination), ORNs/RNs (Optical Remote Nodes/Remote Nodes) and ONUs (Optical Network Units). The OLT is a key element to perform the union between the access network and the metropolitan network. The RNs are incharge for distributing the information from the hub to the ONUs. As shown in Fig.1.3 each hub can be connected to several remote nodes and each RN can be connected to several ONUs. The network between the hub and the RN is called *feeder network* and the network between the RN and ONU is known as the *distribution network.*

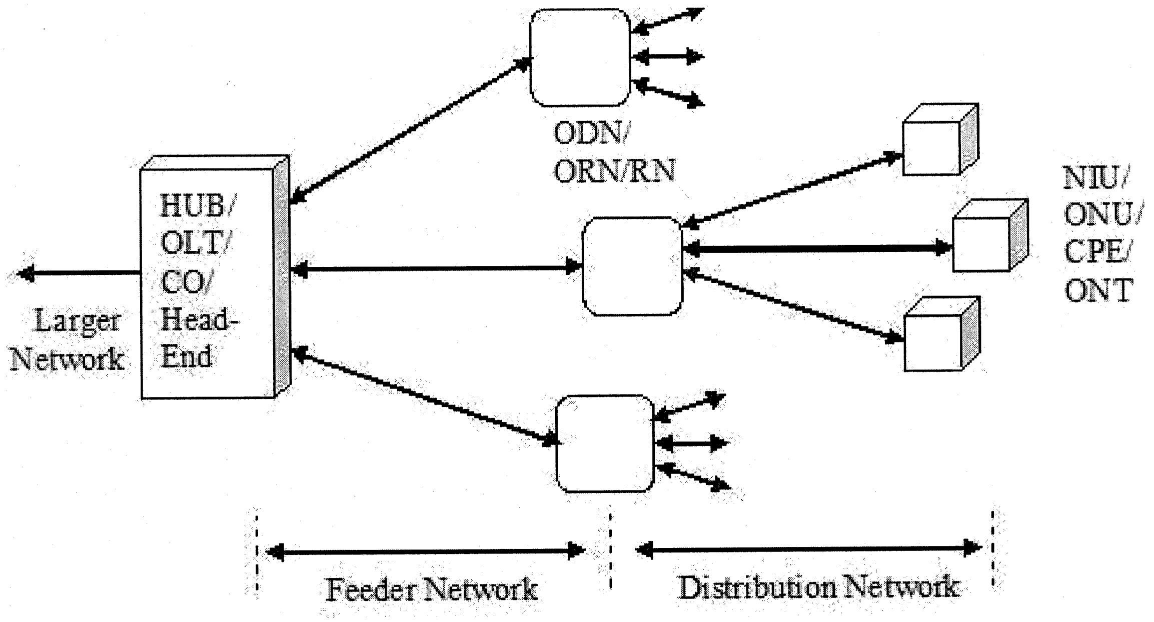

Figure 1.3: General structure of an optical access network

In the telecommunication literature, the elements of an access network can have other names depending on the type of networks. The OLT is also called Hub, HE (Head End), CO (Central Office), and LS (Local Switch). The ORN is sometimes called ODN (Optical Distribution Node). Finally, several names are used to design the ONU:NIU (Network Interface Unit), ONT (Optical Network Termination) and CPE (Customer Premises Equipment).

1.5 FTTx Deployment Scenarios

Driven by the rapidly growing bandwidth demands from end-users and falling cost of photonic components, it is reasonable to start considering deployment of the next-generation access networks based on optical fibers. Although the initial deployment of fiber, or any new media, can be high in cost due to the physical infrastructure, this is a one-time installation for future-proof networks whose cost can be amortized over an exceedingly long time.

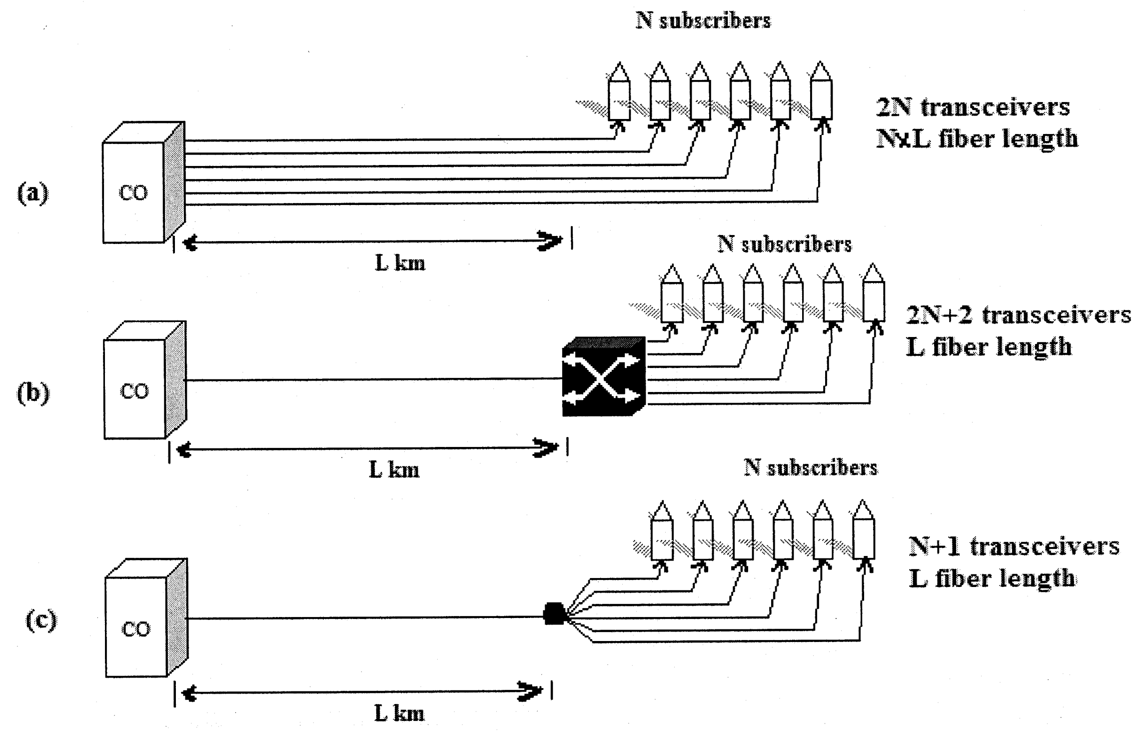

Figure 1.4: FTTx architectures :a) point-to-point b) active star c) passive star (PON)

One logical way to deploy fiber in the local access network is to use a point-to-point topology. Here individual fibers run from the Central Office (CO) to each end-user subscriber (Fig.1.4(a)). While it is the simplest architecture providing the ultimate capacity and the most flexibility to upgrade services for customers individually, in most cases it is cost prohibitive. It requires significant outside plant fiber deployment as well as connector termination space in the CO. Considering N subscribers at an average distance L km from the central office, a PtP design requires $2N$ transceivers and $N \times L$ total fiber length (assuming that a single fiber is used for bi-directional transmission).

A possible solution to it may be using an active star architecture. Here a single fiber carries all traffic to an active node close to the end users, from where individual fibers run to each cabinet/home/building. Only a single feeder fiber is needed and a number of short branching fibers (or twisted copper, or HFC) to the end users, which reduces costs; but active node needs powering and maintenance. From figure 1.4(b), clearly this point-to-multipoint (PtMP)topology will reduce the fiber consumption to only L km (assuming negligible distance between the switch and customers), but will also increase the number of transceivers to $2N+2$, as there is one more link added to the network . In addition, this curb switched network architecture requires electrical power as well as back-up power at the curb switch. Currently, one of the highest costs for Local Exchange Carriers (LECs) is providing and maintaining electrical power in the local loop. It also needs to withstand a wider range of temperatures than in-door equipment.

Another possible solution is employing a passive star architecture. In this architecture the active node of the active star topology is replaced by an inexpensive passive optical power splitter/combiner that feeds the individual short branching fibers to the end users. This only requires $N+1$ transceivers and L km of fiber (Fig.1.4(c). In addition to the reduced installation costs of a single fiber feeder link, the completely passive nature of the outside plant avoids the costs of powering and maintaining active equipment in the field. This topology has therefore become a very popular one for introduction of optical fiber into access networks, and is widely known as the passive optical network (PON).

Viewed by many as an attractive solution to the last-mile problem [14, 15, 16, 17], a PON is a point-to-multipoint (PtMP) optical network with no active elements in the signal path from source to destination. The only interior elements used in a PON are passive optical components, such as optical fiber, splices, and splitters. We will study in greater details about PON technologies, standards, issues, and more in the next chapter.

1.6 Research Paper Organization

In the introductory chapter we reviewed the existing access network solutions that compete with passive optical network schemes. Rest of the paper is organized as follows :
In chapter 2, Passive Optical Network (PON) Technologies are introduced. It starts with the history of PON and briefly touches upon the different Multiplexing and Multiple Access

schemes. The existing PON architectures : APON, BPON, EPON, GPON, and WDM-PON and the standards and protocols are discussed.

The different physical passive components used in the optical access networks like fibers, connectors, splitters, couplers, etc. are analyzed in chapter 3.

Chapter 4 concentrates on the work done in the laboratory which comprises of some basic noise and distortion emulations and measurements using Vector Signal Generator SMIQ03B (Rohde & Schwarz), and the Wireless Communication Analyzer WCA380 (SONY Tektronix).

Finally, the report closes with some concluding remarks and future vision of optical access network.

Chapter 2

PON Technologies

2.1 Historical Overview

Fiber to the Home and business was a consideration from the earliest days of optical fiber technology development. In the late 1970's point-to-point replacement of copper with fiber was being considered as a way of delivering broadband (mainly video) services to customers.These early systems were predicated on multi-mode fiber technology, the only viable solution at that time. The first consideration of a PON approach for the access network was around early 1980's when single mode fiber technology was been seen as a new way forward for optical communications [18, 19, 20].

In the first half of the 1980's, the PON concept was centered on wavelength-switched networks. They used star couplers to interconnect network terminations and wavelength selection to route paths [21] across the network. At the same time ideas of using the couplers as simple passive splitters for broadcasting television signals was also being considered. The concept of multi-channel communication via High Density Wavelength Division Multiplexing (HDWDM) also emerged [22]. In the mid 1980's the joint efforts of the R & D, and Operational unit team at BT led to the invention of the 'TPON'(Telephony over Passive Optical Network) system [23, 24, 25]. TPON was TDM based and the early system had a limited bandwidth of 20 Mbps which was adequate for telephony and ISDN but not for Broadband. The idea was that broadband would be added later, as an upgrade [26, 25], by the addition of extra wavelengths. To facilitate this an optical blocking filter was added to the TPON ONUs, which only passed the original TPON wavelength and blocked all others, enabling additional wavelengths to be added to the PON at a later stage without disturbing the original telephony-only customers. However, because the system was never rolled out on any significant scale, the upgrade system was never developed into a commercial product.

In 1995, a group of seven telecommunication service companies formed a committee to develop ATM-based passive optical networks. This group known as Full Service Access Network (FSAN[1]) expanded later to include many more companies (at present there are around 50 operator and vendor members in FSAN). After producing a set of technical specifications, the FSAN committee submitted them to the ITU-T [2] for consideration. In October 1998 their efforts resulted in the approved international standard known as ITU-T Recommendation G.983.1 [27] for an ATM PON called APON. Initially it used a shared transmission data rate of 54 Mb/s and was mainly designed for compatibility with existing voice and phone services. With the emergence of the Internet, the shared data rate was upgraded to 155 Mb/s using PON. As bandwidth demand continued to grow due to the increasing popularity of the Internet and www,the downstream bandwidth was upgraded again to 622 Mb/s [28]. To reflect this increase in bandwidth, the acronym APON was replaced by broadband PON (BPON).

