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DESIGN OF RADIO OVER FIBER SYSTEM FOR WIRELESS ACCESS

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Hasanain Imad Abdulelah SHANAN

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KABLOSUZ ERİŞİM İÇİN FİBER ÜZERİ RADYO SİSTEM TASARIMI

(Yüksek Lisans Tezi)

Hasanain Imad Abdulelah SHANAN

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ÖZET

Fiber üzeri Radyo-Pasif Optik Ağlar (RoF-PON), kablolu ve kablosuz haberleşme için fiber ve RF teknolojilerinin avantajlarını birleştirerek, kapasite, kapsama, veri hızı, esneklik ve taşınabilirliği iyileştirmek için ana bir çözüm olarak görülmektedir. Dalga Boyu Bölmeli Çoklama (WDM) ise büyük veriyi yüksek hızda taşımak için PON'da uygulanan bir başka yöntemdir. Bu çalışmada, günümüzdeki genişbant sistemlerin artan gereksinimlerini karşılamak için, iki farklı Yansıtan Yarıiletken Optik Yükselteç (RSOA) konfigürasyonda (güçlendirici yükselteç, ön-yükselteç) WDM-RoF-PON sistem mimarisi önerilmiştir. Önerilen WDM-RoF-PON sistemi RSOA kullanarak, 25 km tek mod fiberde (SMF) ve 5.2 m açık alan mesafede temel bantda (BB) 2.5 Gbps, aşağı hatda 1.25 Gbps, yukarı hatda 1 Gbps veri taşıyabilmektedir. WDM-RoF-PON sistemin tasarımı ve benzetimleri Opti System V14 yazılım aracı ile yapılmıştır. Önerilen sistemin kalite faktörü (Q), bit hata oranı (BER), fiber menzili (km) ve göz diyagram performansları incelenmiştir. Benzetim sonuçlarına göre, güçlendirici yükselteçli WDM-RoF-PON'un fiber menzili 10^{-9} BER ile 100 km civarında olurken, yükselteçsiz sistemin aynı BER ile fiber menzili 70 km civarında görülmüştür. Tüm sistem performans parametreleri ve bunların analizi değerlendirildiğinde ve diğer çalışmalarla kıyaslandığında, şu sonuca varılmaktadır ki önerilen WDM-RoF-PON sistemi, yeni ortaya çıkan sistemlerin yüksek hız, genişbant, uyarlanabilirlik, taşınabilirlik gereksinimlerini karşılamak için hem kablolu hem de kablosuz haberleşmede tatmin edici performans ile iyi, esnek bir çözüm olabilir.

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ABSTRACT

Radio over Fiber-Passive Optical Networks (RoF-PON) are viewed as the main answer for expanding capacity, coverage, high data rate, portability and adaptability by combining the advantages of the fiber and RF technology for wired and wireless communication. Wavelength Division Multiplexing (WDM) is also another technology used in PONs to carry big data with high speed. In order to meet the demanding requirements of broadband systems, in this study, we have proposed WDM-RoF-PON system architecture in two different Reflective Semiconductor Optical Amplifier (RSOA) configurations: booster amplifier and pre-amplifier. Proposed WDM-RoF-PON system utilizes RSOA to carry 2.5 Gbps baseband (BB), 1.25 Gbps downlink, 1 Gbps uplink through 25 km Single Mode Fiber (SMF) and 5.2 m free-space distance. Design and simulations of WDM-RoF-PON system have been performed in Opti System V14 software tool. Quality factor (Q), bit error rate (BER), fiber reach (km) and eye pattern performances of proposed system have been investigated. Simulation results show that proposed WDM-RoF-PON's fiber reach is almost 100 km with a BER of 10^{-9} with booster amplifier while no-RSOA system's reach is almost 70 km with the same BER. Considering all the system performance parameters and their analysis, and comparing with the other works, it can be concluded that proposed WDM-RoF-PON system could be a good, flexible solution for wired/wireless communications with satisfactory performance to meet the high speed, broadband, adaptable and portable requirements of emerging systems

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SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below along with their explanations.

Symbols	Explanation
dB	Decibel
EB	Exabytes
GHz	Giga Hertz
km	Kilometer
M/Gbps	Mega/Giga bits per second
N	Node
nm	Nanometer
Pe	Probability of error
Q	Quality factor
THz	Tera Hertz
μ	Average value
λ	Wavelength
σ	Standard deviation

Abbreviations	Explanation
ADSL	Asymmetric Digital Subscriber Line
AM	Amplitude Modulation
APON	Asynchronous Transfer Mode based Passive Optical Network
ASE	Amplified Spontaneous Emission
AWG	Arrayed Waveguide Grating
BB	Baseband
BBU	Base Band Units
BER	Bit Error Rate
BS	Base Stations
CATV	Cable Television
CO	Central Office

Abbreviations	**Explanation**
CPRI	Common Public Radio Interface
C-RAN	Centralized Radio Access Network
CS	Central Station
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
DCF	Dispersion Compensating Fibers
DSBCS	Double Sideband Carrier Suppression
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EPON	Ethernet Passive Optical Network
ETDM	Electrical Time Division Multiplexing
FBMC	Filter Bank Multicarrier
FEC	Forward Error Correction
FOF	Fiber Optical Feeder
FPLD	Fabry Perot Laser Diode
FPR	Formyl Peptide Receptor
FSK	Frequency Shift Keying
FSO	Free Space Optical
FTTB	Fiber to the Building
FTTC	Fiber to the Cabinet
FTTH	Fiber to the Home
GPON	Gigabit capable Passive Optical Network
HDTV	High-Definition Television
HFC	Hybrid Fiber Coaxial
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IM	Intensity Modulation
IoT	Internet of Things
IP	Internet Protocol
ITU-T	International Telecommunication Union Telecommunication
LNA	Low Noise Amplifier
LO	Local Oscillator

Abbreviations	Explanation
LPF	Low Pass Filter
LR-OANs	Long-Reach Optical Access Networks
LR-PON	Long Reach Passive Optical Network
LS	Local Station
LTE	Long Term Evolution
MMW	Millimeter Wave
MZM	Mach Zehnder Modulator
NG-OANs	Next-Generation Optical Access Networks
NG-PON	Next-Generation Passive Optical Network
NRZ	Non-Return to Zero
OCS	Optical Carrier Suppression
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONUs	Optical Network Units
P2P	Point to Point
PA	Power Amplifier
PD	Photo Diode
PM	Power Module
PMP	Point Multi Point
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QD-LD	Quantum Dot-Laser Diode
RF	Radio Frequency
RFA	Raman Fiber Amplifier
RN	Remote/Receiving Nodes
ROADM	Reconfigurable Optical Add/Drop Multiplexers
RoF	Radio over Fiber
RRU	Remote Radio Unit
RS	Reed-Solomon

Abbreviations	Explanation
RSOA	Reflective Semiconductor Optical Amplifier
RZ	Return-to-Zero
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
SRS	Stimulated Raman Scattering
TDMA	Time Division Multiple Access
TPS	Triple-Play Services
VDSL	Very high bit rate Digital Subscriber Loop
VOAs	Variable Optical Attenuators
VoIP	Voice over Internet Protocol
WAN	Wide Area Network
WDM	Wavelength Division Multiplexed
Wi-Fi	Wireless Fidelity
WSS	Wavelength Selective Switch
XG-PON	10 Gigabit-capable Passive Optical Network

1. INTRODUCTION

The communication world is constantly growing due to the introduction of video based interactive, multimedia services and wireless access. High data rates, flexible communication and large bandwidth are required in both wired and wireless networks for High-Definition Television (HD-TV), Video-On-Demand and Online Interactive Gaming, etc. Passive optical networks (PON) are widely used for delivering high-speed internet services to customers. However, the increasing demand for bandwidth requires more efficient solutions. One proposed solution is Radio over Fiber-Passive Optical Network (RoF-PON) technology, which combines the high bandwidth of fiber optic cables with the flexibility of radio frequency (RF) wireless communication to improve network performance. RoF-PON is seen as a potential answer to expanding network capacity, coverage, data transmission, and portability to utilize the full potential of fiber optic technology. This study investigates the use of Wavelength Division Multiplexed RoF-PON (WDM-RoF-PON) structures to transmit multiple signals over a single optical fiber. By using advanced optical and wireless techniques, WDM-RoF-PON can achieve efficient broadband communication with improved network performance. One of the motivations for this study is to address the increasing need for high-bandwidth internet services to support emerging digital technologies. The 60 GHz millimeter-wave (MMW) band has special importance for wireless communication due to its huge free bandwidth of 7–9 GHz in that band. Integrating RoF with WDM-PON could be a good solution to significantly increase the total capacity and coverage area of already existing backbone optical networks, so that baseband data and data modulated by RF signals can be transmitted at the same time for multiservice networks [1].

Fiber to the home (FTTH) innovation is being deployed in numerous countries for wireline access networks because of its higher transmission data transfer capacity than Asymmetric Digital Subscriber Line (ADSL). FTTH is seen as the main future solution for supporting even the conventional phone lines (ADSL, Plain Old Telephone Services (POTS)) or links (Satellite TV, Cable TV (CATV)) to be replaced by optical fiber. FTTH has grown since the 1980s to accommodate the growing network demands of the modern world and is still being used today. Since the 1980s, fiber technology has become cheaper and easier to install. As of today, further developed PON have been deployed to carry out FTTH around the world. The main benefit of FTTH is increased network performance. FTTH provides higher speeds over longer distances that older coaxial cables, twisted-pair cables and DSL cannot reach. FTTH also offers significantly higher bandwidth than other connectivity methods. Recent research is focused on potential increases to flow Gigabit capable Passive Optical Network (GPON) and Ethernet Passive Optical Network (EPON) frameworks, as these frameworks might meet the future the data transfer capacity requirements and do not utilize solely the entire optical data transmission. Among the various FTTH approaches proposed, WDM simply adds another aspect to this for a redesign. WDM-PON is acquiring popularity with the evolving and modern PON.

Institute of Electrical and Electronics Engineers (IEEE) came up with a new standard in 2004 and named it as EPON also known as IEEE 802.3ah standard, it is a “short haul” network that uses fiber optic cables, ethernet packets (instead of ATM cells), and a single network with a single protocol to deliver internet access, voice over internet protocol (VoIP), and digital TV services in populated areas [2–6]. EPON also covers a fiber reach of 20 km with a peak data rate of 1.25 Gbps. It can support a power budget of 30 dB and 16 Optical Network Units (ONUs). Over the period, PON has undergone several updates and upgrades to fulfill the demand for high data rates from consumers and evolved as intermediate standards like GPON, 10 Gigabit Ethernet Passive Optical Network (10G-EPON), and 10 Gigabit-capable Passive Optical Network (10G-PON).

The GPON is developed by ITU-T to enhance downstream data rates to 2.4 Gbps and upstream data rates up to 1.2 Gbps [7]. The first general characteristics were formulated in 2003 and later updated over a period of time and ITU-T G.984.5 is the latest version [8]. GPON covers the reach up to 60 km and for this reason, it is called a Long Reach Passive Optical Network (LR-PON) [9, 10]. GPON utilizes the same wavelength plan and power budget as EPON. It supports a maximum of 64 ONUs which provide advantages over its predecessor [11]. The number of simultaneous users is increased due to Time Division Multiple Access (TDMA) techniques. Performance and privacy are improved using error correcting Reed-Solomon (RS) codes and advanced encryption standard respectively.

IEEE upgraded its EPON standard to 10G-EPON with symmetrical 10 Gbps data rates and also provided an option for 1 Gbps data rate upstream [12– 15]. 10G-EPON is also known as IEEE 802.3av as standardized in 2009. It provides coverage up to 20 km of fiber reach and 16 ONUs simultaneously. It supports 30 dB of power budget and also utilizes the

Forward Error Correction (FEC) technique to improve the performance of the system. 10G-EPON utilizes a separate wavelength plan than EPON to make sure that both standards can co-exist on the same deployed Optical Distribution Network (ODN). Downstream channels range from 190.34 THz to 189.74 THz for 10 Gbps transmission and from 199.86 THz to 202.56 THz for 1Gbps transmission. Upstream wavelength spectrum is shared and separated by dual-rate TDMA, in which, 1 Gbps upstream data can be sent on channels ranging from 220.43 THz to 237.93 THz, and 10 Gbps upstream data utilizes 237.93 THz to 234.21 THz channels. 10G-EPON became popular as the energy-efficient PON enlightened a new area of research in optical access networks [16, 17].

ITU-T developed the Next Generation Passive Optical Network (NG-PON) standard that offers 10 Gbps and 2.5 Gbps of data rates for downstream and upstream respectively. The first standard was completed in 2010 and named as ITU-T G.987 or in general 10 Gigabit Passive Optical Network (10G-PON) [18–21]. In later stages, asymmetric data rate version 10G-PON is specified as XG-PON1 (10 Gbps down; 2.5 Gbps up) and symmetric data rate version as XG-PON2 (10 Gbps down; 10 Gbps up). XG-PON can co-exist with the already deployed GPON and EPON since it typically utilizes the 1577 nm wavelength for downstream and the 1270 nm wavelength upstream. It is considered to be an economical solution since the cost is shared by 128 number of randomly distributed ONUs which are located around the locality of 60 km from the transmitter. The power budget is 35 dB, which is the highest ever proposed by an optical access network as of 2012 [22, 23].

Optical fiber and wireless technologies both have highly changed the world's most complex services and systems. A few examples are mobile banking services, real-time tracking transportation, and many others like home security, fitness routines, and communications. All these services can be scheduled and controlled from the wireless devices. It is expected by many researchers that new applications and services are to be developed in future.

Motivation

WDM-RoF-PON is a recent and significant advancement in the field of optical communication systems. This technology has gained a lot of attention due to its potential to offer high-speed communication services, data transmission, and internet connectivity. The background study of WDM-RoF-PON is based on the need for efficient communication systems that can support the growing demand for high-speed data transmission. This technology is a combination of WDM, RoF, and PON, which makes it possible to transmit data over long distances while maintaining high signal quality and speed. The WDM-RoF-PON system works by utilizing optical fiber technology and RF technology to transmit signals over long distances. The WDM technology allows multiple signals to be transmitted over a single fiber, while the RoF technology enables wireless connectivity by converting optical signals into RF signals. One of the key benefits of the WDM-RoF-PON system is its ability to offer high-speed internet connectivity to remote and rural areas. This technology can provide a cost-effective solution for delivering broadband services to underserved areas, which can help bridge the digital divide.

RoF is an innovation that permits RF transmissions to be dispersed over simple optical connections. Broadband microwave information signals are modified into optical transporters at Central Station (CS) in RoF frameworks and then moved to remote destinations or Base Stations (BS) by means of optical fiber link. The base-stations then use microwave radio to communicate the RF signals over small regions.

Due to the drastic expansion of broadband multimedia and real-time services such as VoIP, high-speed internet, HDTV, interactive games, social networking, cloud computing, and video conferencing, the next-generation access networks have pushed a tremendous increase in bandwidth and capacity for fixed and/or mobile users throughout the last decade.

In 2016, international Internet Protocol (IP) traffic was 96 EB per month and by 2021, international IP traffic has reached 278 EB per month [1, 24] as shown in Figure 1.1. Worldwide IP traffic will boost nearly threefold over the next 5 years and traffic from wireless and mobile devices will account for more than 59 percent of total IP traffic. In the meantime, most of the traffic has moved from voice and text-based administrations to video, media, and cloud administrations in broadband access networks because of customers' requests [25, 26]. FTTH is viewed as a decent answer for this request with large coverage and the absence of dynamic parts. And WDM can carry numerous information signals with various frequencies of light through a single fiber [27, 28]. Current wireless access networks, on the other hand, can support flexibility and mobility in transmission but lack sufficient bandwidth to meet the ultimate bandwidth demand [29-31]. In this respect, analysts and specialists accept that optical/wired or potentially remote and additionally concurrent systems are the most encouraging answer for meeting the coverage, data transfer capacity, portability, and adaptability requirements all over the place.

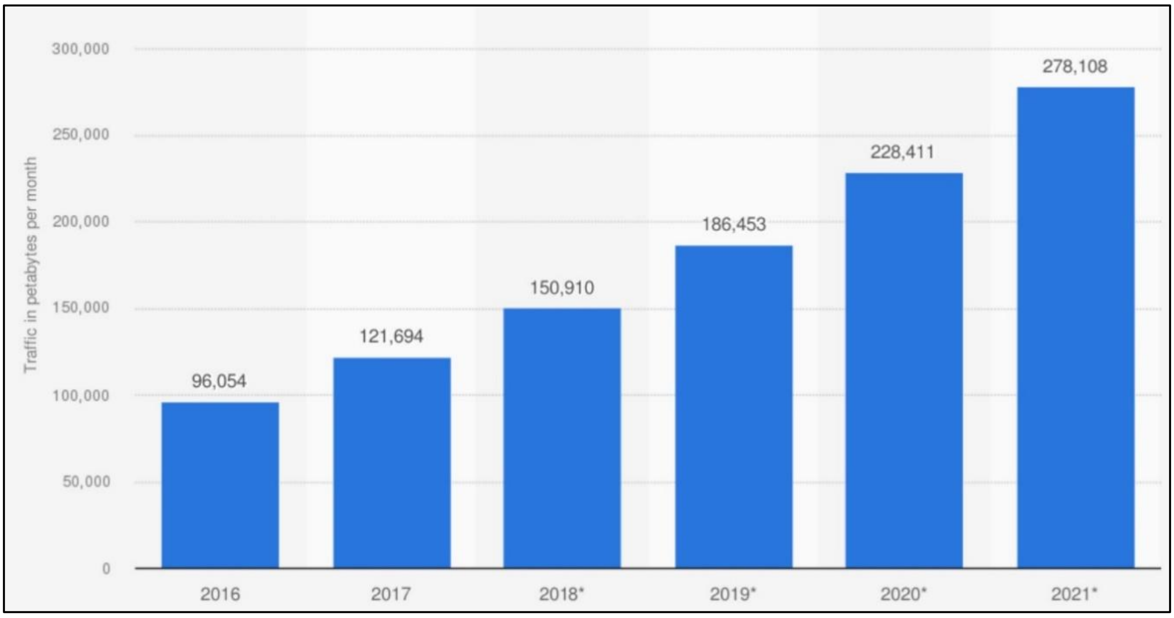

Figure 1.1. Global IP traffic growth and global consumer internet traffic [13].

Wired access networks

Access networks are the communication networks that connect end-user devices, such as computers, smartphones, and tablets, to a Wide Area Network (WAN), such as the Internet. Access networks provide the connection to business services, including cloud-based storage, video conferencing, and software-as-a-service platforms. These services are only accessible through reliable and high-speed connections, making the access network an essential component of modern enterprise infrastructure. Similarly, consumers rely on access networks for broadband internet access, VoIP, cable television, video streaming, and mobile device connectivity.

Wired access networks provide a reliable and secure connection to the internet for both residential and commercial users. Common wired network options include DSL, cable, fiber optics, and ethernet. These use physical cables to connect devices and typically exist in fixed locations. Optical fiber is turning into the most famous mechanism for high information rate transmission over significant distances. Single Mode Fiber (SMF) has proactively been used for significant distances and transport networks because of its many benefits over existing copper wire, Hybrid Fiber Coaxial (HFC), and DSL. It incorporates low power, resistance to electromagnetic impedance, little weight, and tremendous transmission capacity for accessibility [32]. In early times, optical fiber could not be used for applications since it was expensive. Nowadays, reasonable price optical fibers with low losses (0.2 dB/km) are available with other systems' parts and components.

Passive optical network (PON)

The passive optical network (PON) can offer large bandwidth for broadband access networks through optical fiber access. The PON is a point-to-multipoint (PMP) network that usually contains a splitter to divide one point to multiple points at the central office (CO) [2]. PON architecture as revealed in Figure 1.2, constitutes the following components: an Optical Line Terminal (OLT) located at the CO and a number of Optical Network Units (ONUs) close to the customer’s site.

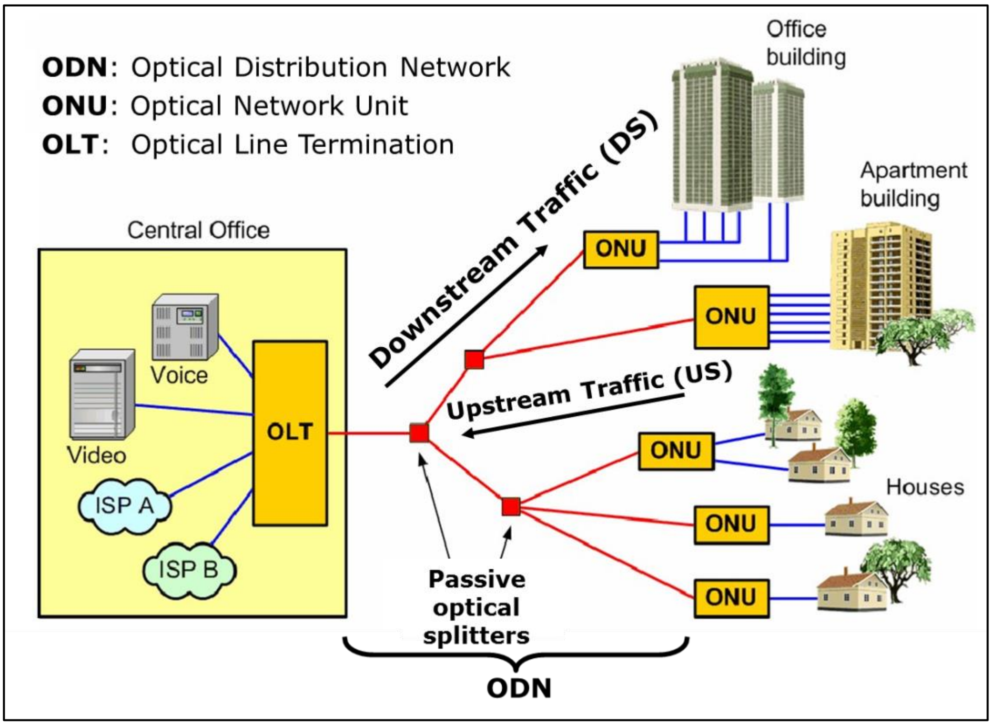

Figure 1.2. Typical passive optical network (PON) architecture [14].

The basic building blocks of a PON-based system can be classified into the following parts which consist of an OLT normally present at the site of the service provider, followed by ONU which is near the end users, and the set of passive components called

Remote/Receiving Nodes (RN). Figure 1.2 portrays the dissemination of the previously mentioned components. The fundamental hardware in the PON is the OLT located at the CO can adjust the changes in the electrical signals utilized by the specialist. One more significant capability of the OLT is to arrange the activity and multiplex the incoming signals from the ONUs by allotting upstream data transfer capacity to the ONUs.

The ONU is a component that is normally located near the customer premises. The ONU is responsible for transforming the incoming optical signals into the corresponding electrical signals at the premises of the customer for providing telecommunication services over an optical fiber network.

A hub that is essential for an optical system, like a power splitter that splits the optical power from one fiber between a few filaments and correspondingly, combine the optical signals from different strands into one complex signal, and furthermore channels' data from any input ports to the output ports.

PONs may be typically classified as:

- Wavelength division multiplexed PON (WDM-PON).
- Time division multiplexed PON (TDM-PON).

<u>WDM-PON</u>

WDM-PON would be a promising answer for satisfying the necessity of more transmission capacity in future since WDM-PON includes the utilization of various frequencies given by numerous laser sources or a single laser source at the transmitter by relegating the various frequencies to the various clients over a single fiber as introduced in Figure 1.3. The frequency channels are communicated from the OLT to the ONUs on a single fiber in the downstream bearing of a WDM-PON utilizing a variety of tunable lasers situated at the OLT. The frequency channels are then demultiplexed at the detached RN, and each ONU port is assigned a dedicated frequency. Each ONU has a transmitter laser hotspot for sending upstream traffic to the OLT and getting downstream traffic from it. The uplink data is received by the OLT using a demultiplexer and combiner. Consequently, WDM-PON can be a good solution for quick, effective, and secure data transmission in the broadband access system [24, 25].

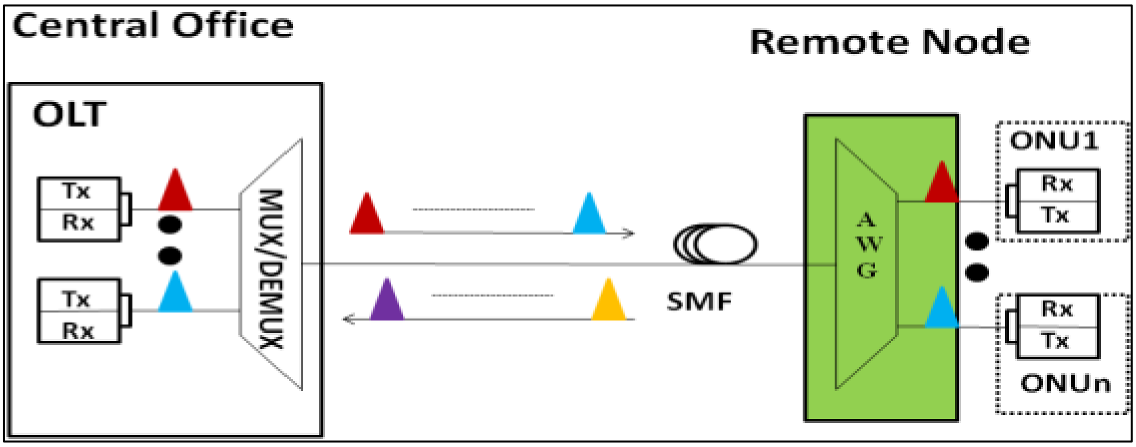

Figure 1.3. WDM-PON architecture [24].

WDM is a method in optical communication that utilizes various frequencies/wavelengths of lasers to move countless optical carrier signals on a single fiber. This method permits bidirectional communication to stream over a single standard fiber with extended limits. An optical system can support very high transmission capacity. The WDM network partitions this into various small transmission capacity optical channels, permitting numerous information streams to be moved along a fiber. A WDM framework utilizes multiplexers at the sending end to multiplex numerous optical signals onto a single fiber and demultiplexers at the receiving side. The transmitter is ordinarily comprised of a laser and a modulator. The laser source produces an optical carrier signal as a fixed or tunable frequency. The beneficiary is comprised of a photodiode (PD), which converts the optical signal into electrical signal. A WDM-PON as shown in Figure 1.3 employs a passive WDM coupler for using it as a RN or a tunable ONU. A shared fiber may be used for carrying the independent wavelengths, which are also multiplexed signals. The advantages of WDM can be written as:

- Absence of synchronization
- High Capacity
- Privacy enhancement

And disadvantages of WDM can be written as:

- Requirement of costly infrastructure
- Lack of flexibility

Time division multiplexing-PON (TDM-PON)

TDM-PON utilizes the time multiplexing convention and is also called power-splitting PON because the circuits use power splitters for synchronization [33]. As displayed in Figer1.4, N clients share a single frequency/wavelength containing downstream data. Endorsers can communicate or potentially get data as per their appointed time allotments in this setup, and the ONUs chooses their information through the particular bundle connected to the signal. Each ONU gets all signals sent by its related header ONU, as do the other ONUs in a similar stage. The OLT's information is broadcast in TDM and reaches all ONUs in the same way.

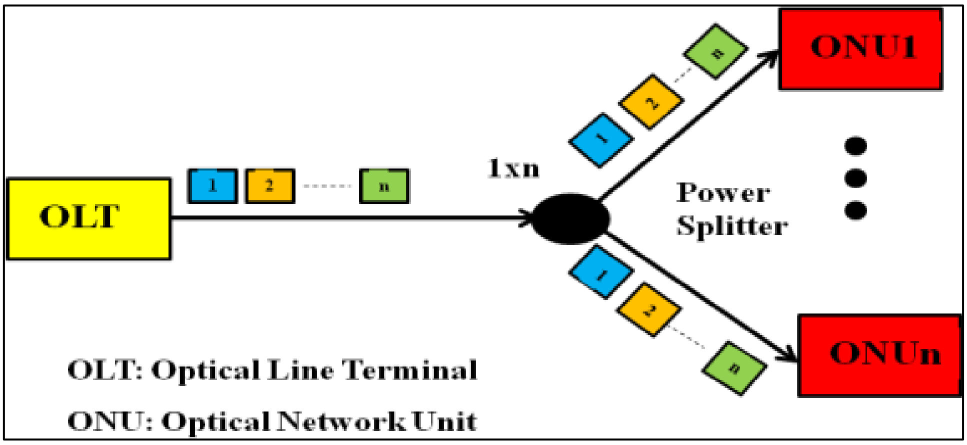

Figure 1.4. TDM-PON architecture [34].

The TDM-PON is a primitive type of PON structure that uses a passive power splitter as the RN for the purpose of dividing the incoming signal power equally to all the ONUs which are connected to it. In this technique, all clients associated with the system utilize a similar frequency to send information upstream. The signal from the OLT is multiplexed in various time slots and communicated to all ONUs during the downstream activity. This method gives a weak security framework to be hacked. The OLT accepts the information by utilizing the location names embedded in the signal. Upstream traffic is communicated in burst mode by each ONU, and a component to staying away from crashes should be carried out. For providing bidirectional transmission, two approaches can be used the first method uses one or two fibers and the second method uses one or two wavelengths. In a business TDM-PON framework, the OLT is connected to the ONUs through a 1:32 splitter, and the longest distance that can be covered is 20 km. The primary benefit of TDM over WDM is that the OLT power necessities are much lower, and TDM does not need a complicated frequency control. The TDM-PON also has many drawbacks such as the lower bandwidth and issues related to the performance. The advantages of TDM-PON can be written as:

- No requirement of controlling the power in the transmitter.
- Data transmission is not continuous, so it results in less power consumption and produces cost-effective configuration.