In November 2000, a group of ethernet vendors started off with their own standardization efforts to develop Ethernet Optical Network (EPON). The Institute of Electrical and Electronics Engineers (IEEE) 802LAN/MAN Standards Committee approved a study group to investigate the subject of "Ethernet in the First Mile (EFM)". In 2001, the IEEE 802.3 [3] working group authorized the 802.3ah EFM task force to carry out the work of drafting the standard which was released in 2002 [29]. Finally, in June 2004,EPON was fully standardized and emerged as a highly successful technology. Lately, IEEE 802.3 working group has formed a 10 Gb/s EPON study group. In September 2006 the 10 Gb/s EPON project was approved, and the work on the specification began in the newly formed IEEE P802.3av 10G-EPON task force [30].

Meanwhile, in 2001, the FSAN group initiated an effort for standardizing PON networks operating at bit rates above 1 Gb/s as a successor to BPON. Thus, using innovations and developments in optical transceiver products, Gigabit PON (GPON) was released and adopted by the FSAN and ITU-T in 2003 and was officially known as ITU-T Recommendation G.984 [31]. Today, GPON is a mature fiber access transmission system. Through 2006, a series of FSAN-sponsored inter-operability events have helped the industry test their equipment

[1]www.fsanweb.org

[2]www.itu.int/ITU-T/index.html

[3]http://grouper.ieee.org/groups/802/3/ah/index.html

against each other, and confirm compliance with the standard. The most recent of these testing events demonstrated inter-operability between G-PON equipment provided by 11 participating companies [30].

2.2 The PON Advantage

The advantages of using PONs in subscriber access networks are numerous.

- PONs allow for long reach between central offices and customer premises, operating at distances over 20 km.
- PONs minimizes fiber deployment in both the local exchange office and the local loop thereby reducing Capital Expenditures (CAPEX).
- PONs provides higher bandwidth due to deeper fiber penetration, offering gigabit per second solutions.
- Operating in the downstream as a broadcast network, PONs allow for video broadcasting as either IP video or analog video using a separate wavelength overlay.
- PONs eliminate the necessity to install active multiplexors at splitting locations, thus relieving network operators of the gruesome task of maintaining active curbside units and providing power to them. Instead of active devices in these locations, PONs use small passive optical splitters, located in splice trays and deployed as part of the optical fiber cable plant. In this way Operating Expenditures (OPEX) are also reduced.
- Being optically transparent end to end, PONs allow upgrades to higher bit rates or additional wavelengths.

2.3 Multiple Access Schemes in PONs

This section provides a brief overview of the various multiple-access techniques that can be used when multiple users share a point-to-multi-point PON infrastructure. These schemes can be generally categorized as time-division multiple access (TDMA), wavelength-division multiple access (WDMA), subcarrier-division multiple access (SCMA), and code-division multiple access (CDMA). These four schemes are illustrated in Fig.2.1.

2.3.1 Time division Multiple Access (TDMA)

TDMA is currently the most popular method being considered for building a PON infrastructure to provide FTTP services. This technique relies on assigning dedicated time slots to each of the multiple subscribers connected to the PON. Each subscriber can then use the full upstream bandwidth of the optical link for the duration of its allotted time slot. Since a PON can typically service N = 32 or more subscribers, the average dedicated bandwidth to each subscriber is usually only a few percent of the channel capacity. To connect the multiple subscribers to a single-feeder fiber, a passive optical-power splitter is used at the Remote Node (RN). This passive power splitter couples 1/N of the power from each subscriber into the feeder fiber for transmission back to the OLT at the CO.

2.3.2 Wavelength Division Multiple Access (WDMA)

WDMA is a highly efficient method for sharing a PON architecture. In this scheme, each subscriber is assigned a pair of dedicated wavelengths; this contrasts to the TDMA case where a single pair of wavelengths is shared among all the subscribers connected to the PON. This means that each user can send data to the OLT at any time, independent of what the other users are doing. In other words, there is no interaction or coupling between the subscribers on a WDM-PON; this eliminates any management issues related to sharing the PON. Each subscriber gets a dedicated point-to-point optical channel to the OLT, although they are sharing a common point-to-multi-point physical architecture.

To realize this WDMA functionality, a WDM multiplexer is used at the RN instead of a power splitter, and an additional WDM demultiplexer is located at the CO to separate the multiple-wavelength signals at the OLT, as shown in Fig. 4. The mux/demux operation can be realized using an arrayed waveguide grating (AWG) or also by thin-film dielectric filters. Using dense-WDM (DWDM) technology, the channel spacing for each wavelength can be as narrow as 50 or 100 GHz, similar to that used in long-haul WDM transmission. The WDM multiplexer can efficiently couple many wavelengths onto the single feeder unlike the TDMA case that uses an inefficient optical-power splitter.

2.3.3 Sub-Carrier Multiple Access (SCMA)

Subcarrier multiple access enables dedicated point-to-point connectivity over a PON architecture by allocating a different RF frequency for each subscriber. In this scheme, each subscriber transmits at essentially the same wavelength but is allotted a unique RF frequency for encoding its data. A single receiver at the OLT detects the N different RF frequencies and demultiplexes them in the electrical-frequency domain. The RF frequencies are the sub carriers, while the transmitted upstream optical wavelength is the main carrier. As in the TDMA case, an optical-power splitter can be used at the RN location. This architecture allows N users to share a common wavelength, while providing a dedicated and uncoupled communication channel.

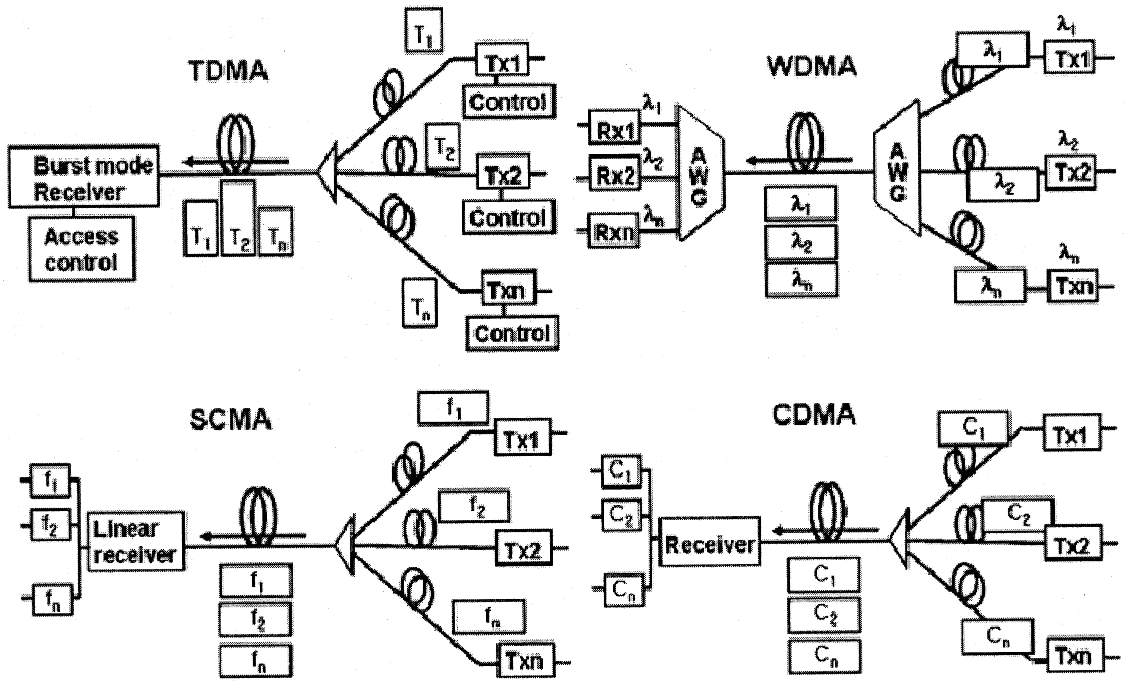

Figure 2.1: Various Multiple Access Methods for Upstream Data Transfer.([32])

2.3.4 Code Division Multiple Access(CDMA)

In this technique multiple users share a common upstream wavelength. Each subscriber is assigned a unique and effectively orthogonal code for transmission at any time regardless of when the others are transmitting. At the OLT receiver, all the overlapping codes are detected using a single receiver and correlated with sets of matching codes associated with each user-data channel. High correlation peaks occur for matched codes, and very small correlation peaks occur for the mismatched codes. This allows simultaneous and independent data transmissions to occur through a single-OLT receiver.

2.4 PON Architectures and Standards

There were many experimental PON systems in the early 1990s. Most of these were based on TDM multiplexing concept, and delivered the digital equivalent There are several PON implementation schemes,the three major ones being Broadband PON(BPON), Ethernet PON(EPON), and Gigabit PON (GPON). Another emerging PON scheme driving researchers' interest is Wavelength Division Multiplexing PON(WDM PON). While all of these follow the basic PON architecture (Chapter 1), the differences between them lie in the transmission protocols that are employed.Whereas an APON uses Asynchronous Transfer Mode(ATM), and an EPON uses Ethernet; a GPON uses the GPON Encapsulation Method (GEM) in addition to ATM to support Ethernet.

2.4.1 ATM PON / Broadband PON : APON/BPON

As mentioned before,broadband passive optical network standards are based on the G.983 series of ITU-T recommendations that specify Asynchronous Transfer Mode (ATM) as the transport and signalling protocol. BPON systems were initially called APON systems [33, 14], but the name APON led people to assume that only ATM services could be provided to end users. The name was changed to BPON to reflect that BPON systems offer broadband services including Ethernet access, video distribution, and the existing high-speed leased line services, and not just ATM services. Downstream transmission uses a 1490-nm wavelength for combined voice and data traffic, and a separate 1550-nm wavelength for video traffic [28]. Voice and data traffic is transmitted upstream by the ONU using a 1310-nm wavelength.The BPON G.983 standard offers downstream bandwidths of 155 Mb/s, 622 Mb/s, upto a maximum of 1.2 Gb/s and for the upstream traffic bandwidths of 155 Mb/s, and 622 Mb/s.

Fig.2.2(a) shows the basic frame structure in the case of a symmetric 155 Mb/s line rate [34]. The downstream frame format consists of 56 cells that have the 53-byte ATM cell length.

There are 54 *Data cells* which carry information including user data, signalling information, and ATM *operation, administration, and management* (OAM) information. Remaining 2 are *physical layer OAM* (PLOAM)cells. These cells are responsible for synchronization, error control, security, maintenance, and bandwidth allocation.In the upstream direction (Fig.2.2(a)),the basic frame contains 53 cell slots, each 56 bytes long. Each cell slot consists of an ATM cell and 3-byte overhead, which the OLT can program for various functions. The three overhead bytes are used to hold *guard time*- to avoid cell collisions, *preamble* - to acquire bit synchronization, and *delimiter* to indicate the start of an incoming cell and to perform byte synchronization.

BPON uses a ranging and grants process to transmit upstream data : since the ONUs use TDMA to send information to the OLT, each ONU must be synchronized with all the other ONUs.To achieve this the OLT uses a ranging process, which determines how far away each ONU is from the OLT. Once this distance is known, the OLT assigns an optimal synchronized time slot in which an ONU can transmit without interfering with other ONUs. This is done through the inclusion of 1-byte transmission permits (grants) contained within the downstream PLOAM cells. Each PLOAM cell has 27 grants that any ONU can read. However, a frame needs only 53 grants, which are mapped into the two PLOAM cells of a 155-Mb/s downstream frame ($27 \times 2 = 54$). As a result, the last grant of the second cell is an idle (dummy) grant. In an asymmetric transmission case, the grant fields of PLOAM cells 3 through 8 are filled with idle grants that an ONU will not use. Thus there is an undesirable overhead of 5 bytes. Also, controlled by the OLT, BPON uses a Dynamic Bandwidth Allocation (DBA) methodology that allows quick re-allocation of bandwidth on the PON based on current traffic requirements [35].

PON extension systems based on BPON specifications have been extensively researched. Extensions of the split factor and of the reach of an ATM PON have been realized in the SuperPON system [36, 37, 38]. Another long-reach PON concept has been demonstrated [39], having a reach up to 100 km and addressing 500 to 1000 ONUs with an aggregate symmetrical capacity of 2.5 or 10 Gb/s using forward error correction (FEC).