And TDM-PON has the following drawbacks:

- Bandwidth sharing.
- Limited transmission range because of the power losses associated with the optical splitter.
- Privacy issue: all the downstream information is broadcast to the entire ONUs.

TDM was the main procedure utilized with upstream and downstream total data transmission of 155 Mbit/s up to 10 Gbps in the XG-PON. TDM was trailed by the presentation of WDM, whose limits had essentially expanded by accomplishing data transmissions near 500 Gbps. WDM design utilizes progressed regulation methods, new codification, and multiplexing designs, and subsequently, there is a huge expansion in transfer speed limit with regards to upstream and downstream, as displayed in Figure 1.5 [35, 36].

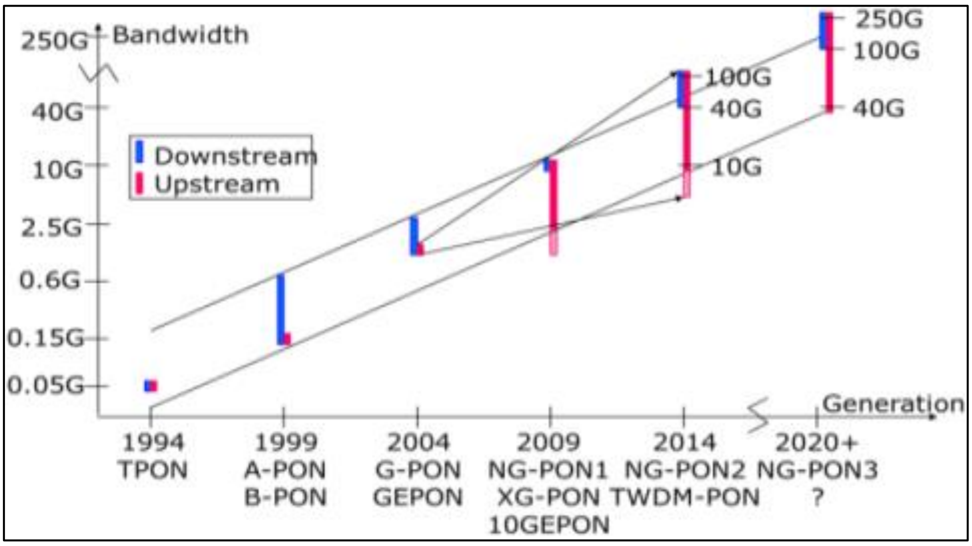

Figure 1.5. Timeline of the evolution of the PON networks standards [37].

Soon, the demand for an ultra-high-speed access network with higher bandwidths and supporting new applications will be continuously growing. The target of the next generation communication networks will be to implement such a network with maximum cost efficiency comprising ONUs, with single fiber operation for upstream and downstream transmissions, and also to have minimal use of optical amplifiers and as well as external modulators providing maximum connectivity to the users with minimum losses at the network level.

Radio-over-fiber (RoF)

One of the notable applications inside fiber optic communication is RoF. This is a framework that regulates light into RF transmission and broadcasts it through an optical fiber interface for remote correspondence, like Wi-Fi, 4G, and 5G. Radio transmissions are straightforwardly incorporated into fiber utilizing numerous low-power receiving wires in fiber optic cell and miniature cells radio systems. Signals transmitted on optical fiber attenuate much less than through other media like metal cables or wireless media. By using optical fiber, the radio signals can reach larger transmission distances, reducing the need for additional repeaters or amplifiers. RoF technology enables integration of the fixed and wireless users. RoF systems are usually classified into two main categories:

- RF-over-fiber.
- Intermediate frequency (IF)-over-fiber.

In RF-over-fiber design, an information-carrying RF signal is enforced on a light wave signal before being carried over the optical linkage. Hence, wireless/RF data is optically dispersed to the base station directly at high frequency and transformed from the optical to electrical domain at the base station before being magnified and radiated by the RF antenna. Consequently, no frequency up–down conversion is needed at the different base stations, leading to a straightforward and cost-efficient performance at the base stations.

In IF-over-fiber design, an IF radio signal with a lower frequency band is utilized for modulating light waves before being carried over the optical linkage. As a result, the data must be up-converted to RF at the base station.

WDM -RoF-PON

RoF relies on the mixture of two ordinary developments: RF for wireless transmission and optical fiber for wired transmission. The wired nature of PON as recently talked about, can provide huge data transfer capacity to end clients through optical fiber. One more perspective is that remote access innovation gives client adaptability, however, they do not accomplish plentiful transfer speed at lower microwave frequencies and deal with issues with longer transmission distances at the MMW band because of high attenuation in the atmosphere. RoF-based optical remote systems are viewed as the main answer for expanding capacity, coverage, transfer speed, and portability to completely use the enormous transfer speed given by fiber and the adaptability given by remote transmission. A typical RoF system as shown in Figure 1.6 consists of a CO, optical fiber feeder network, remote passive node, and a large number of BSs. In the CO, first, the digital signal for the downlink is optically frequency converted through optical MMW generation, and optically transmitted to multiple RN and then to the antenna of BSs and end users via optical fiber. Then when transferring the signal in the reverse path, the uplink signal from the client to the CO is first received by the BS and converted to the uplink at the RNs, the signal at the MMW band is down-converted to a low band in order not to utilize the MMW band optical modulator in every BS and broadband optical beneficiary in CO.

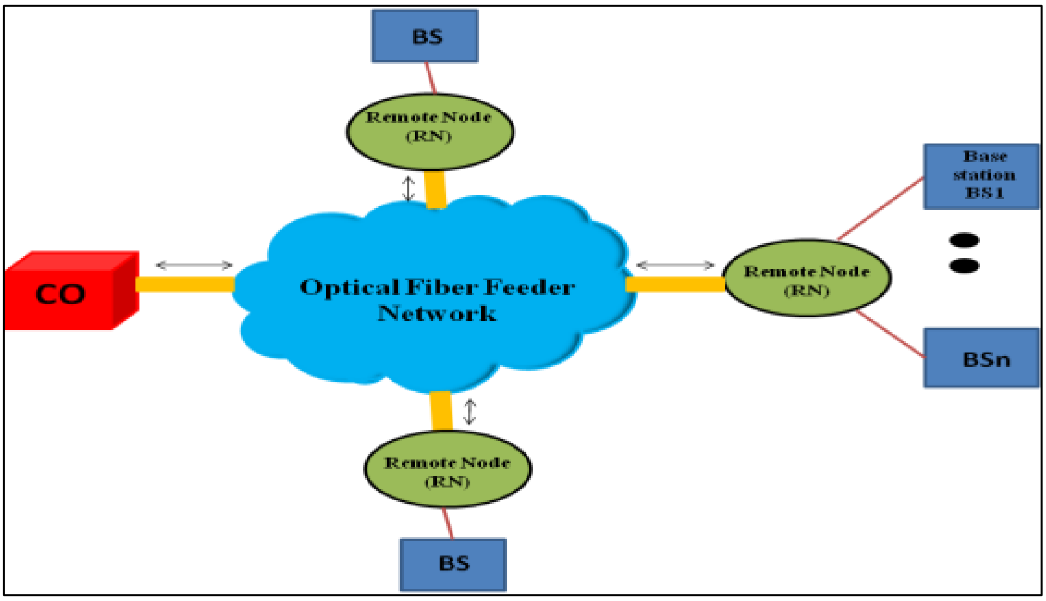

Figure 1.6. Radio-over-Fiber [38].

The capacity of RoF can be significantly improved by the integration with WDM-PON systems, namely WDM-RoF-PON [5, 6] by transmitting multiple signals simultaneously at different wavelengths. WDM-RoF-PON is most popular because of the several following advantages:

- Broadband access in dense areas.
- Lifeline communications.
- Massive Internet of Things (IoT).
- Higher user mobility.
- Extreme real-time communications.
- Ultra-reliable communications.
- Broadcast-like services.
- Broadband access everywhere.

<u>WDM-radio over free space optics-PON (WDM-RoFSO-PON)</u>

Free-Space Optical (FSO) communication has been developed over the few years. There are several benefits of FSO over conventional RF communication such as high bit rates, low power utilization, unlicensed spectrum, etc. [7, 8]. FSO is appropriate for point-to-point (P2P) communication wherever high bandwidth and security are the most priority issues [9].

It can also be integrated with existing fiber backbones to offer last-mile access candidates wherever fiber lines are too expensive or impractical [10, 11]. However, the main drawback of FSO is its greater susceptibility to atmospheric weather environments. Atmospheric effects such as absorption, scattering, and scintillation deteriorate FSO link quality and this makes FSO less preferable than RF communications [39].

Problem statement

As described in sections 1.3, 1.4, and 1.5, PON is a passive optical network which is a new application that modulates light waves from OLT. The OLT is a unit that is regularly situated at the CO and sends information using filaments to ONUs situated toward the end client. ONUs Containing Very high bit rate Digital Subscriber Loop (VDSL), Fiber to the Cabinet (FTTC), and Fiber to the Building (FTTB). Figure 1.2 above depicted a PMP scenario and a single optical fiber to serve numerous premises in the range of 32 and 128. Another optical system with a single, shared fiber that partitions the signal to individual users by utilizing optical splitters is displayed in Figure1.7.

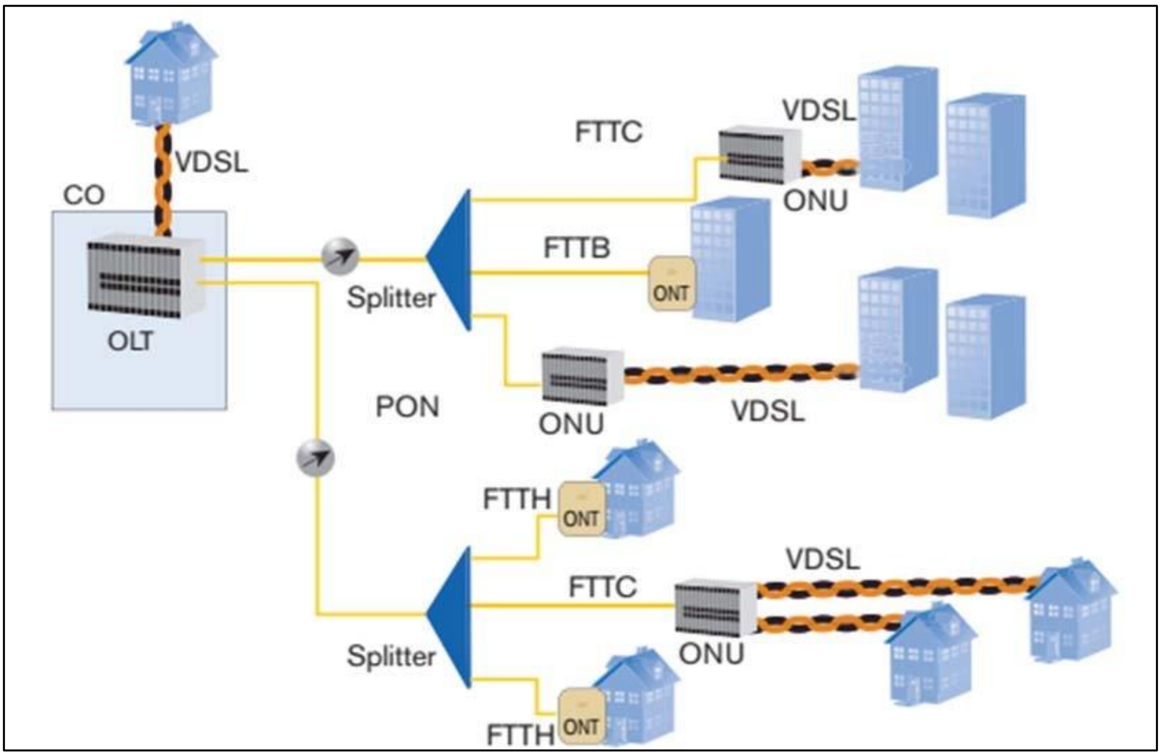

Figure 1.7. Typical optical fiber network components [40].

Objectives and major contributions

The objective of this study is to design a cost-effective optical-remote-hybrid network models that can convey various services to fixed as well as versatile clients. Because such networks are designed for use an unlicensed bandwidth of 7 GHz, adaptability, decreased number of components/wires/parts, and high rate-capacity to address the disadvantages of lower microwave frequencies in current remote systems, RoF systems could be a possible solution in the developing upcoming indoor wireless networks, because of their low cost, high security, long range and high data transmission, one of the major advantages of WDM-RoF is its ability to support multiple radio signals simultaneously on a single fiber, using different wavelengths of light. This eliminates the need for multiple fibers, reducing the complexity of the network. Moreover, WDM-RoF improves the quality of the radio signals, eliminating interference and noise, resulting in a higher quality of service for the end users. Another objective of WDM-RoF is to provide a high bandwidth capacity for wireless communication networks. By using fiber-optic technology, WDM-RoF can provide high-speed data transmission, allowing wireless networks to handle more traffic and support more users. This is particularly important in areas with high-density populations, where the demand for wireless communication is high.

The integration of WDM-RoF-PON has significant benefits for both wired and RF wireless networks. By using WDM-RoF technology, PONs can provide higher bandwidth capacity and support for multiple radio signals, improving the quality of service for the end-users. Additionally, the use of passive components in PONs reduces the maintenance cost and complexity of the network.

2. BACKGROUND

In this chapter, we will go over the fundamental concepts and literature underlying this thesis study. We will focus on PON, Reflective Semiconductor Optical Amplifier (ROSA), Arrayed Waveguide Grating (AWG), and various multiplexing types. This includes their key concepts, advantages, and practical applications.