2.4.2 Ethernet PON : EPON

In 1995, when the FSAN initiative started, ATM had high hopes of becoming the prevalent technology in the LAN, MAN, and backbone. However, since the initiation of Ethernet technology in 2000, it has advanced manyfold as compared to ATM. Although ATM is a proven technology with scalable and flexible traffic-management capabilities and robust QoS features, it has certain limitations. As discussed above, there is an undesirable overhead of 5 bytes out of 53 bytes which makes the cell tax to be approximately 13 percent. That is, to send the same amount of users data an ATM network must transmit 13 percent more bytes than an Ethernet network. Also, a single corrupted or dropped ATM cell requires retransmission of the entire IP packet, even though other ATM cells belonging to the same IP packet may be received correctly. Another very important limitation is its cost. ATM switches and network cards are significantly (roughly 8 times) more expensive than Ethernet switches and network cards [40].

Similar to its function in other PON architectures, in an EPON all communications take place between the OLT and the ONUs. EPON data are carried in standard Ethernet Frames. Fig. 2.3 shows the format of a standard ethernet MAC frame, which can vary in length from 72 to 1526 bytes. First of the eight frame fields is of *preamble*, which enables the receiver to synchronize its timing to the beginning of the frame. In an EPON the preamble is not needed because of the full-duplex operational nature of the network. So, the preamble and start frame delimiter (SFD) fields are replaced by *start-of-packet delimiter* (SPD) and *logic link identifier* (LLID) along with *frame check sequence* (FCS) and 3 reserved bytes (Fig. 2.3). An EPON uses a specially developed *multi-point control protocol* (MPCP) to regulate both the upstream and downstream traffic [29, 34]. Its function relies on two messages - GATE and REPORT. A GATE message is sent from the OLT to an ONU for the assignment of a transmission time slot. A REPORT message is used by an ONU to convey its current bandwidth demand to the OLT to help the OLT make intelligent bandwidth allocation decisions.

Analogous to the BPON scheme, an EPON uses a 1490-nm wavelength for downstream transmission voice and data to the ONUs and a 1310-nm wavelength for the upstream return path from an ONU to the OLT. The 1550-nm window is available for other services, such as multi-channel video transmission from the OLT to the users. Recently IEEE 802.3 working group has formed a 10 Gb/s EPON study group. In September 2006 the 10 Gb/s EPON project was approved, and the work on the specification began in the newly formed IEEE P802.3av 10G-EPON task force (visit http://www.ieee802.org/3/av). The 10GEPON task force has set its objectives on specifying both symmetric and asymmetric line rate operations. The symmetric option will operate at 10 Gb/s in both the downstream and upstream directions. The asymmetric option, which reflects the fact that video services create capacity pressure mostly in the downstream direction, will use 10 Gb/s downstream and 1 Gb/s upstream. The task force places significant emphasis on enabling simultaneous operation of 1 Gb/s and 10 Gb/s EPON systems on the same outside plant.

2.4.3 Gigabit PON : GPON

The growing demand for higher speeds in the access network, and the widespread use of both ATM and Ethernet motivated the FSAN group in 2001 to develop a PON with the capabilities beyond those of BPON and EPON architectures. Consequently the ITU-T Recommendation series G.984.1 through G.984.4 for a gigabit PON (GPON) evolved [31]. GPON enable the transmission of both ATM cells and Ethernet packets in the same transmission frame structure.

A GPON is a full-service network, which means that it should be able to carry all services. These include 10- and 100-Mb/s Ethernet, legacy analog telephone, digital T1/E1 traffic (i.e., 1.544 and 2.048 Mb/s), 155-Mb/s asynchronous transfer mode (ATM) packets, and higher-speed leased-line traffic. To accommodate all these services efficiently, a GPON encapsulation method (GEM) is used [31]. Supported data rates are 1.244 Gb/s and 2.488 Gb/s downstream, and 155 Mb/s, 622 Mb/s, and 1.244 Gb/s upstream. At the same time, GPON capable transceivers provide an adequate loss budget to enable higher split ratios upto 1:64 splits and the ability to achieve the necessary optical loop length distances. Thus the attributes of GPON make it a logical choice for all FTTx deployments.

Fig. 2.4 shows the GPON frame format, which has a fixed 125-μs length called the P-Frame [41]. Upstream and downstream are synchronized by this P-Frame. A Grant for upstream is assigned in the header of P-Frame header of downstream. The frame consists of a *physical control block* (PCB) and a payload composed of a pure ATM segment and a GEM segment. In downstream, the PCBd includes framing related fields, the PLOAM field, and the bandwidth map field specifying the ONUs upstream transmission allocation. On the upstream, each ONU transmission is headed by a physical layer overhead field (PLOu), including a preamble and delimiter, which are configurable by the OLT. To assist with dynamic bandwidth allocation (DBA), the PLOu may include the dynamic bandwidth report field (DBRu), which carries traffic queuing reports from ONUs. The PLOu may also include a PLOAM field of identical format to the downstream PLOAM. The PLOAM and DBRu are optional and present in a frame only upon OLT request.

2.4.4 WDM-PON : WPON

Although PON provides higher bandwidth than traditional copper-based access networks, there exists the need for further increasing the bandwidth of the PON by employing Wavelength-division-Multiplexing (WDM) so that multiple wavelengths may be supported. Such a PON is called a WDM-PON A W-PON is a point-to-point access network (as opposed to point-to-multi-point in PON). Thus, WDM PONs have been actively researched as a potential technology for the next generation PON [42, 32, 43]. This PON uses multiple wavelengths in a single fiber to multiply the capacity without increasing the data rate. Different realizations have been proposed, of which a majority focus on the network architecture in which a passive wavelength router is used to replace the passive splitter in the PON fiber plant. As a result of this, each OLT-ONU pair has a dedicated and permanent wavelength assignment, and requires two transmitter/receiver pairs to form a point-to-point link (Fig. 2.5). A passive wavelength router located at the remote node is realized by arrayed waveguide grating (AWG)[4] or a set of thin film filters (TFFs). An AWG can operate over multiple free spectral ranges, permitting use of the same device for both downstream and upstream transmission.

In addition to its efficient use of wavelengths, a WDM-PON also has advantages in its use of optical-transmission power. TDM-PON architectures typically use a 1×32 power splitter at the RN that results in an insertion loss of about 17 or 18 dB. In contrast, the loss through typical AWGs can be in the range of 35 dB. Although two AWGs are required in WDM-PON, the insertion-loss improvement between a transceiver pair is on the order of 8 to 11 dB. In addition to the much lower insertion loss, an additional optical efficiency occurs since the noise bandwidth of each receiver can be $1/N$ that of a TDM-PON approach. For a PON with 32 users, this can result in an addition improvement of about 10 dB in the receiver sensitivity. This improvement becomes even larger when the PON is scaled up to service more users since the insertion loss through an AWG is effectively independent of its splitting ratio.

Although a WDM-PON has many technical advantages, there have been several issues that have prevented it from being a suitable solution for access applications. One issue has been related to the wavelength stability of the AWG located at the passive remote node (RN).

[4]An AWG is a passive device with a fixed routing matrix, so it fits well with the PON architecture.

Until recently, AWG required temperature control to keep their optical channels locked to a wavelength grid. This would have required electric power at the RN that would be unacceptable for a PON solution. Technology advances have allowed the recent commercialization of athermal AWGs that can remain locked to a DWDM-wavelength grid over temperature ranges experienced at the passive-node location.

Another issue is the concern of using wavelength-specific sources such as DFB lasers in a WDM-PON system. If DFB lasers were used, these lasers would require thermo-electric coolers (TEC) to stabilize their wavelengths that would result in relatively expensive packaging. Also, this scheme would require a different or colored transceiver for each user, resulting in high costs for inventory management and maintenance. To address this issue, much effort has been done on trying to develop low-cost sources like Fabry-Perot lasers [44]. It may also be possible to provide color-free operation by using relatively expensive wavelength-tunable lasers, if prior information of the channel wavelength is known [45].

Another major drawback of WDM PON compared to TDM PON such as EPON or G-PON is the requirement to provide multiple optical ports at the CO. To gain acceptance, it is therefore necessary to use highly integrated multiple channel transmitter and receiver arrays. Optimized array designs also offer the potential to reduce electrical power consumption and heat dissipation.

Recently, some hybrid PONs have also been proposed by researchers like WDM-Ethernet PON [46] and DWDM-TDM long reach PON [39] to incorporate the best attributes of different PONs into one.

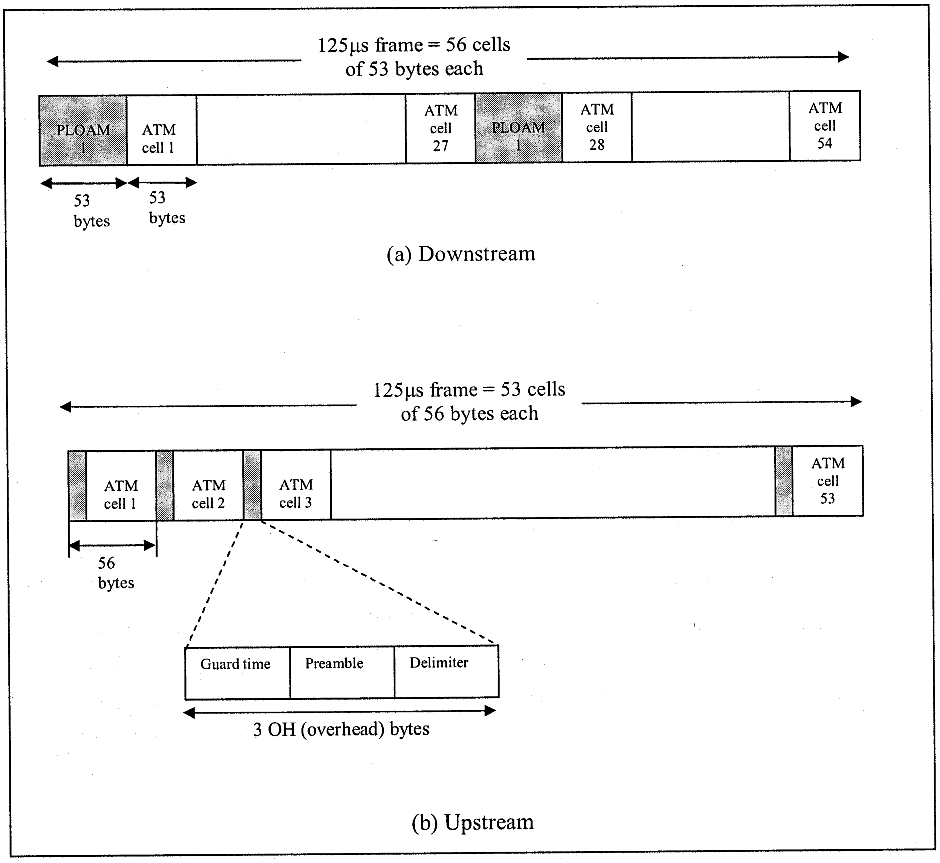

Figure 2.2: BPON frame format for a symmetric 155 Mb/s rate : (a) Downstream and (b) Upstream