Optical networks are capable of transferring high-demanding services for long distances. One of the architectures to deploy optical fiber to the access network is to use a P2P network. Lines from the main office will end up to the ONU at the destination. In addition, using PON where no power is required to split the signal from one source to multiple destinations in combination with WDM technology, multiple wavelengths are supported for downstream or upstream signals. Optical networks are one of the means of transportation that can also support the upcoming 5G technology. The architecture where the processor unit Base Band unit (BBU) is geographically separated from the Remote Radio Unit (RRU) and centralized in a main CO, is referred to as Centralized Radio Access Network (C-RAN). The C-RAN has the potential to bring several advantages concerning current radio access networks. Due to a smaller number of BBUs used, it is cost-effective. Also, it may reduce the rollout difficulties in dense urban areas [25] since there is limited space in urban places. Removing equipment from the antennas and centralizing them may provide ease for new installations. Furthermore, C-RAN architecture enables features of Long Term Evolution (LTE) for better coordination between neighboring cells [25]. Another aspect that should be considered in the C-RAN architecture is the communication between the RRU and the BBU. So far, those two elements were in a close arrangement at the same base station site. The communication between them is achieved through the Common Public Radio Interface (CPRI). The above design where the BBU is centralized and the communication between BBU and RRU is achieved with the CPRI is referred to as a fronthaul network. CPRI protocol is quite demanding in terms of bandwidth and latency. Dense Wavelength Division Multiplexing (DWDM) is the method for transporting CPRI signals, due to its high bandwidth as well as stringent latency/jitter requirements [25]. Today, the major DWDM switching technology is deployed using Reconfigurable Optical Add/Drop Multiplexers (ROADMs). ROADMs are used to automate the rearrangement of wavelengths on multichannel fibers that enter and exit the nodes [26]. A multi Wavelength Selective Switch (WSS) is a ROADM that selectively rearranges the wavelengths in different directions [27]. However, not only

ROADMs are used. OADMs with fixed routing matrices are also used. One switch used for the routing matrix is AWG.

The optical access network is mainly focused to deliver 10's of Gbps to the ONUs or to users. Optical access network data transmission is majorly dominated by digital information/ bits (ones and zeros) and in recent years analog radio signal is also transmitted over optical fiber infrastructure to gain advantages like low loss, wide bandwidth, and immunity to electromagnetic interference. When laser light is modulated by an analog electrical signal and transmitted through passive fiber infrastructure, it is called a RoF system. Thus far, the RoF system is considered a part of microwave photonics and explored in the same area. Recently, efforts are initiated by ITU-T to standardize RoF technology, and the task is assigned to study group 15 for technical specifications giving shape to global communication infrastructure whereas, on the other side, digital information transmission-based PON is booming with different standards, fulfilling the demand.

PON has enabled high-speed broadband connectivity over the years and it has become popular by providing high data rates at an economical cost. The popularity of PON started with BPON, EPON, and GPON in 2000, 2004, and 2008 respectively [5, 7, 30]. The EPON was proposed by IEEE in 2004 as standard 802.3ah with a peak data rate of 1.25 Gbps. The BPON and GPON both are proposed by ITU-T as standard ITU-T G.983 in 2005 and ITU-T G.984 in 2008 respectively. BPON provides a data rate of 1.20 Gbps and GPON provides a data rate of 2.5 Gbps. Over time, these standards got updated in terms of data rates, reach and number of simultaneous users based on the demand as 10G-EPON and XG-PON also referred to as NG-PON to transmit 10 Gbps of information [41, 42].

2.1. A Fiber- Optic Communication System

Fiber optics is a basic part of the broadcast communications system. It is reasonable for gigabit or higher transmission rates because of qualities, for example, high transfer speed capacities and low constriction [27]. Fiber optics presently provides almost a lossless medium to significant distance data transmission involving light as the transporter wave. Ordinary copper wire transmission is electrical in nature while fiber optics uses optical signals. A common fiber optics framework comprises three parts: a transmitter, an optical fiber as a channel, and a receiver. At the transmitter side, the electric signal is converted into optical/light signals by transducers, which are then sent through an optical fiber link to the receiver [1]. The received light is converted into electrical signals by the detector. Figure 2.1 portrays a summed-up fiber optic communication framework, which comprises an optical transmitter, a communication channel, and an optical receiver [1].

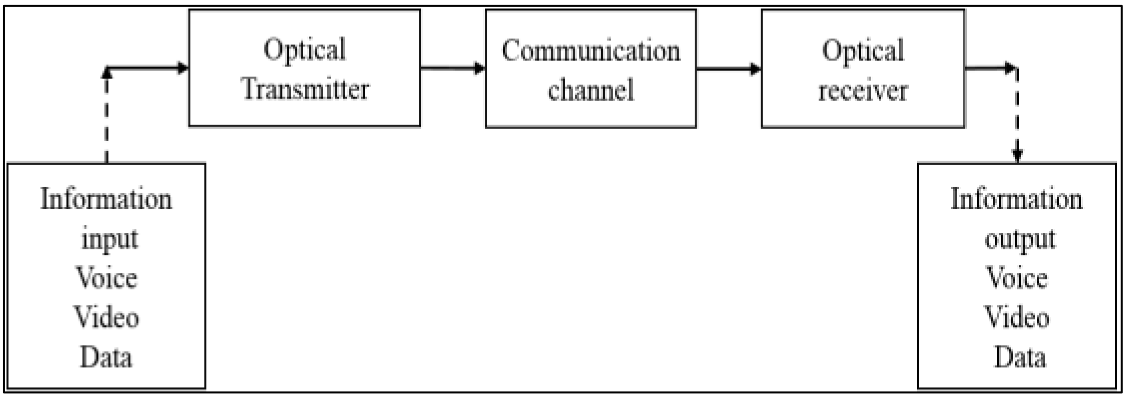

Figure 2.1. A general fiber-optic communication system [27].

2.1.1. Optical transmitter

There are three segments in an optical transmitter: an optical source, a modulator, and a channel coupler. As a light source, a semiconductor laser or a light-emitting diode can be used in optical communication in order to create light pulses [25]. The light pulses could be categorized in two ways: the first one is a directly balanced laser, which changes the infusion current, and the second one is the one with an external modulator. Balancing by changing the infusion current is a modest and direct method, however, it can create side tones, especially in high information rate signals. To avoid these side tones, an external modulator can be used to regulate high information rate signals. A channel coupler with a miniature focal point effectively illuminates a balanced light signal onto an optical fiber [27].

2.1.2. Communication channel

The communication channel is, in fact a fiber cable commonly made of silica. It has attenuation characteristics of 0.2 dB/km in the 1550 nm band, making it ideal as a communication channel for light wave systems. Figure 2.2 portrays the fundamental design of a center clad as an optical fiber. The center of an optical fiber is a round and hollow glass pole that is utilized to spread light [27]. This center is encircled by cladding, a barrel shaped coaxial shell of glass with a lower refractive index. The support covering safeguards the fiber from external environments [26].

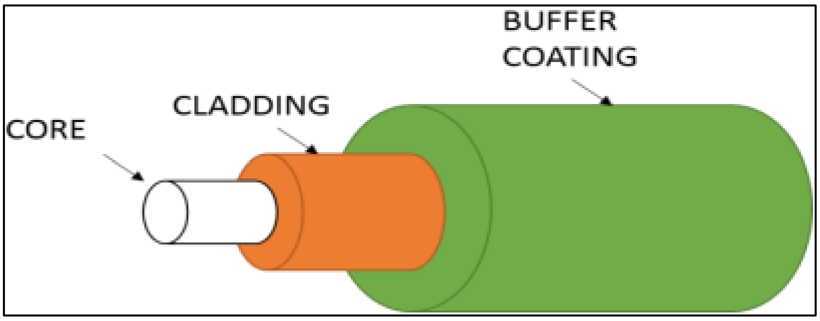

Figure 2.2. Optical Fiber [26].

2.1.3. Optical receiver

An optical receiver is an essential part of the fiber optical network. Its function is to translate pulses of light that are sent through optical fibers into electrical signals. Once the information is converted into electrical signals, the information can be processed by electronic devices, such as a computer, that is attached to the network. The heterodyne and homodyne demodulation methods are ordinarily utilized in the frequency-shift keying (FSK) and Phase-shift keying (PSK) receiver designs. Most of the light wave frameworks utilize the Intensity Modulation (IM) design, for example, Quadrature Amplitude Modulation (QAM). The demodulators at the receiver identify the 1 and 0 by using Signal to Noise Ratio (SNR) of the photodetector signal. Since light may be attenuated and distorted while passing through the fiber, photodetectors are typically coupled with an amplifier and a limiting amplifier to produce a digital signal in the electrical domain recovered from the incoming optical signal. Further signal processing such as clock recovery from data performed by a phase-locked loop may also be applied before the data is processed further [27].

2.2. Access Network

Access networks are responsible for interfacing specialist co-ops with their clients (either business or potentially private). Most normal nearby access systems, for example, phone systems continue with using twisted pair and coaxial links [28-30]. Due to advanced internet applications and HDTV etc., clients' data rate and capacity needs are expanding dramatically.

Twisted pair and coaxial links cannot meet these requirements [31]. To resolve these issues, fiber has been introduced close to private and independent company properties. Numerous players are leaving their conventional copper networks in the ongoing situation, making them ready for the optical fiber system. FTTH administrations arise as a clear long-haul decision because of their capacity to force data transmission in the future on similar equipment [6].

2.2.1. WDM access PONs

In the advancement of access systems, the cutting edge is WDM-PON. They can give the most transmission capacity to a minimal measure of cash. The preparation of a WDM-PON is like that of a PON. The principal qualification is that ONUs work on various frequencies, taking into account higher transmission rates. Figure 2.3 depicts an explanatory example of this architecture.

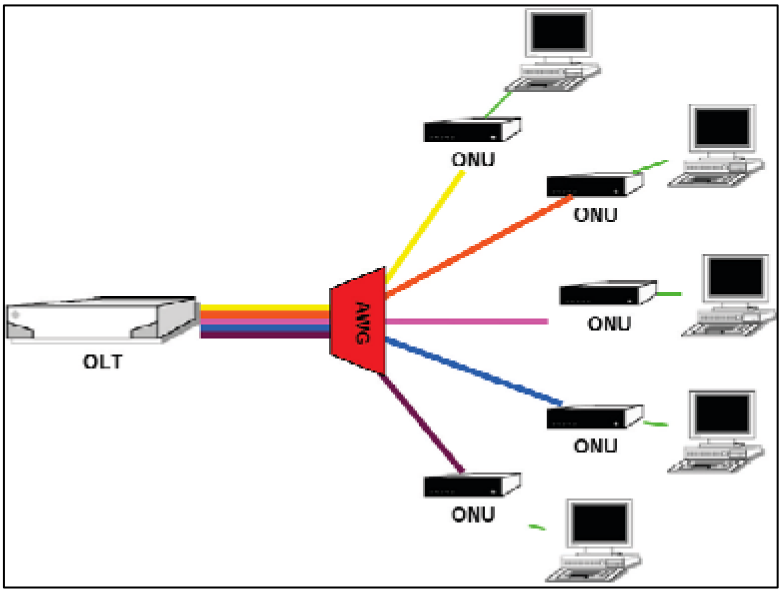

Figure 2.3. WDM-PON FTTH network configuration [32].

The central concern with WDM-PONs is that the frequency allocated to an ONU is generally fixed, making updates in the system geographically troublesome. Manual reconfiguration of the hardware is expected on the client's side, which altogether expands the expense of support. The arrangement is to utilize ONUs, which identify which frequency is utilized in the downstream bearing and send information on that frequency in the upstream heading. A framework can have up to 128 distinct frequencies that are utilized to convey the signal to the clients. An ONU adjusts the carrier frequency furnished by the OLT with its information in the upstream bearing. The benefit is that ONUs need not bother to be equipped with expensive light sources. This does not just decrease the general expense of the equipment, but in addition also makes ONUs straightforward to the signal, permitting various frequencies to be utilized whenever. In any case, the drawback of WDM-PONs is the high cost of the devices. Much exploration has been directed to further develop WDM-PONs' capacity to serve a more prominent number of clients to increment profit from contributed assets and cost-effectiveness. Thus, a few crossover structures utilizing both WDM and TDM modes have been proposed to expand the quantity of possible clients [32, 43].

2.3. Basic Components of WDM-PON Supervision

2.3.1. Arrayed waveguide grating (AWG)

PON utilizes beginning to end optical transmission by means of ODN, which is partitioned into two segments: feeder and dispersal. A distant center point of RN with just lethargic optical parts interfaces these two pieces. An optical power splitter is utilized at the RN in TDM-PON. The OLT sends downstream messages through the feeder fiber, which is then steered by the power splitter to different ONUs situated close to the client. The optical power splitter is supplanted in WDM-PON by a frequency multiplexing part, for example, an AWG, which is utilized to course unique frequency channels to various ONUs [8].

An arrayed waveguide grating is a device which can separate or integrate signals with different wavelengths. It is generally built as part of a planar light wave circuit, where the light coming from an input fiber first enters a multimode waveguide section, then propagates through several single-mode waveguides to a second multimode section, and finally into the output ports. The light is partitioned into a few channels, each with its own frequency. In business applications, the quantity of channels goes from 8 to 80 in commercial devices [19], also, the channel separation is usually around 100 GHz. The incoming light (1) traverses a free space (2) and enters a bundle of optical fibers or channel waveguides (3). The fibers have different length and thus apply a different phase shift at the exit of the fibers. The light then traverses another free space (4) and interferes at the entries of the output waveguides (5) in such a way that each output channel receives only light of a certain wavelength. The orange lines only illustrate the light path. The light path from (1) to (5) is a de-multiplexer, from (5) to (1) a multiplexer. This process is irrefutable and is represented in the Figure 2.4 [46].

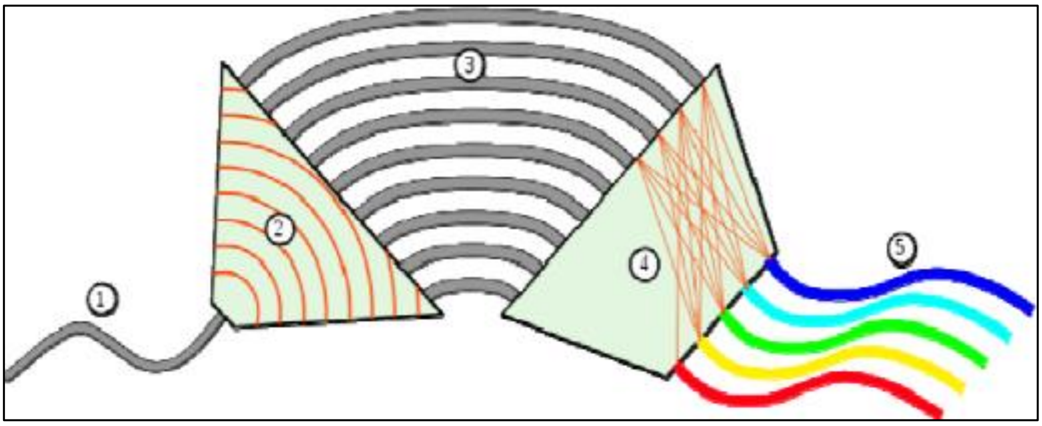

Figure 2.4. The structure of an arrayed waveguide grating (AWG) [44].

2.3.2. Reflective semiconductor optical amplifier (RSOA)

Reflective semiconductor optical amplifier (RSOA) is a high-performance, low-cost device used for data amplification and modulation in RoF systems, full-duplex optic access networks and microwave photonics. It is less notable, but due to its properties, it is getting more popular than the semiconductor optical amplifier (SOA). For WDM PON applications, although its waveguide structure is similar to a structure SOA, RSOAs have a low noise figure and high optical gain at low drive currents. RSOAs have shown promise for applications in wavelength division multiplexed passive optical networks (PONs) and in fiber ring mode-locked lasers. Figure 2.5 portrays the fundamental design of a Reflective Semiconductor Optical Amplifier [45].

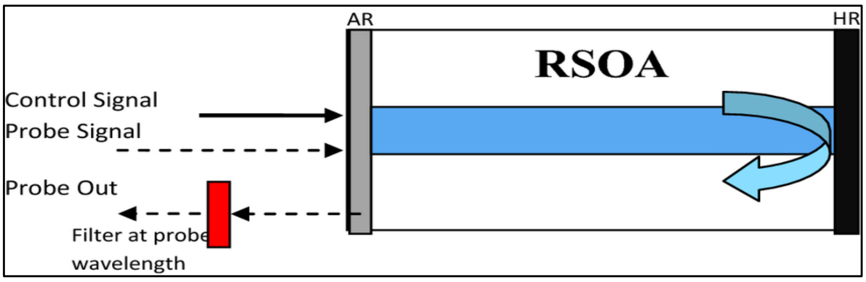

Figure 2.5. Reflective Semiconductor Optical Amplifier [45].

Optical amplifiers can be used mainly in two ways as:

- Booster Amplifier.
- Pre-Amplifier.

A booster amplifier is installed in the upstream end of the fiber optic network, which can amplify the optical signal that is launched into the fiber link. It is usually used in DWDM network where the multiplexer attenuates the signal channels. A booster amplifier usually provides low gain and high output power. A pre-Amplifier is usually installed at the downstream end of the DWDM network to amplify the optical signal to the required level to ensure that it can be detected by the receiver.

2.4. Multiplexing Techniques

2.4.2. Wavelength division multiplexing (WDM)

Wavelength division multiplexing (WDM) is a high-speed communication framework for multiplexing. Every communication channel has an alternate frequency relegated to it and is multiplexed onto a single fiber. Frequencies are spatially isolated to various recipient areas at the destination. The high transporter data transmission is utilized in this scheme to send various optical signals through a single optical fiber. Figure 2.6 depicts the WDM technique

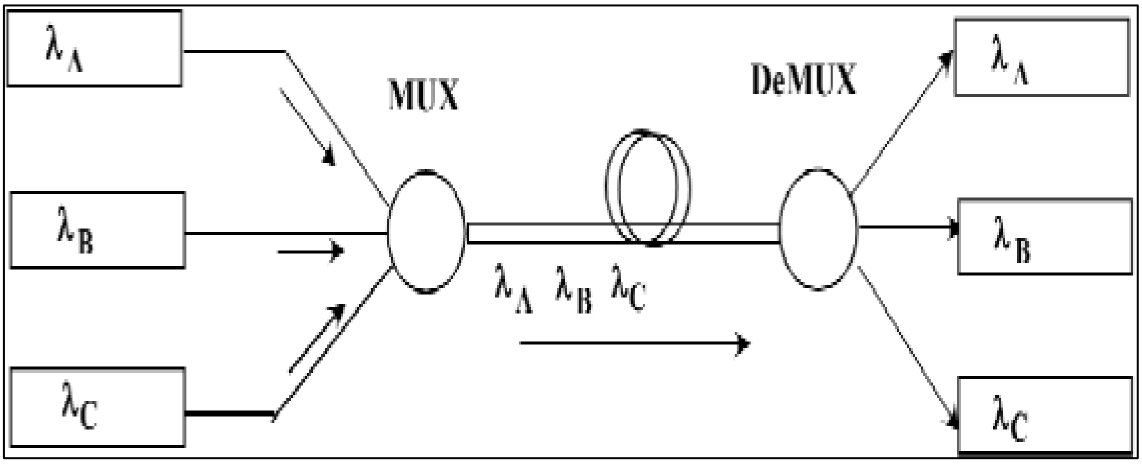

Figure 2.6. WDM technique [18].

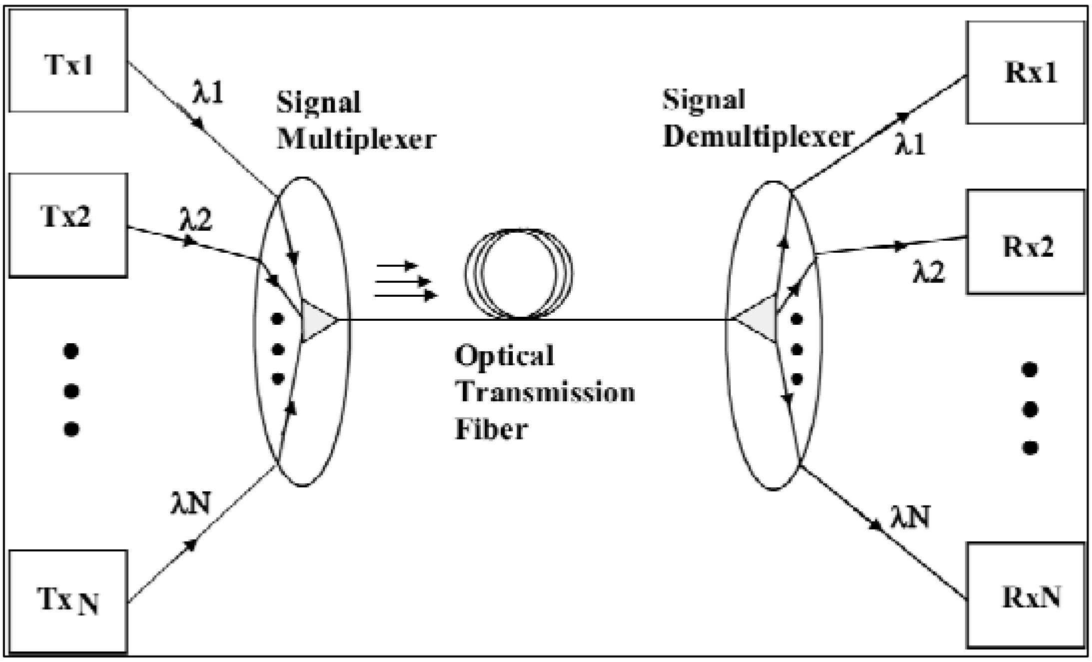

Figure 2.7. WDM Network (P2P Communication) [18].

Figure 2.7 depicts WDM systems, also known as P2P communication network. Due to dispersion, the bit rate for single frequency P2P links is limited to 100 Gbps. This is far below the optical carrier frequency's capability. While the power diminishes by a component of 1/N, this problem can be counterbalanced by utilizing an optical amplifier before the second star coupler. In order to combine several WDM into one signal, DWDM is used. DWDM is a technology in which several optical signals (laser light) of multiple wavelengths are grouped into one signal and are shared over the connecting medium to a wide area. The wavelength separations in these systems are on the order of 0.3 - 0.8 nm.

Despite the fact that WDM innovation is turning out to be more predominant in transportation network, there is another technique for bringing WDM downstream, nearer to the end client. TDM-PONs like APON, BPON, GPON, and EPON are at present being used. TDM-PONs have a restricted hub supplement and cannot fulfill the needs of future system development with regards to adding up to data transfer capacity. Future access networks should give practical, high-limit support for a rising number of new broadband end-client administrations. WDM-PON networks furnish end clients with high security, optical straightforwardness, and expanded limit. However, there are a few burdens to WDM-PON systems. When compared with TDM-PON parts, WDM parts like multiplexers, de-multiplexers, frequency switches, and multi-frequency sources are more costly. The expanded sending of WDM in center and metropolitan systems has decreased WDM parts costs and brought WDM closer to the client. Due to its high frequency selectivity, low power, small size, high channel numbers, and possibly minimal expense, the AWG is a significant key in WDM innovation. By using dynamic coarse AWGs, these designs can support an enormous number of clients while offering versatility and further developments [18].

2.4.3. Wavelength selective switch (WSS)

A WSS include an array transposition that operates on light that has been dispersed in wavelength without the need that the dispersed light be physically demultiplexed into separate ports. WSS has been the central core of the modern DWDM optical network. WSS can dynamically switch, block and pass all DWDM wavelengths within a network node. Figure 2.8 shows WSS's functionality [46].

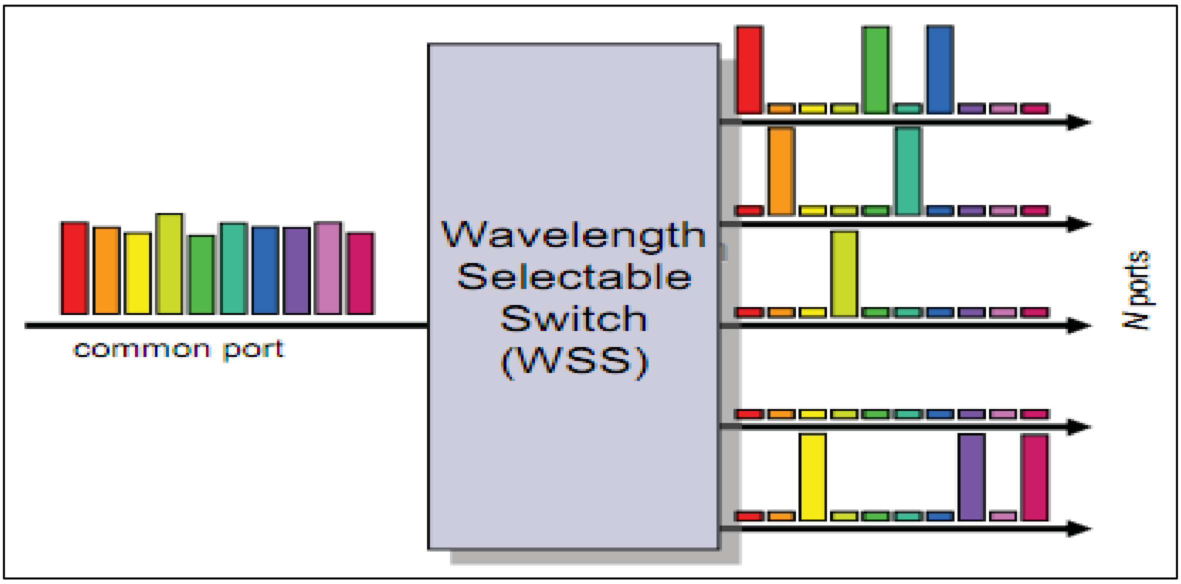

Figure 2.8. WSS technique [46].

A WSS consists of a single common optical port and N conflicting multi-wavelength outputs where each DWDM wavelength input from the common port can be switched to any one of the N multi-wavelength output ports, no matter how all other wavelength channels are routed. This wavelength routing process can be dynamically changed through an electronic control interface on the WSS [47, 48].

2.5. TDM-PON vs. WDM-PON

In the downstream scheme, the splitter transmits all bundles from the OLT and sends them to each ONU. All ONUs perceives their own parcels utilizing the location marks implanted in the bundle heads [46]. Signals from various ONUs are multiplexed in the time-space by the distant hub and shipped off the OLT in the upstream scheme. TDM-PONs are used in the majority of commercial PONs today, such as BPON, EPON, and GPON. Figure 2.9 shows a typical architecture of a TDM-PON [31].

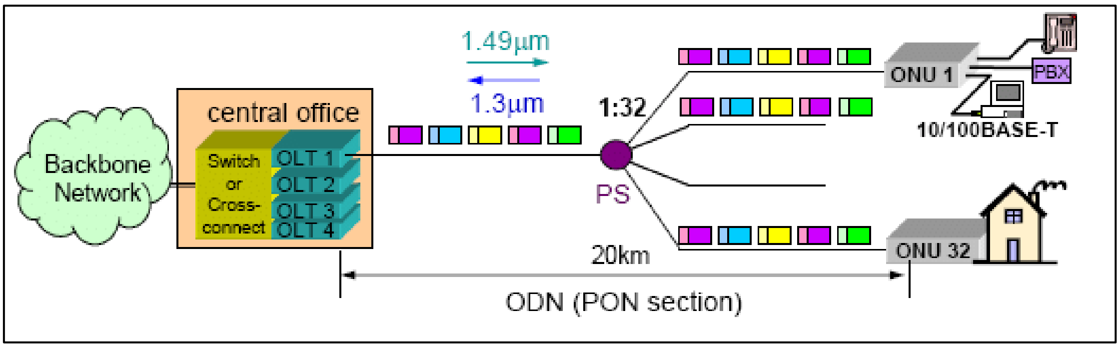

Figure 2.9. Typical architecture of a TDM-PON [31].

Despite the fact that TDM-PON gives more data transfer capacity than ordinary access systems, it will be unable to address the issues representing things to come network as far as the always expanding interest for data transfer capacity. Moreover, the utilization of an optical power splitter causes security worries as well as critical power problems. A 1:32 optical splitter, for instance, has an inclusion loss of in excess of 17 dB.

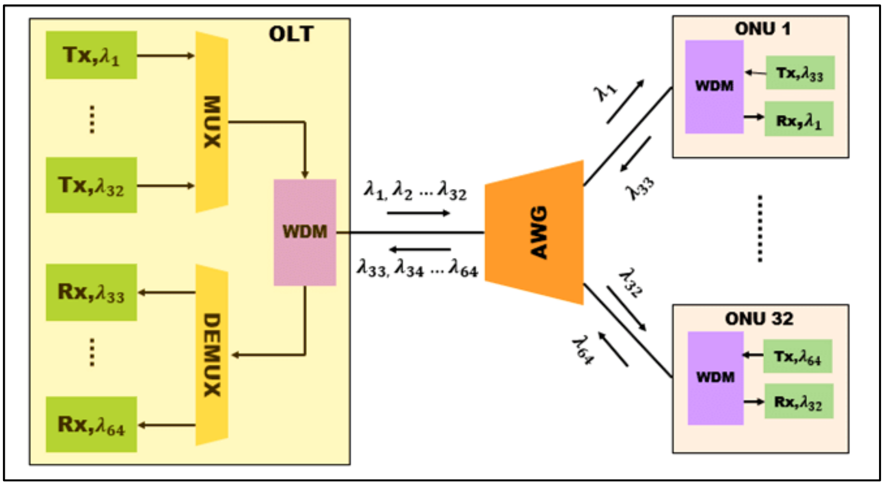

Figure 2.10. Typical architecture of a WDM-PON [15].