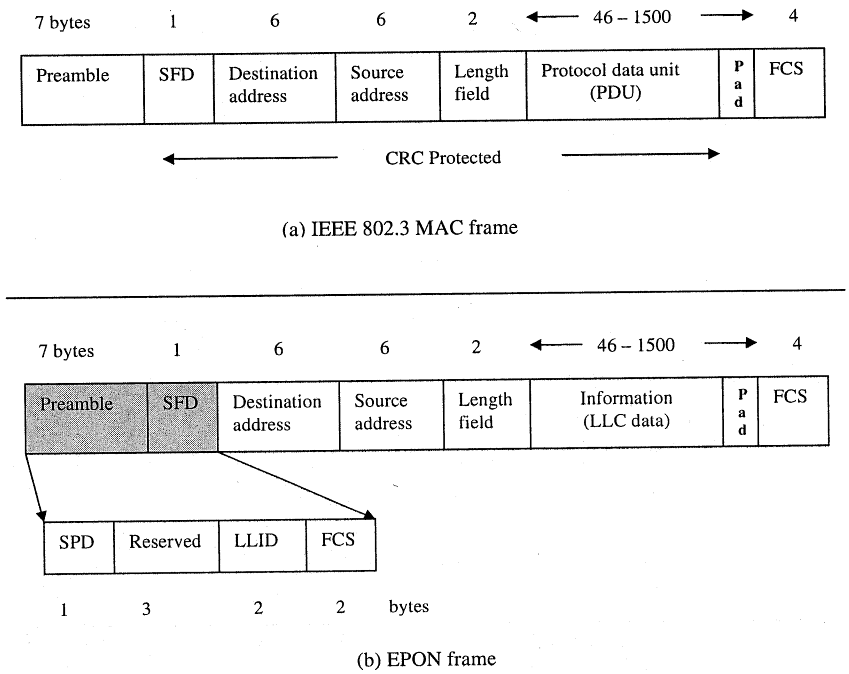

Figure 2.3: (a) Format of a standard Ethernet frame (b) EPON frame format

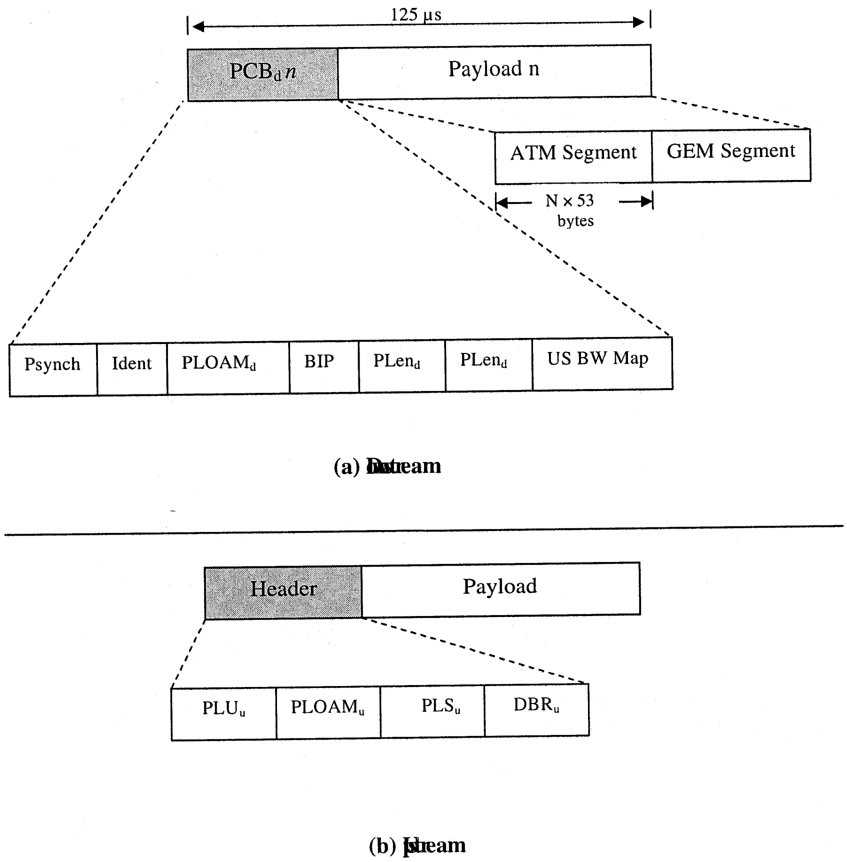

Figure 2.4: GPON frame format (a) Downstream and (b) Upstream

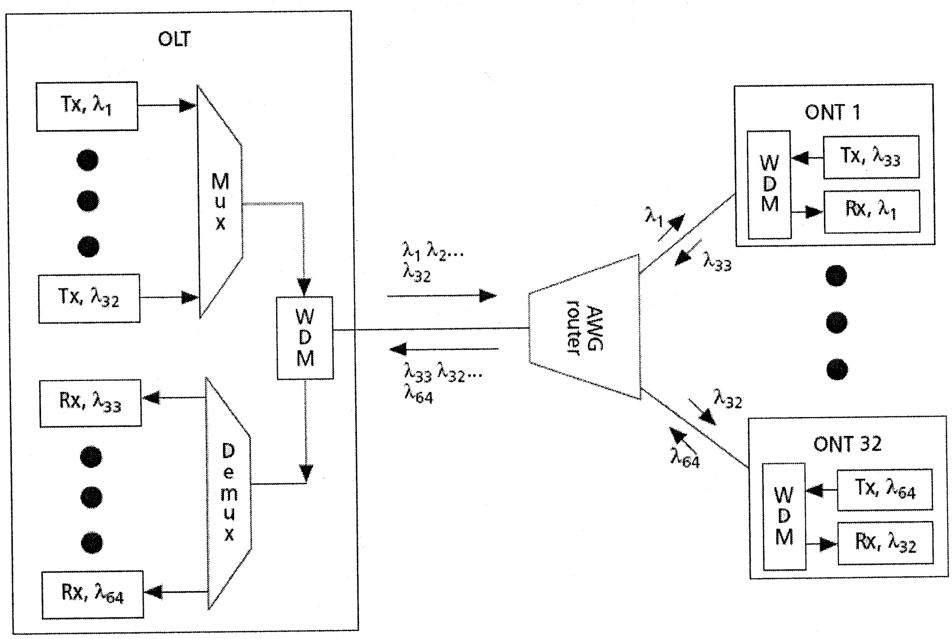

Figure 2.5: A typical point-to-point WDM architecture

Chapter 3

Passive Optical Components

In addition to fibers, light sources, and photodetectors, many other components are used in a complex optical communication network to split/combine, connect, route, amplify, or multiplex optical signals. The devices can be categorized as either passive or active components. Active optical components require some kind of external energy either to perform their functions or to be used over a wider operating range than a passive device, thereby offering greater flexibility. However, these devices typically are not used between endpoints in a PON, except within the end equipment [6]. A PON employs passive (not requiring any power) devices between the central office and customers' premises to manipulate the optical signal. In this section details on passive devices and fiber cables used for PONs has been provided. Some basic passive functions and the devices that enable them are shown in Table3.1. The passive components described in this chapter for PON applications include optical connectors, optical splices, optical splitters/couplers, cables, and Bragg Gratings.

3.1 Fiber Interconnections

A significant factor in any fiber optic system installation is the requirement to interconnect fibers in a low-loss manner. These interconnections occur at the optical source, at the photodetector, at intermediate points within a cable where two fibers join, or at intermediate points in a link where two cables are connected. The particular technique selected for joining the fibers depends on whether a permanent bond (splice) or an easily demountable connection (connector) is desired.

Table 3.1: **List of some basic passive functions and the devices that enable them**

Passive Functions	Devices which enable them
Transferring light signals	Optical Fiber
Attenuating light signals	Optical Attenuator, Isolator
Influencing the spatial distribution of a light wave	Directional Coupler, Star Coupler, Beam Expander
Modifying the state of polarization	Polarizer, Half-Wave Plates, Faraday Rotator
Redirecting light	Circulators, Mirrors, Gratings
Reflecting light	Fiber Bragg Grating, Mirror
Selecting a narrow spectrum of light	Fiber Gratings, Mach-Zehnder Interferometer
Combining or separating independent signals at different wavelengths	WDM Devices Providing lightpath continuity from one fiber to another Optical Connectors, Optical Splices

3.1.1 Optical Connectors

Optical connectors are temporary joints connecting two fibers in an optical link. They have traditionally been the biggest concern in using fiber optic systems. While connectors were once bulky and difficult to use, connector manufacturers have standardized and simplified connectors greatly. This increasing user-friendliness has contributed to the increase in the use of fiber optic systems; it has also taken the emphasis off the proper care and handling of optical connectors. Fiber optic connector types are as various as the applications for which they were developed. Different connector types have different characteristics, different advantages and disadvantages, and different performance parameters. A list of some of the popular connector types is given in Fig.3.2[1] and description provided in the next few paragraphs. Visit http://www.senko.com/fiberoptic/products.php and http://www.home.agilent.com/

1. **DIN 47256/4108 :** DIN 47256 (LSA) connectors feature a single unit body with spring-loaded free floating zirconium ferrule. The DIN connectors are manufactured of

[1]Pictures courtesy SENKO Advanced Components and Agilent technology.

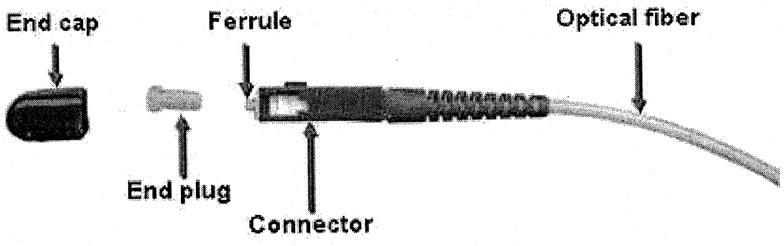

Figure 3.1: Parts of a connector

precision screw machined brass for consistent performance and durability.Its corrosion resistant body, compact design, and low insertion loss makes it suitable for a variety of applications ranging from CATV & Multimedia, LANs and WANs, to test equipment, premise installations, telecommunication networks, and data processing networks. It also finds applications in industrial, medical & military areas.

2. **E-2000 :** The E-2000 Connector Series is one of the few fiber optic connectors featuring a spring-loaded shutter which fully protects the ferrule from dust and scratches. The shutter closes automatically when the connector is disengaged, locking out impurities which could later lead to network failure, and locking in potentially harmful laser beams. The E-2000 Standard Connector is available for Singlemode and Multimode applications with Physical Contact (PC) end face. Angled Physical Contact (APC) 8 polish is also available. It complies with European (EN 186270) and International (IEC 61754-15) standards. Its major application areas are LAN, WAN, CATV, metrology, railway, and industry.

3. **PC/SPC/APC :** PC stands for physical contact and it refers to an optical connector that allows the fiber ends to physically touch. It is used to minimize backreflection and insertion loss. APC is an abbreviation for angled physical contact. It refers to a style of fiber optic connector with a 5-15 angle on the connector tip for the minimum possible backreflection. In each of them, metallic and ceramic ferrules are used.

4. **Biconic :** A Biconic Connector is a Fiber Optic connector that has 2 conical mating

surfaces that provide mating between 2 connectors. It is a high performance fiber optic connector that incorporates latest in precision molding techniques to yield fractional dB insertion loss. These connectors are used for cable to cable, or cable to equipment single fiber connections and can be installed on interconnect cable, buffered or unbuffered fiber. Its major applications are in local area and premise network, data processing systems, medical instrumentation, and remote sensing. Some of its features are : Precision Molding, High Connectability, Easy Installation, High Performance, Environmentally stable, Insertion Loss typical 0.5dB, Can be plugged and re-plugged easily, Available in Single mode and Multimode versions.

5. **ST :** The Straight Tip (ST) connector is a popular fiber optic connector originally developed by AT&T. ST connector has bayonet-style housing and a long spring-loaded ferrule hold the fiber. It is available in both multimode and singlemode versions. Horizontally mounted simplex and duplex adapters are available with metal or plastic housing, with a choice of phosphor bronze or zirconium split sleeve. The ST is one of the older generations of connector, but is still widely used for a variety of applications : Local Area Networks (LANs), data processing networks, premise installations, and instrumentation.

6. **SC :** The Subscription Channel (SC) Connector is known for its locking mechanism which gives an audible click when pushed in or pulled out. This push-pull design prevents rotational misalignment.Its key features are - high packing density, low loss, low backreflection, and low cost. It has a wide range of applications in CATV, active device termination, test equipment, and telecommunication networks.