WDM-PON as shown in Figure 2.10, as a competent arrangement, can recuperate execution like transfer speed, security, and power problems. In the distant hub of a normal WDM-PON framework, in wavelength division of light, a passive wavelength de-multiplexer, for example, an AWG (see Figure 2.9), is utilized. The de-multiplexer switches signals to various ONUs by coding them on various frequency channels. The utilization of a de-multiplexer eliminates the high insertion loss presented by optical splitters, extraordinarily further developing the general framework's influence spending plan [2]. This strategy lays out a PTP connection by distributing a committed frequency channel between the OLT and each ONU [3].

Besides, in light of the fact that each ONU just accepts its own signs, this P2P coherent design gives essentially more protection and security than TDM-PON. One more kind of WDM-PON, known as the power-dividing approach, actually utilizes an optical splitter at the far-off hub, from which information signals of variable frequencies are communicated to each ONU. The optical diverters are set straightforwardly before the handsets at the ONUs then, at that point, assist with picking and sending only one repeating channel while eliminating all the others. This kind of WDM-PON can be easily updated from a current TDM-PON plan without requiring any progressions to the ODN. However, it cannot resolve the issues of low security and high impact occurrence.

2.6. Hybrid WDM/TDM-PON

Hybrid WDM/TDM-PON is the system in which both the advantages of WDM and TDM are incorporated in a single network architecture as depicted in Figure 2.11 and consequently system capacity will be enhanced [15, 16].

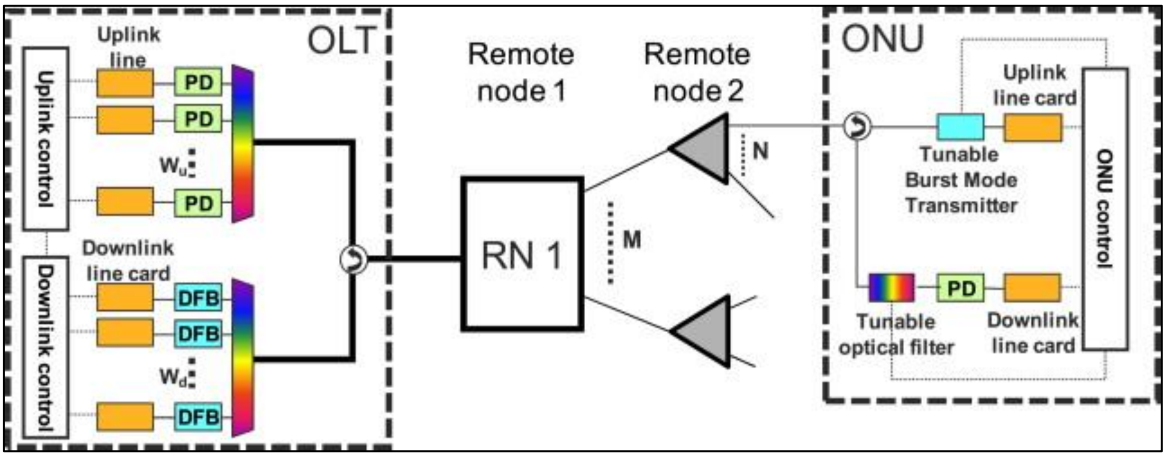

Figure 2.11. Hybrid WDM/TDM PON [49].

Various frequencies are utilized in this engineering to empower communication between the CO and the quantity of end users. Communication occurs in two phases. First, various groups of ONUs utilizing the WDM scheme are allocated to various quantities of frequencies. Then, at that point, utilizing TDM, every frequency will be shared on a period premise by numerous ONUs in the same group.

The combination of these two technologies in a hybrid WDM/TDM-PON network offers several advantages over traditional PON systems. Firstly, it enables higher data rates, as multiple wavelengths can be used simultaneously, which increases the available bandwidth. Secondly, it provides flexibility in terms of network design, as different wavelengths can be assigned to different services, allowing for prioritization and optimization of data traffic. Thirdly, it allows for the delivery of both TDM and WDM services, making it a versatile solution for different types of applications. Another advantage of hybrid WDM/TDM-PON is its scalability. The technology can be easily upgraded to support higher bandwidth and accommodate more users, without requiring major changes to the existing infrastructure. This makes it a cost-effective solution for service providers, as they can gradually increase the capacity of their networks as demand grows. Lastly, hybrid WDM/TDM-PON offers improved reliability and security. By using multiple wavelengths, it is less susceptible to interference and signal degradation, ensuring a consistent and stable connection. Additionally, it allows for the implementation of encryption and authentication mechanisms, enhancing the security and privacy of the data transmitted over the network [49].

2.7. Literature Review

To uncover the concept of RoF technology from its basics to advanced applications, we have carried out a literature survey. We have mainly noticed that dispersive and nonlinear behavior of optical fibers are most significant challenges in the implementation of RoF technique-based systems. Also in long wireless channels, problems like high path loss, signal strength degradation due to shadowing, refraction, and diffraction effects are encountered. Such performance limiting signal phenomena put difficulties to design RoF systems with a higher data rate for long-reach applications. So, it becomes essential to mitigate or to suppress such system performance degrading effects. Many studies deal with the use of appropriate dispersion and non-linearity pre-compensating techniques at the transmitter side such as dispersion compensating fibers (DCF). Use of appropriate, coherent detection methods and offline DSP algorithms at the receiver side can also help the optimization of performance of RoF systems. Because each new technology comes with its own merits and demerits, we have to use them wisely with their practical limits.

In Rahman and Mohamed’s work [50], state of the art LR-WDM-PON architectures have been summarized. They advocated the use of coherent detection techniques for their capabilities such as high capacity and extraordinary passive split ratios. To select a single channel from DWDM sources, they mentioned the use of tunable LO laser. Use of such laser does not require complex optical filtering process while proving a reconfigurable and scalable network.

In 2013, Lavery and Savory [51] have reported that rapidly developed bandwidth-hungry services created fast growth for broader bandwidth per user requirement. So, to meet such demands, evolution from TDM-PONs to Next-Generation Optical Access Networks (NG-OANs) must be realized. They mentioned that in NG-OANs, other specifications such as longer range, higher capacity and unrestricted mobility are also equally essential, to have an optimized performance from them. On the base of a literature survey, they mentioned about different architectures satisfying such essential requirements of Long-Reach Optical Access Networks (LR-OANs). They concluded that LR-OANs have got much attention because of their cost-effective solutions.

Mohammad and Shaddad [50] have presented an advanced solution to upsurge the bandwidth for optical access networks. The broadband access network has been addressed as the key solution for PMP optical communications. They demonstrated 4-channel system with each channel having data rate of 10 Gbps. PON technology has been used in between the CS and end-users. Further extensive research suggested using CWDM-PON for metro and long-haul fiber applications.

Al-Rubaye and Al-Raweshidy [51] have introduced a PON system based on coherent heterodyne receiver in 2009. Wavelength selectivity and sensitivity of heterodyne receivers have enabled a filterless ultra-dense-WDM system with extended reach and simplified logistics. It could offer 1 Gbps sustained data rate per user. They concluded that coherent reception along with the use of integrated photonic components and electronic signal processing offers the possibility to design an efficient access system. Such systems merged with PON technology offer reasonable P2P connections. So, possibilities increase to add seamless single wavelengths and services without many modifications in existing networks.

In 2009, Rohde and Gottwald [52] have reported about the investigation of optical access techniques for implementation of PON technology. WDM and TDM networks performance have been compared in terms of attenuation, scattering and dispersion effects on the Bit Error Rate (BER) values of received signals. On the base of the literature survey, they reported smooth merging of PON techniques with broadband access optical networks like WDM and TDM.

Davey and McCammon 2006 [53] studied about the integration of the optical and radio networks of RoF technology to transmit signals towards different remote antenna units. After a detailed literature study, they mentioned factors like installation of a large number of BSs, losses in cables, cost of climate control systems in BSs which increase the overall capital expenditure and operational expenditure costs in the systems.

Rajpal and Goyal 2017 [54] proposed that RoF as a promising technology could minimize such costs. They studied about RoF technology & methodology, quality factor and challenges for application. Such RoF systems could offer essential broadband wireless connectivity to a number of services in many applications. They mentioned that RoF technologies could realize future proof system configurations supporting several communication standards and radio services.

A cost-effective and flexible approach has been reported to interface multiple remotely located antennas with a centralized architecture, which in turn offers use of a simplified BS to remote end users by Vyas and Agrawal [55] in 2012. They presented RoF technology as a more straightforward pathway to distribute wireless signals in broadband wireless networks through optical networks. RoF technology has been adapted as a measure to spectral congestion in lower end of frequency spectrum utilized for existing applications. Such approach has provided help to overcome spectral optical bottlenecks faced while designing next-generation mobile fronthaul networks.

In 2009, Rahman and Kim [56] have presented a different challenges in widespread deployment of RoF system networks for in demand triple play services. Different techniques to mitigate those challenges have also been discussed. They suggested the use of high-power input signals at transmitter side and optical amplifiers in channel span for enhanced performance of such RoF systems. Improper power level of signals could give rise to various signal impairments like inter-channel modulation distortions etc. Randomly chosen excessive power level could even damage optical detectors at the receiver side.

Opatić 2009 [57] introduced different Wi-Fi networks with respect to their applications, architectures, hardware complexity levels and capital expenditure. Bandwidth allocation requirements and services offered by different systems have been listed out. Operating such networks at MMW bands could resolve issues like unavailable spectral resources at lower end of frequency spectrum and high data rate transmission as MMW bands offer spectral potential. Several systems to assist different P2P and broadcasting applications have been listed.

Lee 2005 [58] has presented the design of a RoF system with 1550 nm wavelength for 20 km channel span. He analyzed system performance in terms of variations in Q factor, BER value and eye-opening height with different wavelengths, bit rates and channel spans. Opti System 10 software has been used to design the testbed for proposed system. He used Non Return to Zero (NRZ) and Return-to-Zero (RZ) modulation schemes. He concluded that, due to higher peak power, NRZ is affected more by nonlinearity effect, whereas RZ suffered from the dispersion effects because of shorter pulse widths. He suggested the use of RZ modulation in high power regime for better results.

Lim and Ranaweera 2019 [59] mentions various technical challenges of RoF networks for their extensive deployment. In general, parameters such as average power per channel, maximum number of allowed channels, channel spacing and total amount of needed dispersion compensation are to be taken proper care for design of efficient DWDM systems. Use of appropriate dispersion compensating techniques like pre- and/or post- dispersion compensation, etc. could also play an important role in such designs to attain trustworthy results. Optimization process of such existing systems become even trickier with increasing number of channels, bit rates and channel span. In such situations to manage signal impairments triggered due to dispersive and nonlinear behavior of optical channel become a great challenge. In addition, multipath dispersion effects of the wireless channel combined with signal make channel estimation and equalization tasks more complex. To estimate and compensate for such signal impairments, advanced signal processing algorithms could be used. Multiuser environments might even create many other problems in such positions.

3. PROPOSED SYSTEM

3.1. Introduction

In 2021, global IP traffic was 278 EB each month, and it is expected to increase more and more in the future [1, 24]. In the meantime, traffic loads have moved away from voice, and text-based administrations toward video, media communications, and other broadband applications [25, 26]. The current wired/wireless access networks need to be improved for future demanding services. Transporters and specialist co-ops are effectively looking for broadband WDM solution with PON for wired or wireless communication to disseminate various administrations to both fixed and versatile clients.

WDM is a system for transporting data at different wavelengths through a single fiber. But the use of WDM in PON could be a promising contender for FTTH wired networks due to its enormous data capacity, upgradability, adaptability, and low cost [27, 28]. Notwithstanding, current remote access associations can keep up with their flexibility in transmission by satisfactory increase in speed to meet necessity limits [29-31]. In such a manner, analysts and architects accept that optical/wired or potentially remote as well as joined networks are the most encouraging answer for reaching the limits, coverage, data transmission, portability, and adaptability everywhere such as air terminals, lodgings, gathering lobbies, shopping centers, and at last to private or business endorsers.

Optical fiber is the most well-known mechanism for high-speed transmission over significant distances. SMF is being utilized in long distance and metro transport associations because of its low cost, security, lightweight, and high trade speed receptiveness over existing copper wire, (HFC), and DSL [32]. Fibers with low loss (0.2 dB/km) and other optical parts are also produced with low-cost and high performance. So, they can be used in various multi-terabit data transmission applications.

3.2. Problem Description

The interest for availability is at a record-breaking high and will remain so all through the twenty-first century. Consequently, the interest in information rate and data transfer capacity per client develops, as does the quantity of specialized tools. The interest in the delivery of tools per client is expanding as innovation progresses in hardware, electrical, vehicle, transportation, banking, and numerous different fields. The entrance network associates clients' tools with the web to empower triple-play administrations. The entrance network collects the web traffic analysis and distributes it to an optical access network port for backbone availability.

Our work is hoped to meet current and future optical access network traffic demands by utilizing existing optical access network foundations [60-62]. New frameworks have additionally also been investigated to meet the client's prerequisite while completely using the conveyed structure. This work will presumably plan a related optical access connection, driven by higher broadband applications, to meet the noteworthy improvement of traffic relaxed the alliance.

3.3. Proposed System

On account of the presentation of new administrations, for example, portability, distributed computing, and the IoT, information rates, adaptability and versatility, and enormous data transfer capacity are expected in both baseband (BB) and remote systems. WDM-PON will be a possible solution for future wired transmission systems. To accomplish high capacity and portability, RoF transport frameworks are also a good solution for future access networks [11]. The upcoming 60 GHz MMW band is extremely important for wireless communication because of its immense data transfer capacity over the 7-9 GHz unlicensed bandwidth [61]. Therefore, combining RoF with WDM-PON could be a promising solution for fundamentally expanding the capacity and coverage of existing systems, permitting wired and wireless communications to be engendered simultaneously for multiservice systems.

This study proposes and probably endorses a WDM-RoF-PON for sending downlink (DL) and uplink (UL) wired more than 25 km SMF, as well as a DL distant transmission of more than 25 km SMF and 5.2 m free space. By using fitting distorted light implantation from an improved Amplified Spontaneous Emission (ASE) source, the various modes component of a Fabry Perot Laser Diode (FPLD) is converted into two modes. The main mode sends 2.5 Gbps information, while the subsequent mode conveys 1.25 Gbps distant data messages through the DSBCS method. RSOA is utilized at the receiver site to successfully impart 1 Gbps upstream (US) wired information.

The optical wireless signal is converted to an electrical signal by 60 GHz PIN PD and boosted by a 60 GHz Power Amplifier (PA) and wirelessly transmitted through 5.2 m by a 60 GHz horn antenna with 25 dBi gain. Another 60 GHz horn antenna is used to receive the RF signal and then amplified by a 60-GHz Low Noise amplifier (LNA). A 60-GHz Local oscillator (LO) is mixed with the signal carrier frequency by a mixer and eventually converted the RF signal into the baseband signal [62]. LO frequency signal synchronizes in phase with the carrier frequency signal and enhances the received power of the wireless signal. Then it is filtered by a Bessel Low Pass Filter (LPF) and fed into BER analyzer for BER performance.