7. **D4 Crimp Style :** The D4 connector is one of the older generation connectors which is keyed, and spring loaded. The ferrule has a diameter of 2.0mm. D4 Crimp Style Connector features a nickel plated brass body for enhanced durability, and comes with a choice of boots in a variety of colors. A singlemode epoxy/crimpless version D4 connector for quick and easy termination is also available.Its major application areas are in the telecommunication networks and Local Area Networks (LANs).

8. **BNC :** BNC is a popular coax bayonet style connector, often used for baseband video.

3.1.2 Splices

Knowledge of fiber optic splicing methods is vital to any company or fiber optic technician involved in Telecommunications or LAN and networking projects. In most fiber optic systems, connectors are used at the end equipment and splices are used to join links of cable together. While connectors are demountable joints at the end of the cable, splices are permanent joints usually within the cable. Connecting two fiber-optic cables requires precise alignment of the mated fiber cores or spots in a single-mode fiber-optic cable. This is required so that nearly all the light is coupled from one fiber-optic cable across a junction to the other fiber-optic cable.

Splicing Methods

There are two basic types of splices: Fusion and Mechanical.

- **Fusion Splicing** : Fusion splices use an electric arc to weld two fiber-optic cables together. Fusion splices are made by positioning cleaned, cleaved fiber ends between two electrodes and applying an electric arc to fuse the ends together. The process of fusion splicing involves using localized heat to melt or fuse the ends of two optical fibers together. In fusion splicing, splice loss is a direct function of the angles and quality of the two fiber-end faces. This method may produce fusion splices with losses less than 0.2 dB per splice and averaging 0.3 dB on multimode fibers. Sophisticated fusion splicing systems for single-mode fibers produce typical splice losses of 0.05 to 0.1 dB [34].

- **Mechanical Splicing:** Mechanical splicing systems position fiber ends closely in retaining and aligning assemblies. Focusing and collimating lenses may be used to control and concentrate light that would otherwise escape. Index matching gels, fluids and adhesives are used to form a continuous optical path between fibers and reduce reflection losses. Mechanical splices are easily implemented in the field, require little or no tooling, and offer losses of about 0.5 to 0.75 dB.

3.2 Optical Coupler/ Splitter/ Combiner

A PON employs a passive device to split an optical signal (power) from one fiber into several fibers and reciprocally, to combine optical signals from multiple fibers into one. This device is an optical coupler. In its simplest form, an optical coupler consists of two fibers fused together. It is a method of making a multimode or single-mode coupler by wrapping fibers together heating, and pulling them to form a central unified mass so that light on any input fiber is coupled to all output fibers. Commercial–Singlemode Monolithic (Single Fused) Couplers are manufactured using Fused Biconic Taper (FBT) technology, and are suitable for a wide range of optical communications systems. The couplers provide a cost effective solution for high density multi-port optical power management, exhibiting very low insertion loss, low polarization dependent loss and excellent environmental stability. Accurate coupling ratio with very tight uniformity is available over a wide wavelength range (1310 and 1550nm windows).

Often, couplers are manufactured to have only one input or one output.A coupler with only one input and multiple outputs is referred to as a **splitter**. A coupler with only one output and multiple inputs is known as a **combiner**. Combiner and Splitter fall under the category of **Tree couplers**. Another type of coupler is a **Star coupler**. It is a passive device that distributes optical power from more than two input ports among several output ports. Star and tree couplers distribute the input power uniformly among the output fibers.

A **Tee Coupler** is a three-port optical coupler and a **Y Coupler** is a variation on the tee coupler in which input light is split between two channels (typically planar waveguide) that branch out like a Y from the input. Fig.3.4 illustrates star and tree couplers, T- and Y- couplers and some commercially available WDM couplers.

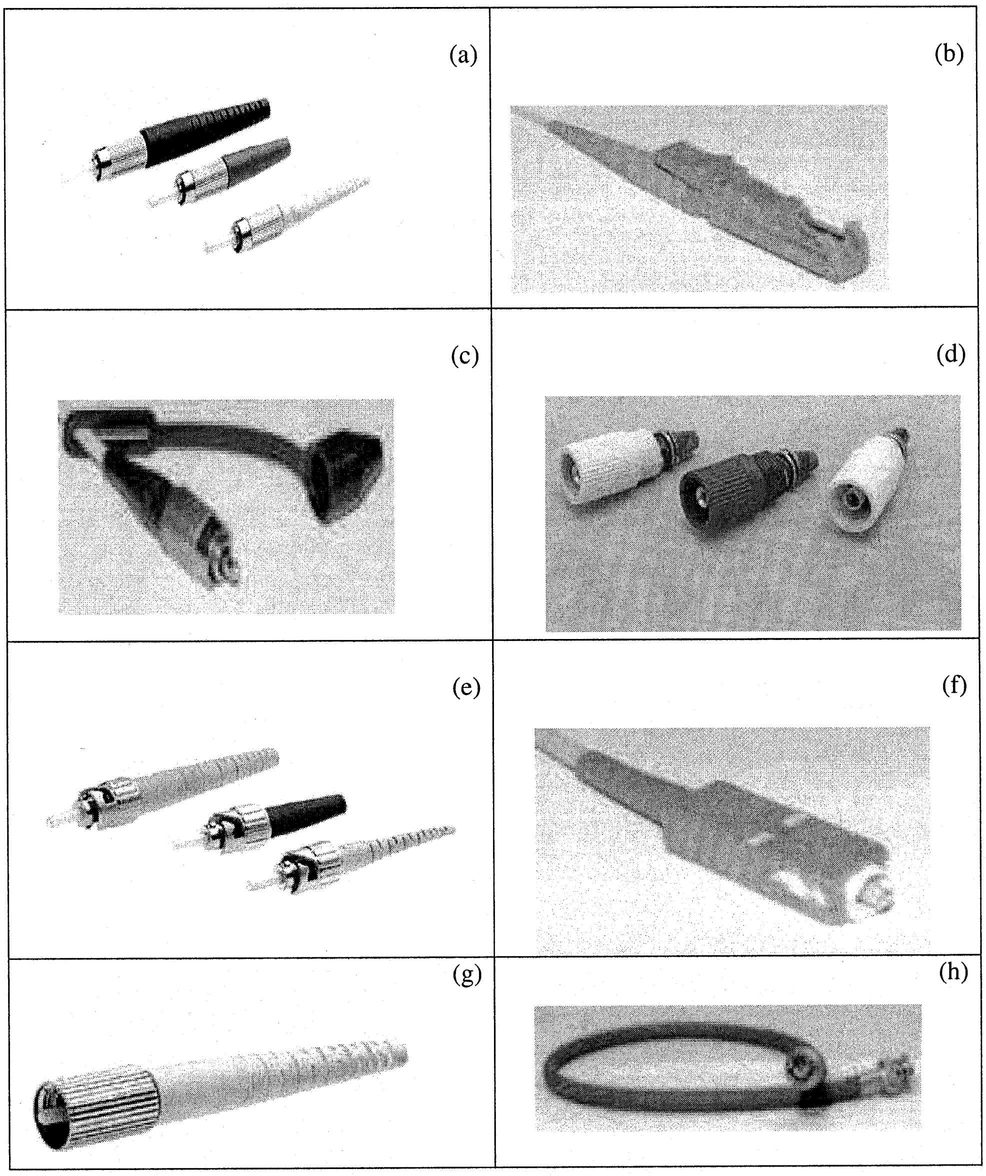

Figure 3.2: Commonly used optical connectors : (a) DIN 47256 (b) E-2000 (c) PC/SPC/APC (d) Biconic (e) ST (f) SC (g) D4 Crimp Style (h) BNC

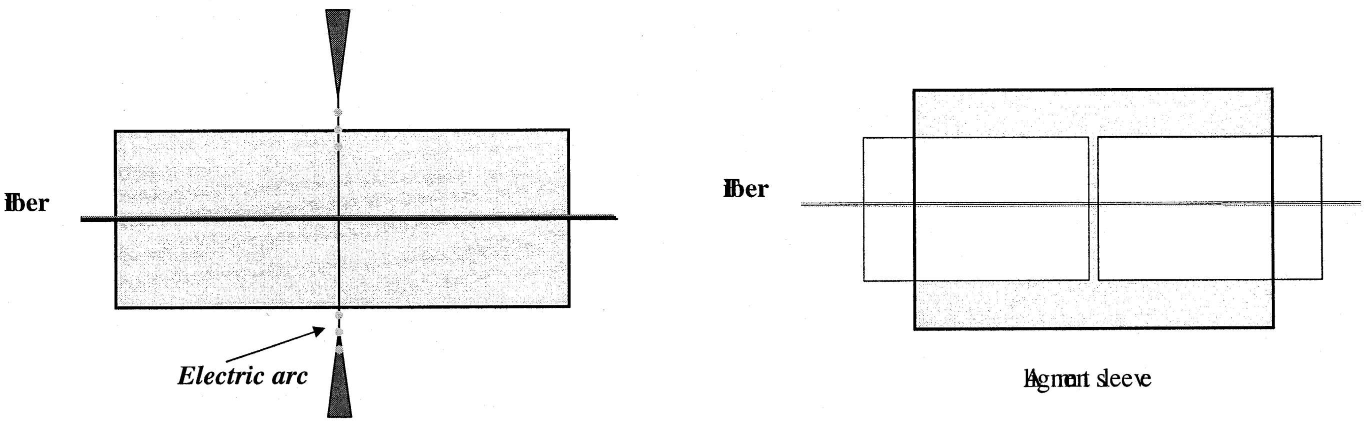

Figure 3.3: Common splicing techniques: (a) Fusion splicing (b) Mechanical splicing

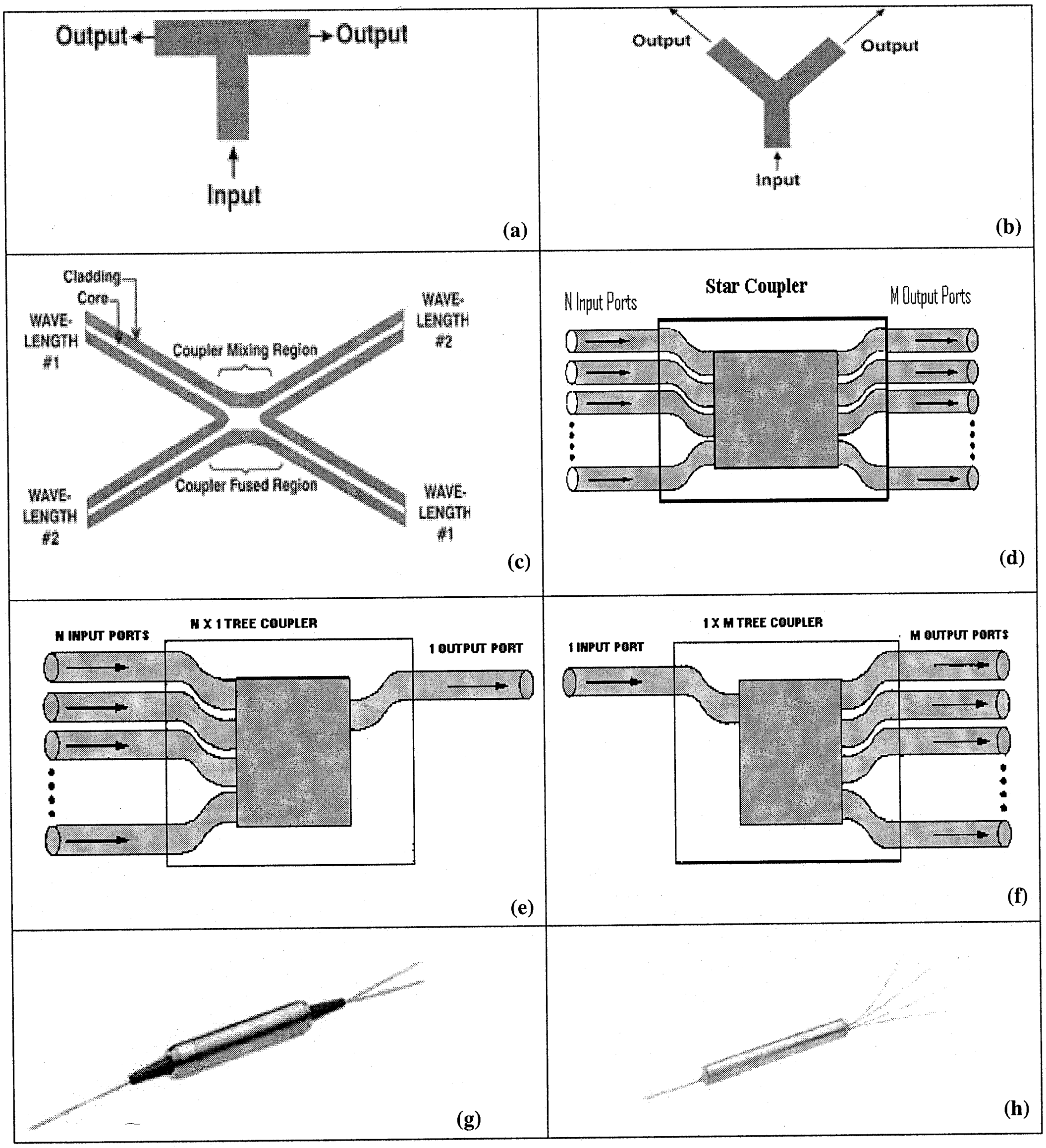

Figure 3.4: Coupler Types : (a) Tee-coupler (b)Y-coupler (c)Fused coupler (d) N $\times M$ Star coupler (e) $N \times 1$ Tree coupler (Combiner) (f) $1 \times M$ Tree coupler (Splitter) (g) Commercial 1×2 WDM coupler (photo: SENKO Advanced Components)(h) Commercial 1×4 WDM coupler (photo: SENKO Advanced Components)

Chapter 4

Laboratory Measurements

Following section discusses about a few measurements made in the lab using the Vector Signal Generator SMIQ03B (Rohde & Schwarz), and the Wireless Communication Analyzer WCA380 (SONY Tektronix)

4.1 Theory

4.1.1 RF over PON

Radio Frequency PON (RF-PON) , is a type of passive optical networking, that proposes to transport RF signals that are now transported over copper (principally over coaxial cable) over PON. RF-PON is an optical overlay for existing PON such as GPON or GEPON/EPON. The overlay for RF-PON works in the same way that some CWDM PON or potential WDM-PON overlays work. RF-PON offers backwards compatibility with existing RF modulation technology, but offers no additional bandwidth for RF based services. It offers a means to support RF technologies in locations where only fiber is available or where copper is not permitted or feasible.

4.1.2 Measurements

Following is a brief background on the types of measurement which we will be taking in the estimation of noise, fading, and distortion.

- Eye Diagram View : A diagram that shows the proper function of a digital system.

The "openness" of the eye relates to the BER that can be achieved. Eye diagrams are a very successful way of quickly and intuitively assessing the quality of a digital signal. A properly constructed eye should contain every possible bit sequence from simple 101's and 010's,through to isolated ones after long runs of consecutive zeros and other problem sequences that often show up weaknesses present in system design. Common ways of characterizing an eye are to measure the rise times, fall times, jitter at the middle of the crossing point of the eye, the overshoot present and many other numerical descriptions of eye behavior in order to compare devices being measured. Instruments usually offer automated measurements that simplify and speed up the taking of such measurements. There can be an immense amount of information stored in an eye diagram if it is taken correctly, and to enough data depth. This can tell a designer a lot about the parametric performance of his design, and a manufacturing engineer whether parts will cause problems in the field later.

- EVM View/Error Vector Analysis : Error vector magnitude (EVM) is a common figure of merit for assessing the quality of digitally modulated telecommunication signals. EVM expresses the difference between the expected complex voltage value of a demodulated symbol and the value of the actual received symbol. The error vector is the vector difference at a given time between the ideal reference signal and the measured signal. Expressed another way, it is the residual noise and distortion remaining after an ideal version of the signal has been stripped away. EVM is the root-mean-square (RMS) value of the error vector over time at the instants of the symbol (or chip) clock transitions. The red points represent the symbol positions of the measurement signal, and the green traces represent the differences between the measurement signal and the ideal signal. There are two kinds of EVM measurements

    1. Phase EVM
    2. Magnitude EVM

- Polar View/Vector and constellation Displays : The Polar View displays the digitally-modulated signal in the vector or constellation form.

    1. Vector Display : The vector display uses the polar co-ordinate or IQ diagram to display signals represented by the phase and amplitude. The red points show the measurement symbol positions and the green trace show the locus of shifts

between the symbols. Each point through which multiple concentrated traces pass corresponds to the symbol of the measurement signal. The error vector size may be estimated by comparing such points with the red points. The cross hairs show the symbol positions of the ideal signal.

2. Constellation Display : Like the vector display, the constellation shows the signal in the polar co-ordinate or IQ diagram. However, the constellation shows only the measurement signal symbols in red without displaying the symbol-to-symbol locus.

- Symbol Table Display : The Symbol-Table view inputs the signal processed in the Polar view and displays the demodulated digital data in a bit string form. The bit strings can be represented in binary, octal, or hexadecimal notation. The start position of digits is merely a relative position of symbols, so it can be changed using 'Rotate' in the Symbol-Table view menu. The Symbol-Table view can display the ideal signals as well as the measurement data.

4.2 Emulation

We tried to emulate an RF over PON assuming FTTC (Fiber-to-the-curb) scenario. We assume insignificant fiber dispersion, linear transmitter, and AWGN channel with fading. We use the in-built emulation capabilities of a Vector Signal Generator SMIQ03B (Rohde & Schwarz) for generating signals on such a system and the Wireless Communication Analyzer WCA380 (SONY Tektronix) to analyze the signal and obtain measurement outputs. The block diagram is shown in Fig. 4.1

Following general settings are initially made:

RF signal Freq = 1.8 GHz

Level = -10 dBm

System bandwidth = 10.0 kHz

Fiber Length = 1 km

Optical Transmitter = Direct Modulated DFB Laser

Reciever = PIN Diode

Wavelength = 1310 nm

Digital modulation:
Source = PRBS (pseudo random binary sequences)
Modulation = $\frac{\pi}{4}$DQPSK
Filter = sqr cos/0.35
Coding = PDC
EXT Inputs - 50 ohm/GND

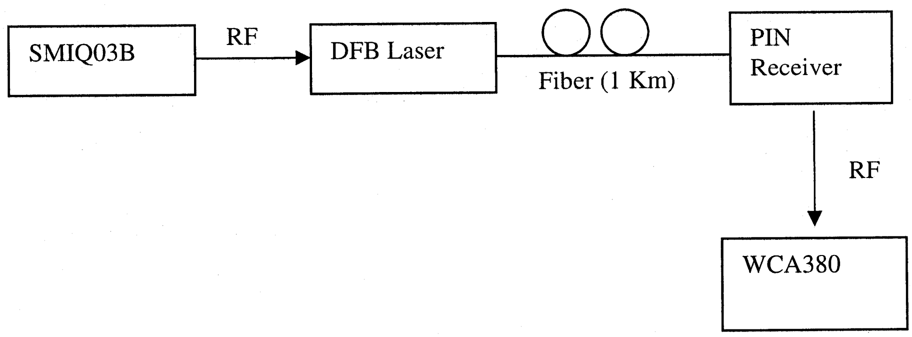

Figure 4.1: Block diagram of measurements

4.2.1 Noise Emulation

Here we keep rest of the parameters unchanged and vary only the signal-to-noise ratio (SNR) to see the effect. We take four sets of measurements for four different cases.

Case I : No noise Initially no noise is introduced in the system. Outputs generated are shown in 4.2. We notice that a perfect looking eye and a symmetric polar plot is obtained. Also, from the EVM plot, the value of rho comes out to be equal to 1 indicating no noise in the channel.

Case II: Noise introduced. A 0dB SNR is first emulated Now noise is introduced in the system . We begin with first keep the signal-to-noise ratio equal to 0dB, i.e., introducing a large amount of noise . Outputs are shown in 4.3. Here, an extremely noisy channel is indicated by distorted eye, polar, and EVM plots. Also, the value of rho is very low = 0.8049 and the magnitude and phase errors are significantly high = 36.11 $\%rms$ and 11.088deg respectively.

Case III: Noise introduced. A +15dB SNR is next emulated Now noise is reduced, with the signal-to-noise ratio of +15dB. Refer figure 4.4. Improved signal is clearly noticed. A better eye diagram and polar plot is witnessed. The rho value in this case = 0.9543, magnitude error = 15.634$\%rms$, and phase error = 8.665deg.

Case IV : Noise introduced. Lastly a +30dB SNR is emulated Lastly SNR is raised to a max. value of +30dB. See figure 4.5 and notice that a very good eye diagram and polar plot is obtained. Also note that the numerical value of rho reaches a value equal to 0.9985 which is very high. The magnitude error becomes 2.595$\%rms$, and phase error = 1.614deg. ,

4.2.2 Distortion Emulation

For emulating distortion in the signal, we keep the general settings as described before. We consider three cases :

Case I : No Distortion First when no distortion is introduced in the system (Fig. 4.6).

Case II : Polynomial Distortion Second, when distortion is introduced in the system and the characteristic of such distortion is chosen to be a polynomial. In a polynomial distortion the distortion follows a polynomial equation $x + k_2x^2 + k_3x^3 + k_4x^4 + k_5x^5$ where the value of k is between -10dB and +10dB. We randomly choose values of $k_2, k_3, k_4, andk_5$ to be equal to -1.5dB, -1.0dB, 3.0dB, and 2.0dB and get the result as shown in Fig. 4.7

Case III : List Distortion Lastly, characteristic of the distortion introduced is chosen from a list. We choose a TWTA list and obtain the graph as shown in Fig.4.8

4.2.3 Fading Emulation

We now consider that after the FTTC termination node, signals travel wirelessly. This is when fading comes into picture. We choose Rayleigh fading and consider different cases for it.

Case I : No Fading in the channel In the begin we do not introduce any type of fading and see the channel. It is shown in Fig. 4.9.

Case II : Standard Rayleigh Fading introduced Next we introduce the rayleigh fading with speed = 20 m/s and path loss = 5.0dB. See Fig. 4.10

Case III : Rayleigh Fading with three times standard speed Now we keep rest of the things constant and change the speed from 20 m/s to 60 m/s. We clearly see faster fading (Fig.4.11) than in case I.