3.4. WDM-RoF-PON

WDM-RoF-PON is getting popular not just in light of the fact that it offers a promising answer for speeding up the system of PON and FTTH, yet additionally on the grounds that it offers end clients high data transmission capacity for a minimal price.

3.4.1. WDM-RoF-PON architecture

WDM-RoF-PON is a cutting edge detached optical system that furnishes buyers with high information rates. A proper sets of frequencies is selected to lay out a protected, dedicated communication interface among supporters and specialist co-op. Figure 3.1 illustrates the block diagram of proposed WDM-RoF-PON system design. It gives consolidated downstream and upstream information up to 40 Gbps. Through the ODN, 40 Gbps collected information is sent the two different ways from a specialist system's OLT to system hardware introduced at client areas known as ONU. The WDM multiplexer and de-multiplexer at the CO or OLT, as well as the splitter not included at the far center, are utilized to plan and reenact WDM-RoF-PON.

Every transmitter block incorporates a continuous wave (CW) laser source with a frequency that is regulated with 2.5 Gbps of information using a Mach-Zehnder Modulator (MZM). Every one of the sixteen transmitters sends 2.5 Gbps of downstream information. The downstream frequencies start at 1550 nm. The single transmitter signal is multiplexed by 16:1 WDM-multiplexer, which totals 40 Gbps. An optical capacitor block gets the multiplexed signal. The EDFA amplifies the multiplexed signal. ONU is comprised of an EDFA, a fiber optical feeder (FOF), and a photo detector unit. Downstream signals are communicated from the OLT to the ONU by means of the circulator, and upstream signals are gotten from the ONU to the OLT through the circulator. The optical framework between OLT and ONU should be separated, as per the meaning of a non-overlapping optical system. Accordingly, in the proposed WDM-RoF-PON, a functioning EDFA enhancer can be put at either the OLT or the ONU. Parameters of the proposed WDM-RoF-PON system is given in Table 3.1.

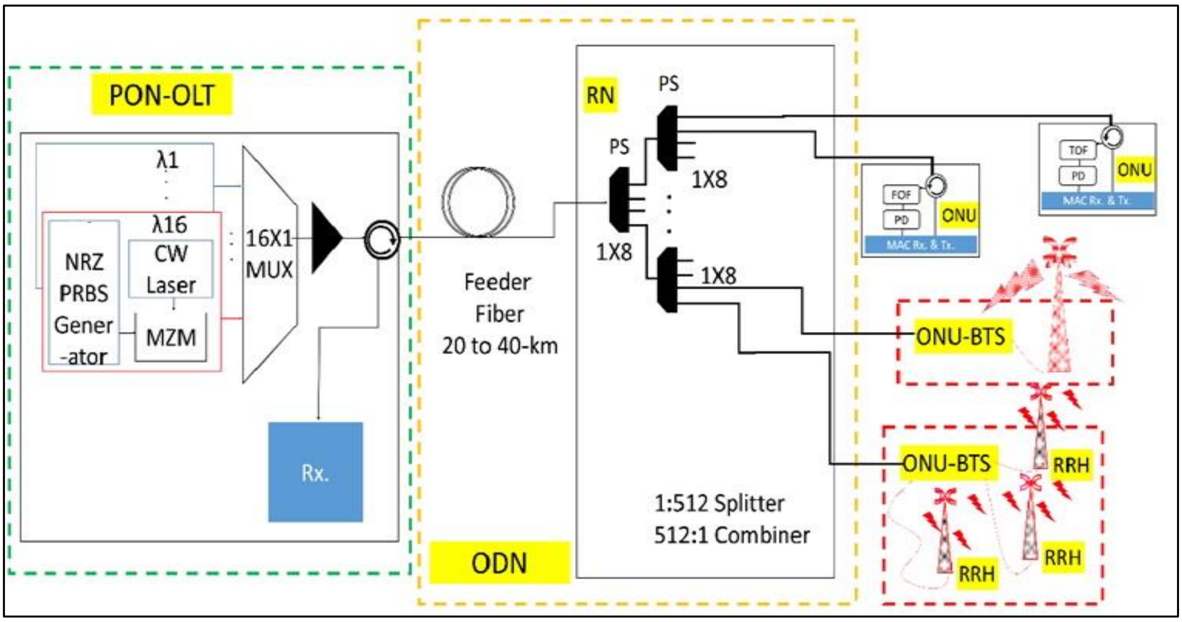

Figure 3.1. Block diagram of WDM-RoF-PON system architecture.

Table 3.1. Simulation parameters of WDM-PON architecture.

Parameters	Downstream	Upstream
No. of wavelengths	16	16
Wavelength spacing (nm)	1	1
Starting wavelength (nm)	1550	1530
Modulation type	PM-16-QAM	
Line coding	Level nonreturn to zero (NRZ)	
Peak data rate (Gbps)	2.5	
Aggregated data rate (Gbps)	40	

4. SIMULATIONS, RESULTS AND DISCUSSION

For different optical fiber ranges of the PON, two distinct WDM-RoF-PON setups are planned and simulated. They are booster amplifier setup and pre-amplifier setup. Quality factor (Q-factor) values were calculated for two separate systems of WDM-RoF-PON. In this communication system, Q-factor addresses the SNR values of related logic levels of '1' and '0'.

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \tag{4.1}$$

$$P_e = 0.5erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{4.2}$$

Where μ_1 and μ_0 are the average values of logic '1' and logic '0', individually, 0 and 1. σ_0 and σ_1 are the standard deviations of noise power for logic ‘1’ and logic ‘0’ respectively, P_e is a probability of error which is the BER associated with Q-factor. The tolerable limit for the WDM-RoF-PON system is recommended as Q-factor ≥ 6 and corresponding BER ≤ 10^{-9} [63], and the value of each parameter is as follows:

- μ_1 (average value of logic '1') = 0.8
- μ_0 (average value of logic '0') = 0.2
- σ_1 (standard deviation of noise power for logic '1') = 0.1
- σ_0 (standard deviation of noise power for logic '0') = 0.05

The table 4.1 gives the simulation parameters for the downstream/upstream, the choice of these parameters depends on the specific requirements and limitations of the WDM-RoF-PON system being simulated. For instance, the fiber reach depends on factors such as the size of the geographical area that needs to be covered by the PON and the attenuation of the fiber being used. The downstream BER depends on factors such as the acceptable error rate for the system and the SNR of the receiving equipment. In general, a simulation can be used to evaluate the impact of different parameters on the performance of the system and to optimize the system design accordingly. Therefore, the choice of these parameters depends on the research objectives and the hypotheses being tested in the simulation, as well as the available resources and constraints. It also depends on trial and error and previous literature to choose the best parameters and their values.

Table 4.1. Simulation parameters for the downstream/upstream

Simulation Parameters	
Simulator	Opti system V 14
Transmission distance	60-70 km
Data rate	40 Gbps
Downstream/Upstream Wavelength	1490/1290, 1510/1310, 1530/1330, 1550/1350
Passive Splitter	1:128
Attenuation	0.32 dB/km
Dispersion	-20 ps/nm/km
gain	25 dB
Cut off frequency of Low pass Bessel filter	0.75xBit rate Hz

4.1. Simulations of WDM-RoF-PON with Booster Amplifier and Pre-Amplifier

Table 4.2 records the Q-factor values for both WDM-RoF-PON designs: booster amplifier WDM-RoF-PON and pre-amplifier WDM-RoF-PON arrangement. As per the information in Table 4.2, as the length of the fiber builds, Q-factor diminishes for the two arrangements. The decrease in the Q-factor is more severe in pre-amplifier WDM-RoF-PON than in booster amplifier WDM-RoF-PON.

Table 4.2. Q-factor performance comparison of booster amplifier and pre- amplifier based WDM-RoF-PON at various fiber lengths

Fiber Reach (km)	Downstream Q-factor	
	Booster amplifier WDM-RoF-PON	Pre-amplifier WDM-RoF-PON
10	33.76	49.55
20	28.89	54.39
30	23.06	50.72
40	17.74	37.39
50	14.82	27.19
60	12.36	21.92

Figure 4.1 portrays the eye pattern of booster amplifier and pre-amplifier WDM-RoF-PON arrangements. Pre-amplifier WDM-RoF-PON has a better open eye pattern than that of the booster amplifier WDM-RoF-PON. Both designs prove to be effective, the choice between booster amplifier and pre-amplifier setup depends on the design of the WDM-RoF-PON

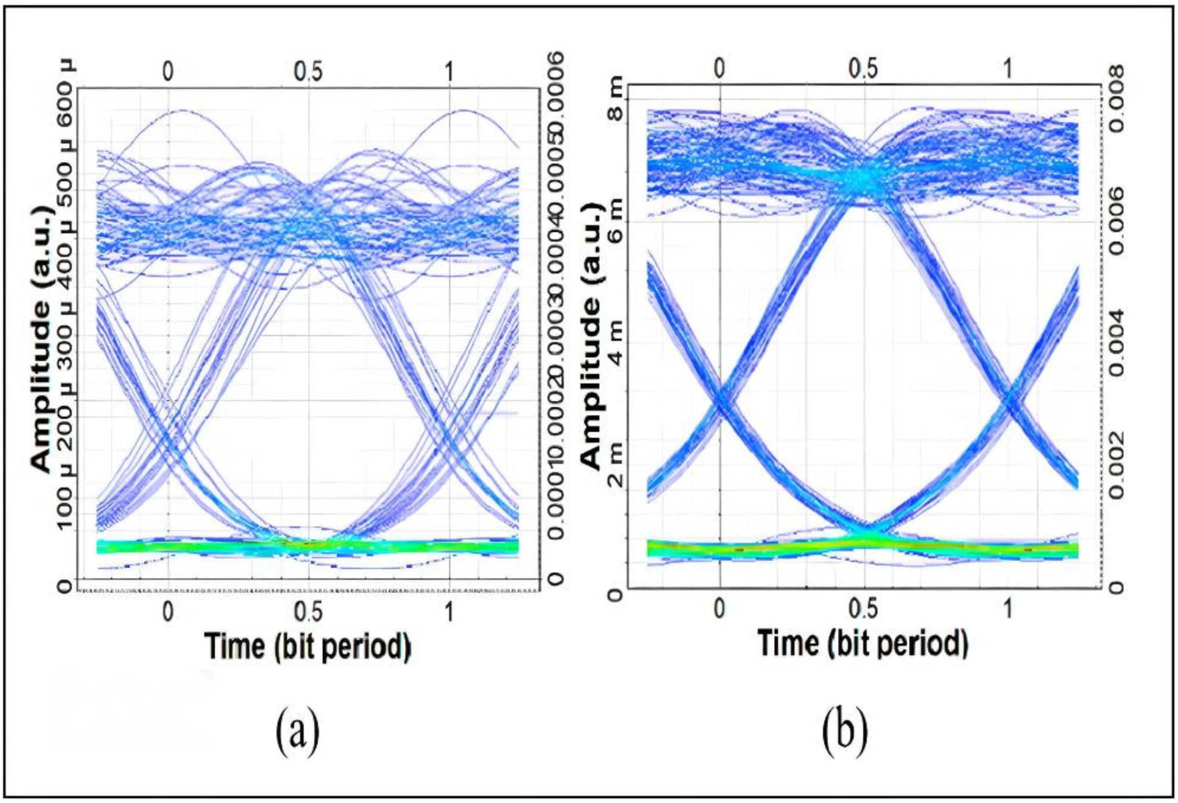

Figure 4.1. Q-factor and eye pattern at 60 km fiber reach for (a) booster amplifier and (b) pre-amplifier WDM-RoF-PON configuration.

system, besides the specifications and operating conditions of the amplifiers being used. The booster amplifier setup is generally used for long-haul optical communication, where the signal needs to be amplified to compensate for the loss of signal power over a long distance. On the other hand, the pre-amplifier setup is used for shorter distances or where the signal power is already relatively high, and the goal is to amplify the signal while minimizing noise.

In the context of booster amplifier and pre-amplifier, booster amplifier refers to the use of amplification before the signal has been transmitted, while pre-amplifier refers to the use of amplification after signal transmission. The purpose of using RSOA is to reduction for the dispersion effect that arises due to differences in the propagation speed of different wavelengths of light because RSOA is an anti-reflective coating on the front facet and has high reflectivity on the rear aspect.

Also, the choice between booster amplifier and pre-amplifier depends on factors such as the type of fiber being used, the length of the fiber link, and the wavelength of the signals being transmitted. In general, the use of booster amplifier allows for longer fiber reaches but requires more complex equipment, while the use of pre-amplifier is simple but is limited by the dispersion limits of the fiber. Table 4.3 shows the BER performance for three different WDM-RoF-PON with unamplified, booster amplifier and pre-amplifier versions.

Table 4.3. Downstream log (BER) of unamplified, booster amplifier and pre- amplifier at various fiber lengths

Fiber Reach (km)	Downstream log (BER)		
	unamplified	booster amplifier	pre-amplifier
20	-16	-7	-18
45	-15	-9	-25
75	-8	-17	-20
105	-2	-12	-12
115	-2	-8	-2

Figures 4.2, 4.3, and 4.4 display Log (BER) curves for WDM-RoF-PON with unamplified, booster amplifier and pre- amplifier versions. It is understood from the graphs that unamplified WDM-RoF-PON has BER of 10^{-9} up to 70 km, while booster amplifier and pre-amplifier has almost 100 km of optical fiber reach with a BER of 10^{-9}.