Case IV : Rayleigh Fading with thrice the initial speed and twice path loss Lastly we keep the speed as 60 m/s and at the same time also increase the path loss from 5 to 10 dB. Fig. 4.12

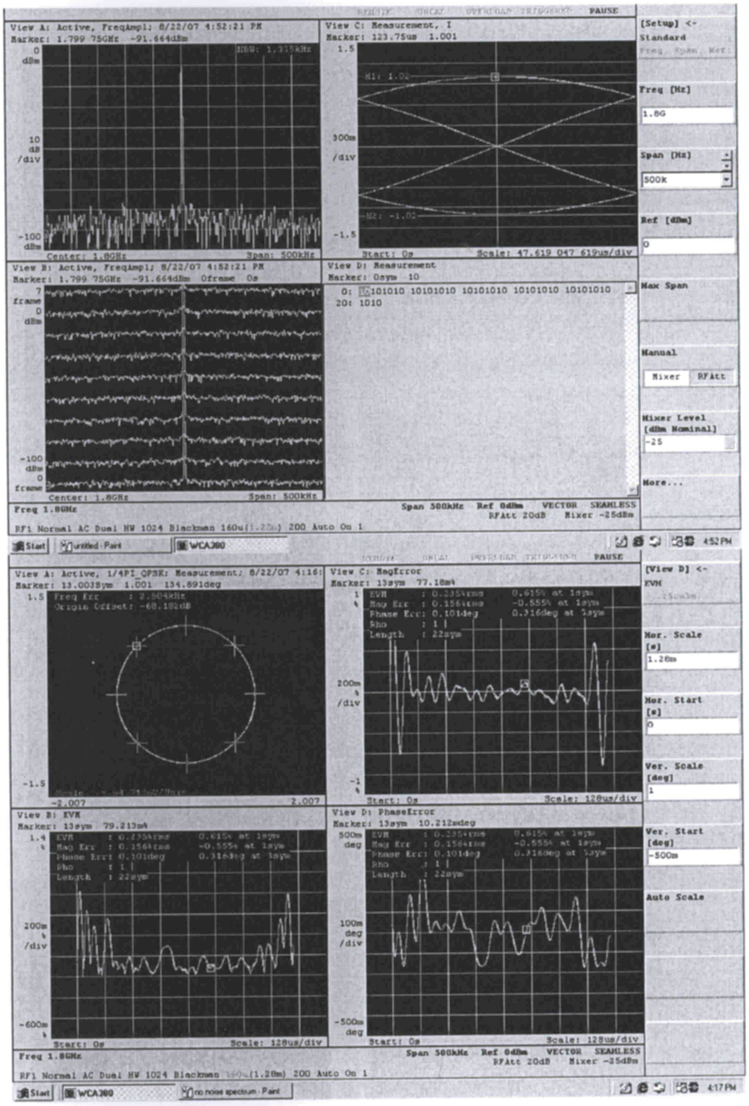

Figure 4.2: Graph when no noise introduced in the system

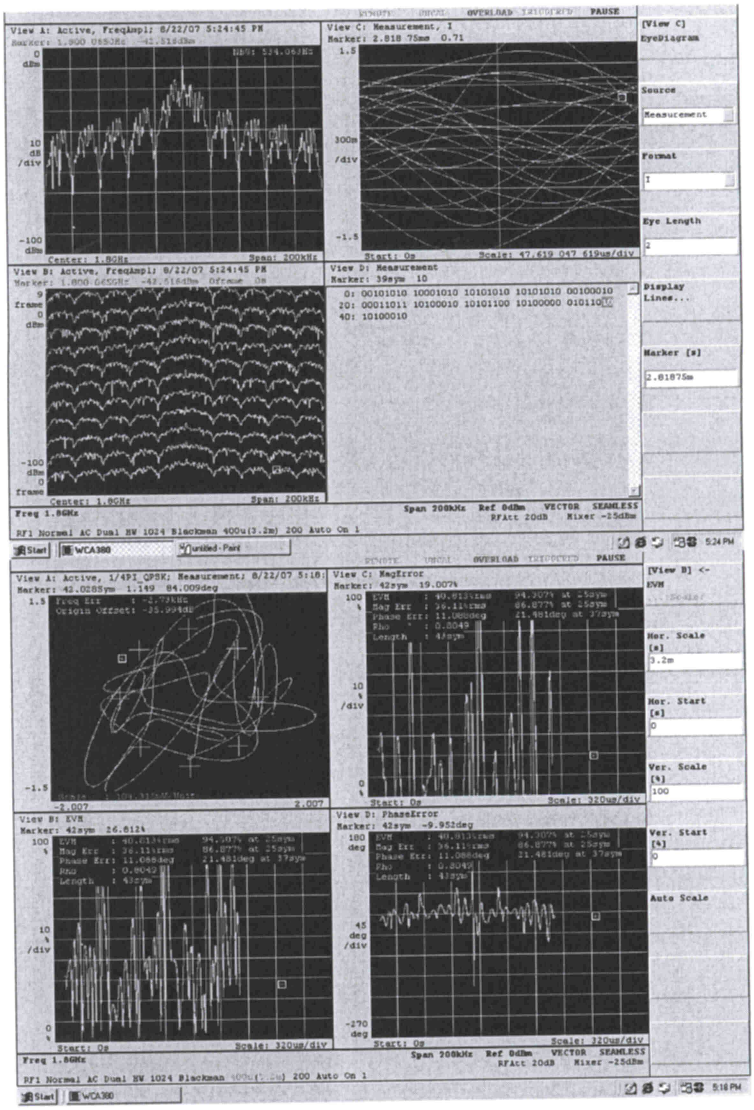

Figure 4.3: Graph when noise with 0dB SNR introduced in the system

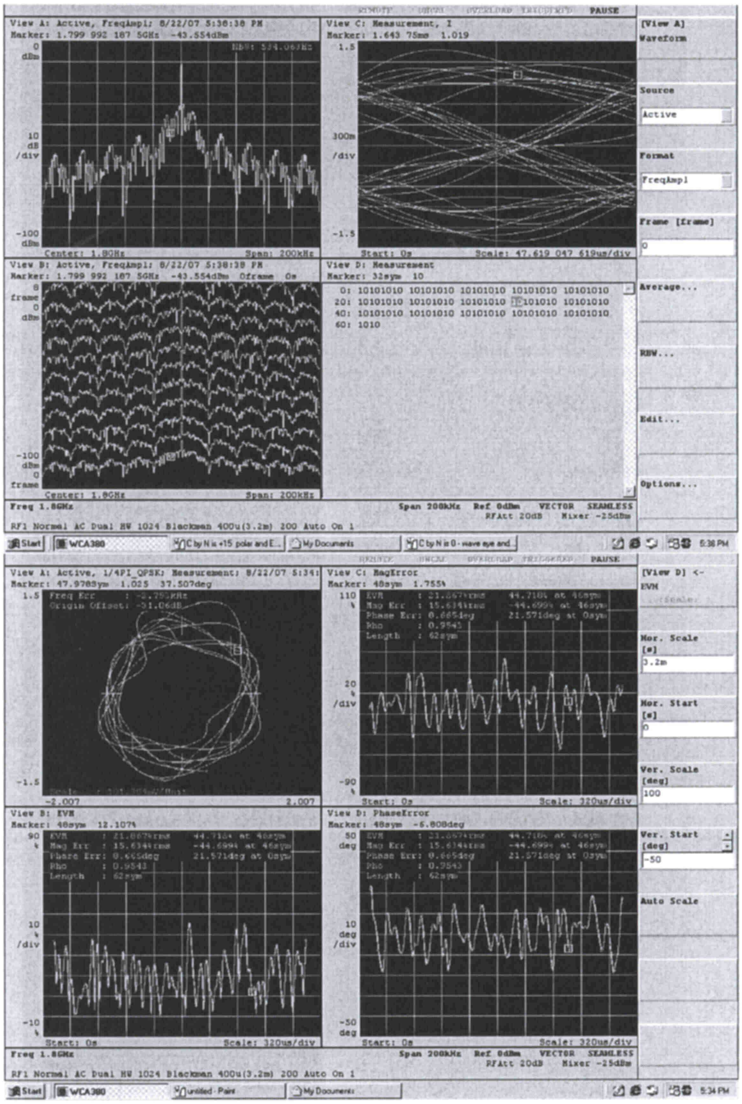

Figure 4.4: Graph when noise with +15dB SNR introduced in the system

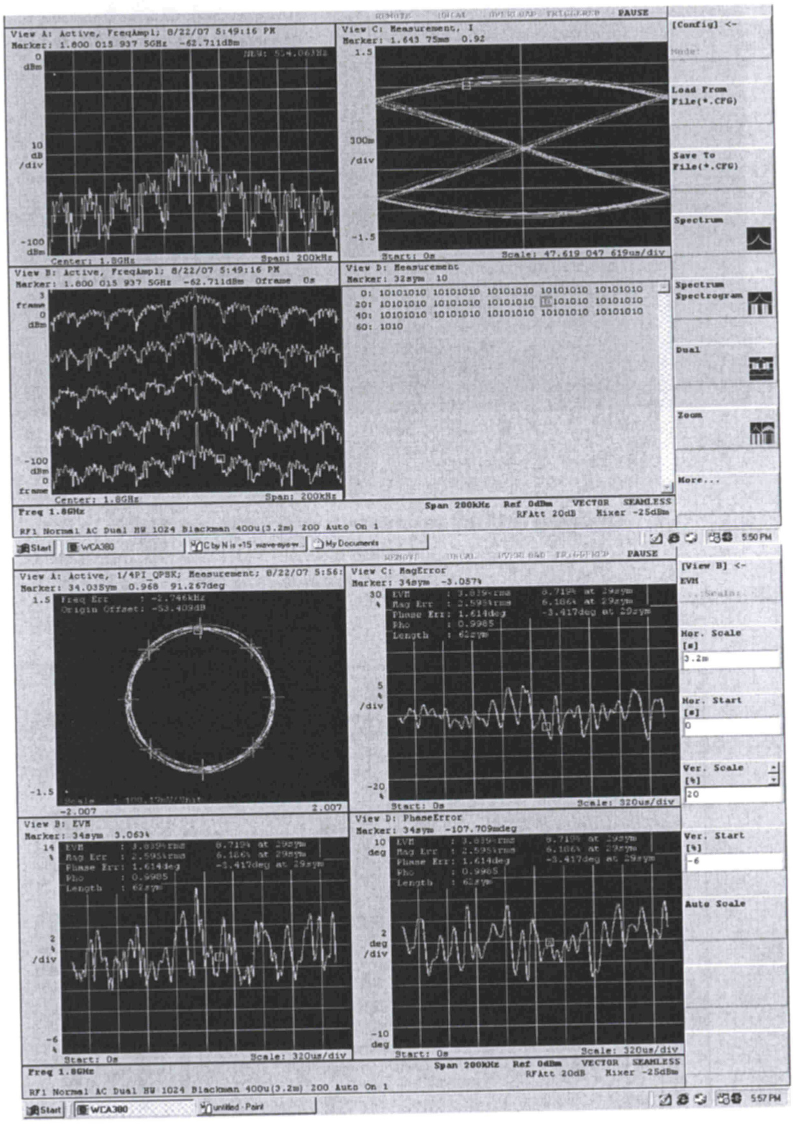

Figure 4.5: Graph when noise with +30dB SNR introduced in the system

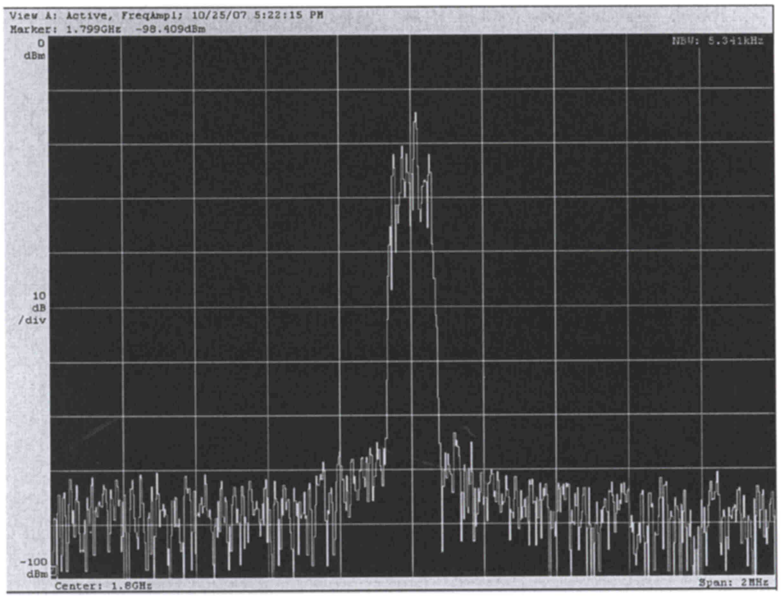

Figure 4.6: No distortion in the System

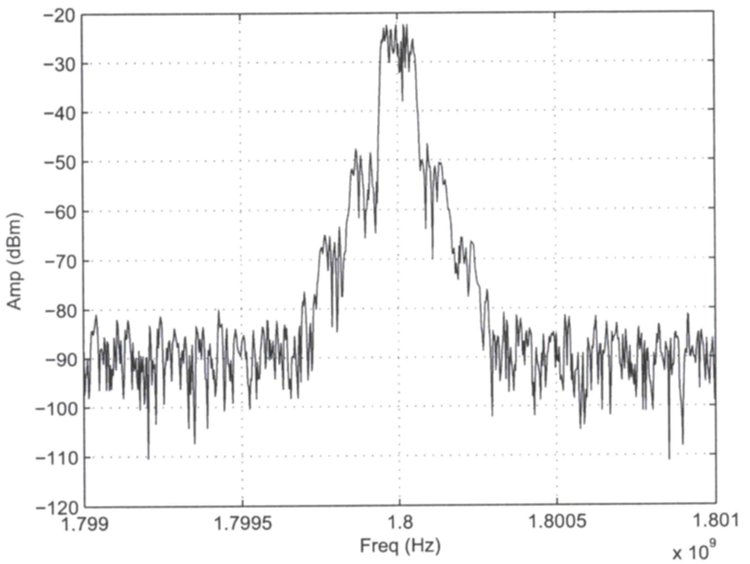

Figure 4.7: Polynomial distortion

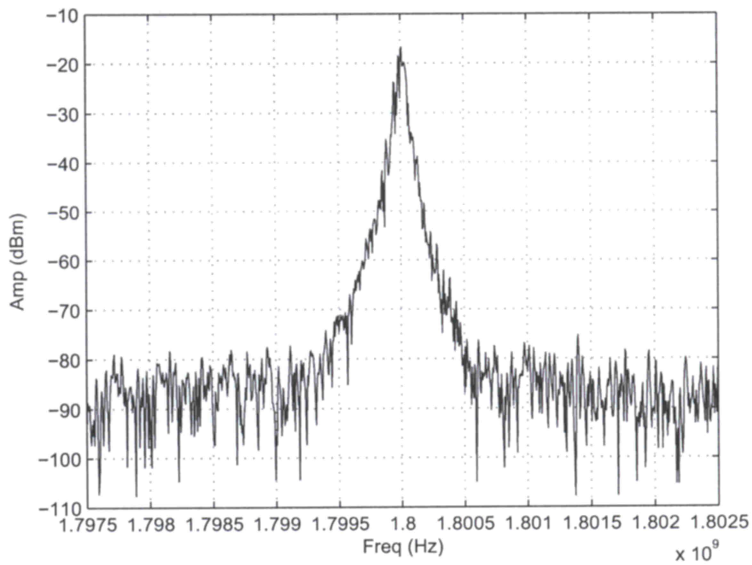

Figure 4.8: List distortion

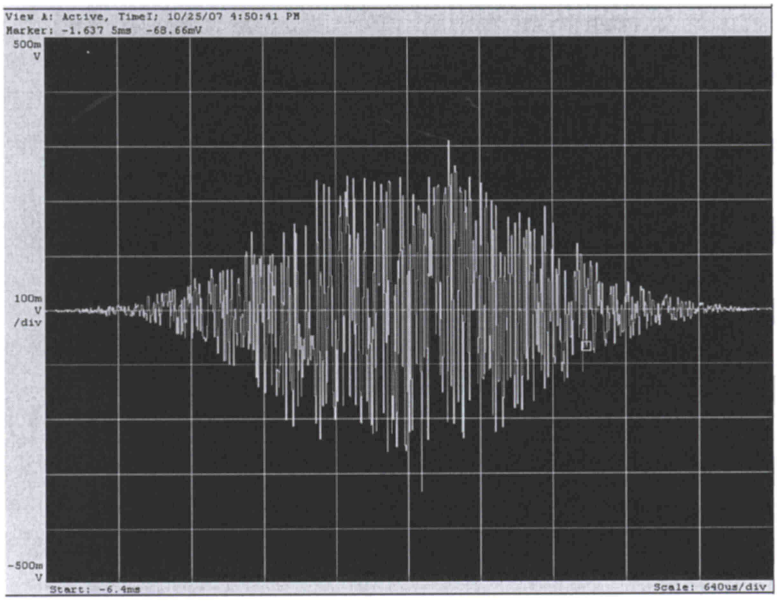

Figure 4.9: No fading

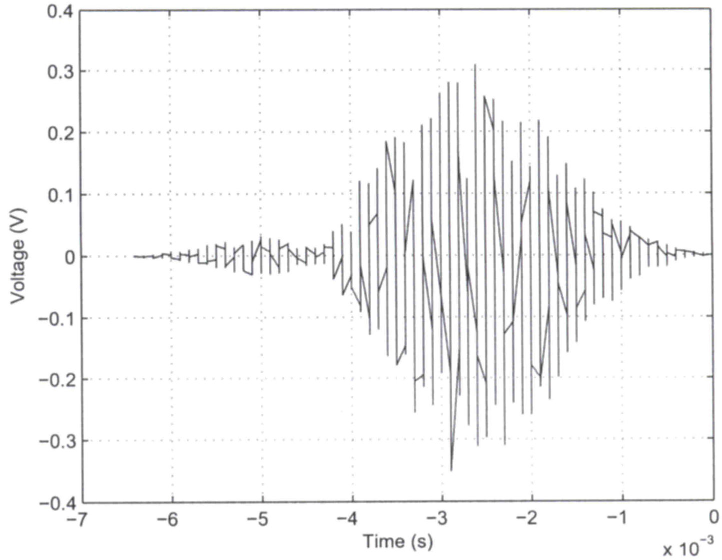

Figure 4.10: Rayleigh fading for setting 1

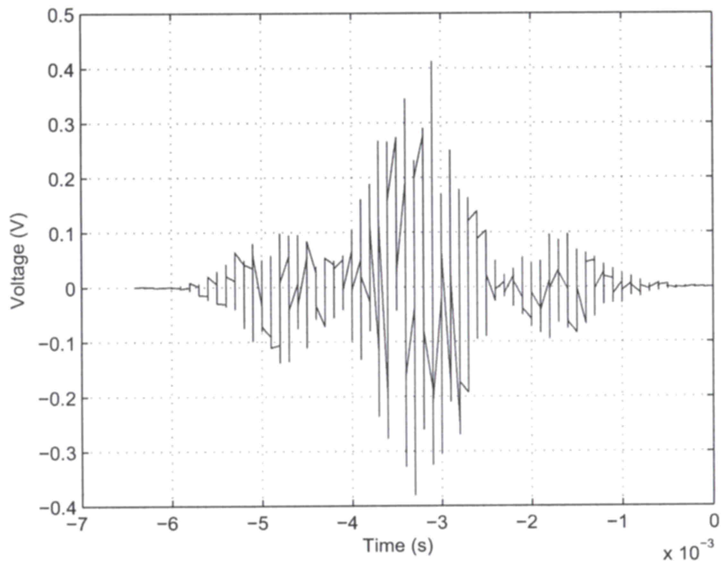

Figure 4.11: Rayleigh fading for setting 2

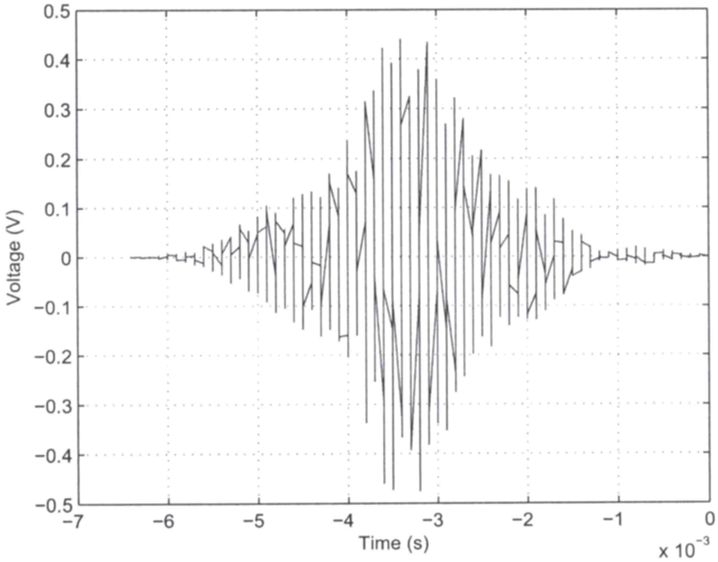

Figure 4.12: Rayleigh fading for setting 3

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Fiber in the access has been neglected and for long. In this report we outlined the current status and technologies of Optical Access Networks. We started by highlighting the significance of fiber in access networks in providing the last mile bottleneck solution. Access networks can be subdivided into two major classes: wired and wireless. Wired networks include a telephone-line-based digital subscriber line (DSL), power lines (BPL/PLC), cable TVs hybrid fiber-coaxial networks (HFC) and optical access networks (OAN). The currently popular access solutions like copper, BPL, xDSL, and HFC do not seem to meet the ever increasing bandwidth demands. The need of fiber in the optical access solution has never been so strong as it is now. FTTx is being chosen because it maximizes bandwidth to the residence; future-proofs one's network; and provides for enhanced network reliability, increased customer satisfaction, expanded service capability, and improved network OPEX.

Wired optical networks are being deployed in two main versions: active optical networks (AONs) and passive optical networks (PONs). In this report we focused on point-to-multipoint PON architecture, in which only the passive optical components are employed at the ends of the network links. A brief historical review of evolution of fiber in the last mile was made which followed the different PON flavors - APON/ BPON/ EPON/ GPON/ G-EPON/ WDM-PON. There are different protocols and standards behind each of the PON. FSAN has developed three versions of PON: APON, BPON and GPON while EPON has been developed and standardized by the IEEE. The term APON is reserved for a PON dedicated to delivering voice and data, while BPON denotes an extended version of the original network enriched with transmission capabilities and additional services. GPON is a PON version capable of delivering traffic at the gigabitper- second bit-rate range. Another emerging PON technology is WDM-PON which further increases the bandwidth of the PON by employing Wavelength-division-Multiplexing (WDM) so that multiple wavelengths may be supported.

The fundamental difference between ATM and Ethernet is that ATM provides better support of all legacy time-division multiplexing (TDM) traffic, such as T/E and SONET/SDH, whereas Ethernet is a data-transport technology that inherently supports IP-oriented traffic. The most critical problem with ATM is that the manufacturing of ATM components is at a relatively low level today and continues to decline; as a result, ATM switches and network cards are significantly more expensive (roughly eightfold) than the same Ethernet components. On the other hand, Ethernet continues to boom andthanks to its inexpensive equipmentthis technology is ubiquitous; it is also interoperable with a number of legacy technologies. The variable length of the Ethernet frame advantageously contrasts with the fixed-length ATM frame in regard to flexibility of transmission of various types of data traffic. However, ATM-based GPON is now capable of carrying the encapsulated Ethernet traffic.

In Summary, fiber is finally making its move into the edge of network. The technology is sound, the demand is here and the cost structure is compelling.

Passive optical components are as important in any Passive optical network as PONs themselves. Passive components do not require any external energy to guide, attenuate, redirect, and manipulate signals. We also provided details on some of the passive optical components like optical splices and connectors, and couplers , combiners and splitters. Different passive component types have different characteristics, different advantages and disadvantages, and different performance parameters.

Radio over fiber is another emerging technology in access networks that proposes to transport RF signals that are now transported over copper (principally over coaxial cable) over PON. Though details have been omitted in this report, we tried to carry some noise, fading, and distortion emulation measurements. Making use of the in-built emulation capabilities of a Vector Signal Generator SMIQ03B (Rohde & Schwarz), we successfully showed that as SNR increases we get better signals at the receiver end. For the distortion settings higher distortion is noticed for polynomial case. For fading scheme we see that by increasing the speed of rayleigh fading and increasing the path loss large-scale fading results.

5.2 Future Work

- This report examines only the basic PON architectures - A/BPON, EPON and GPON. Rapidly evolving next generation hybrid PONs like SuperPONs, Long reach PONs, WDM-Ethernet PONs e.t.c. is another area of interest

- In this report we do not deal with some of the critical areas of PONs like - the cost, QoS, and security issues, which can be researched further.

- Current deployment state of FTTH in different parts of the globe is another topic of interest. United States, Japan, Europe, Korea, China, and Australia are currently involved in numerous projects.

- The laboratory work can be extended further. Some more cases in distortion emulations may be considered. Like, the values of k in the polynomial distortion may be varied, and a suitable comparison made. Likewise, in fading emulations, other channel fading options besides rayleigh fading may be considered and results noted.

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