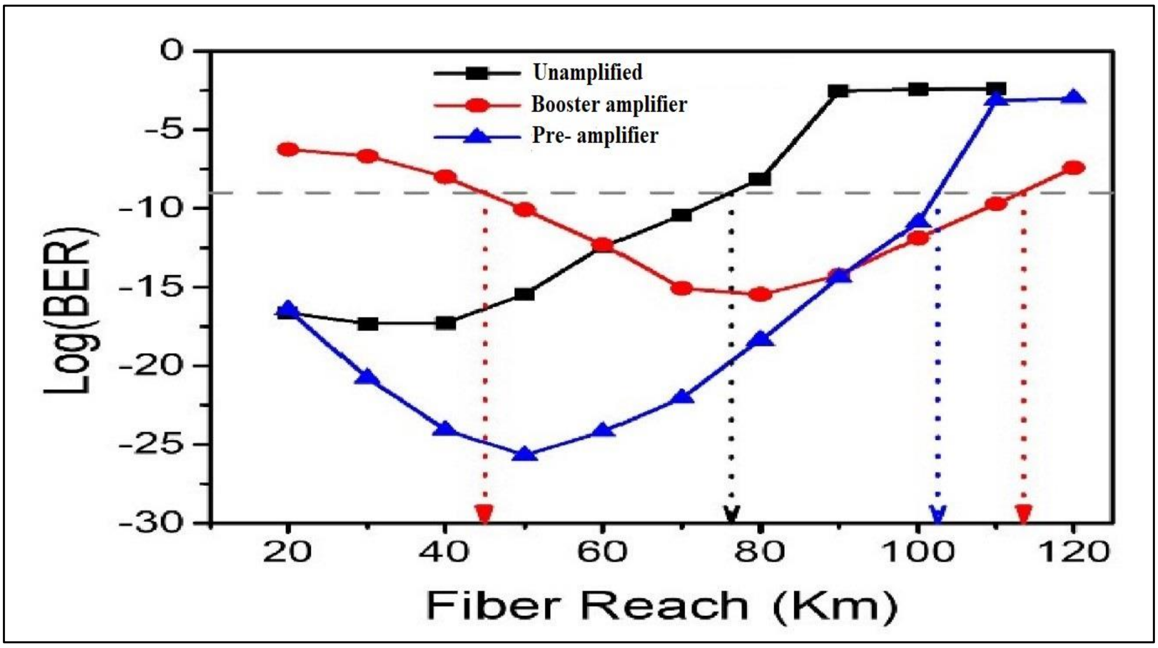

Figure 4.2. Log (BER) vs fiber reach for downstream unamplified, booster amplifier and pre- amplifier configuration.

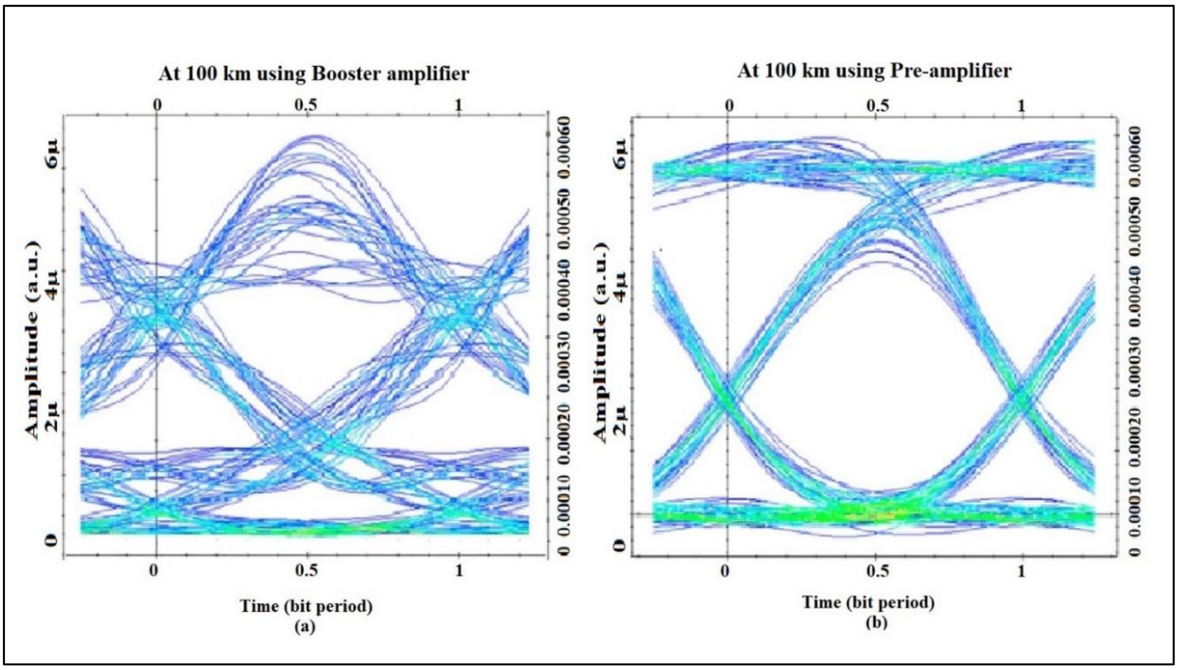

Figure 4.3. Eye pattern at 100 km fiber reach for (a) booster amplifier and (b) pre-amplifier WDM-RoF-PON configuration.

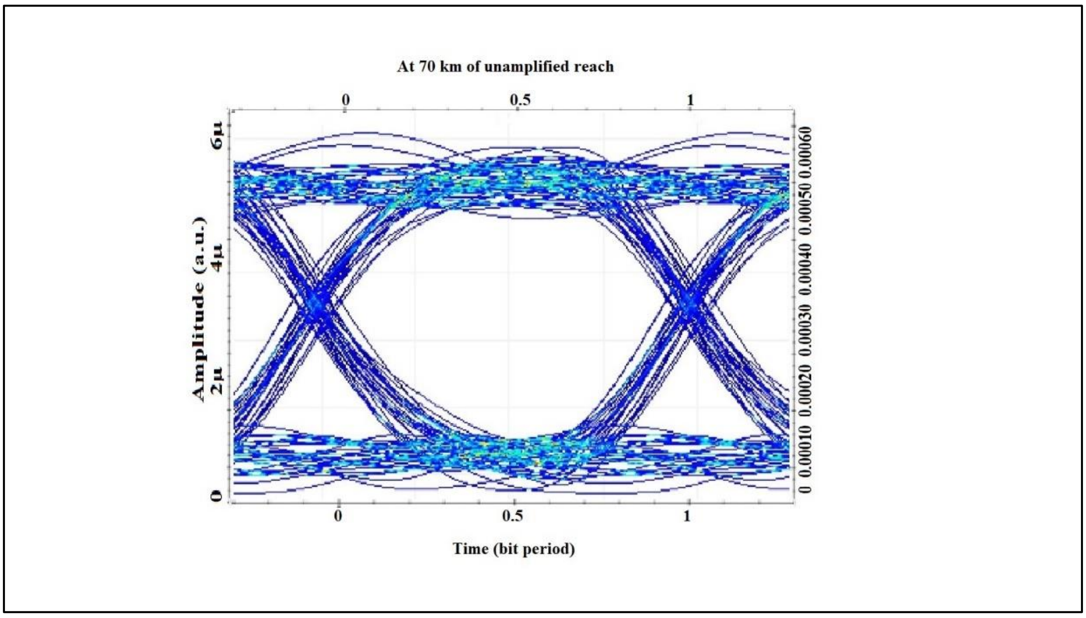

Figure 4.4. Eye pattern at 70 km fiber reach for unamplified WDM-RoF-PON configuration.

In order to validate our method, we have analyzed the results in the unamplified signal's eye pattern in figure 4.4 that it has a Q-element of 6.48 and a Log (BER) of -10.42 at 70 km.

Figure 4.3 likewise portrays the eye example of the received signal after booster amplifier remuneration and pre- amplifier pay after a 100 km WDM-RoF-PON reach. The Q-factor of the received signal after amplification is 6.98, and the Log (BER) is -11.88. The Q-factor of the received signal before amplification is 6.65, and the Log (BER) is -10.88. In this situation, we found that our method completely matches the results presented in [64].

No previous results are available, on the contrary, when a consolidated light implantation method and (DSBCS), are taken into account, we have thus validated our model by comparing our results with numerical simulations obtained using the optical system simulator Opti System V14. In these simulations, the system BER has been estimated through error counting.

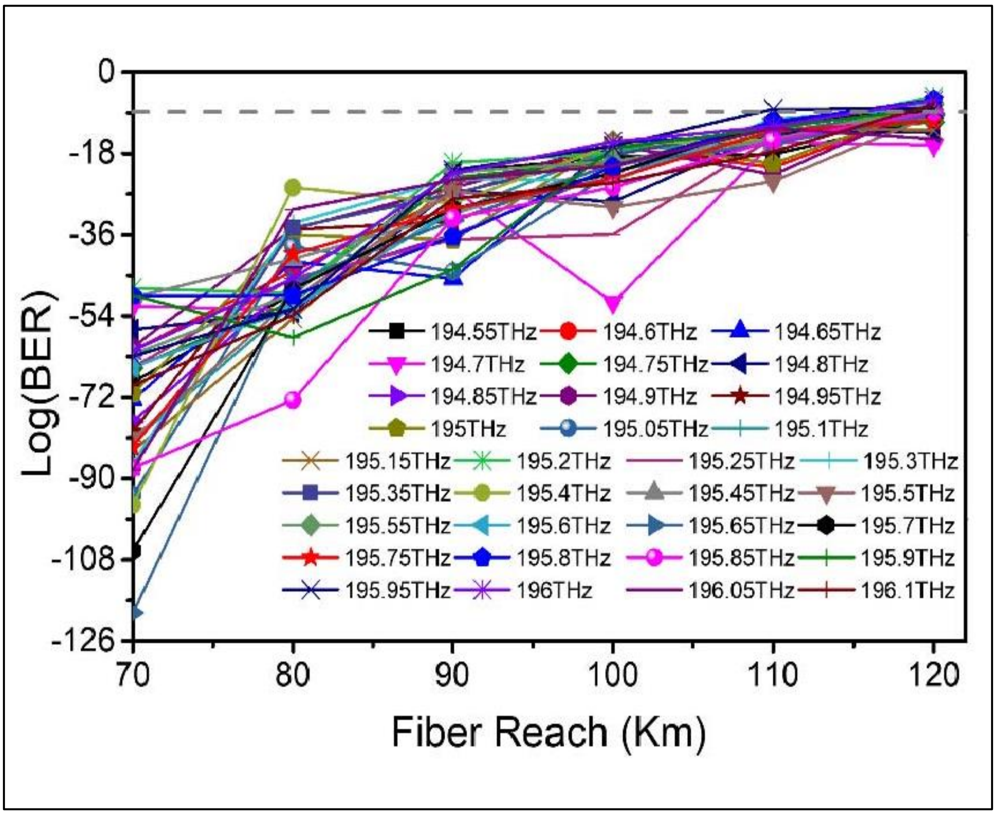

Figure 4.5. Log (BER) vs fiber reach of the upstream WDM-RoF-PON.

Figure 4.5 portrays the presentation of 32 upstream frequencies vs. fiber reach. Upstream frequency gives dependable execution up to 100 km fiber reach. Since upstream frequencies are tweaked at a rate of 2.5 Gbps, the distortions due to scattering and fiber nonlinearity are minor when compared with downstream frequencies regulated at a rate of 10 Gbps.

4.2. Comparison of Related Works

In this work, a 2.5 Gbps WDM-RoF-PON based on a coherent receiver and advanced higher order modulation scheme has been designed and investigated. Single-channel polarization multiplexed signal is used to achieve long-haul downstream 2.5 Gbps information transmission for different numbers of end terminal users. From the results, it can be concluded that the proposed WDM-RoF-PON system successfully transmits 2.5 Gbps information up to a maximum propagation length of 100 km with good BER and received power performance. Also, by using the algorithms at the receiver terminal as discussed in this work, there is a notable performance improvement of the received data signal at the receiver. Further, we have compared the proposed WDM-RoF-PON performance with existing literature (Table 4.4), and from the comparison it can be concluded that the proposed architecture provides a more spectral-efficient and high-speed transmission over longer fiber length.

Table 4.3. Performance comparison of the proposed WDM-RoF-PON system with related other studies.

Ref.	system used	distance	data rate	Q-factor	Log (BER)
[65]	Hybrid WDM-TDM-PON	50 km	10 Gbps	6.5	10^{-9}
[66]	Hybrid WDM- OTDM-PON	96 km	10 Gbps	6.11	10^{-9}
[67]	Hybrid MDM- DWDM-NG-PON	1 km	25 Gbps	6.8	10^{-9}
[68]	TWDM-based NG-PON	130 km	20 Gbps	4.23	10^{-4}
[69]	OCDMA-PON	142 km	40 Gbps	2.5	10^{-6}
[70]	Hybrid PON (WDM-TDM)	45 km	5 Gbps	6.33	10^{-4}
Pre-Amp.	WDM-RoF-PON	100 km	2.5 Gbps	6.98	10^{-12}
Boost-Amp.	WDM-RoF-PON	100 km	2.5 Gbps	6.65	10^{-11}

4.3. Conclusion

In this study, a 16-channel hybrid WDM-RoF-PON has been designed and implemented. An aggregate data rate of 40 Gbps was achieved for a distance of up to 100 km. The performances of the receiver for these fiber lengths can be demonstrated in Table 4.2 at 60 km with the booster amplifier the Q-factor was 12.36 and with pre-amplifier Q-factor was 21.92. From the table, it can be seen that the quality factor of the pre-amplifier is better than the booster amplifier because the pre-amplifier is installed at the downstream end while the booster amplifier is installed in the upstream end. Overall, the Q-factor for both amplifiers is excellent with good eye pattern for both of them.

From the result of unamplified, booster amplifier and pre-amplifier simulation, the unamplified signals have a Q-factor 6.48 and a Log (BER) of -10.42 at 70 km, booster amplifier has Q-factor 6.65 and a Log (BER) of -11.88 at 100 km and pre-amplifier has Q-factor 6.98 and a Log (BER) of -12.78 at 100 km, these techniques are presently used because it eliminates the effects of dispersion in long-haul .It is observed that both booster amplifier, and pre-amplifier techniques provide better results for short haul communication as well as long haul communication.

BER and Q-factor has been improved and these results show that with the amplifier, the WDM-RoF-PON can be used for long-haul transmission system.

5. CONCLUSIONS AND FUTURE WORKS

5.1. Conclusions

We have suggested and showed an enhanced low-cost RSOA-based WDM-RoF-PON supporting simultaneous transmission of BB and wireless signal using incoherent light injection technique. Optical techniques and RSOA to offer higher signal bandwidth and spectral efficiency have been utilized to overcome the congestion of lower frequency bands and make the system cost-effective respectively. In the architecture, we have planned a hybrid WDM-RoF-PON with FTTH for triple-play services to transmit voice, data, and video services simultaneously to congregate the growing bandwidth demand for residential customers. So, the suggested hybrid WDM-RoF-PON architecture has a modern practical application for fiber-wireless communication to provide broadband wireless communication, HDTV, and cable TV services in a cost-effective manner with satisfactory performance. RoF-based optical-remote combined framework has been trusted the most proficient goal to increase the coverage, capacity, data rate, and versatility as well as reduce the expense for future access networks. This hybrid system gives the incorporated benefits of optical and remote systems to serve both fixed and remote purchasers. The WDM-RoF-PON system essentially involves a transmission BB and wireless signal using an incoherent light injection technique. RoF offers low attenuation with broad bandwidth. It has the advantage of an immune system to the electromagnetic interference. A roof system employing WDM-RoF-PON was simulated using Opti System V.14 simulation software. WDM can be considered the best method used in RoF. WDM allows the transmission of multiple signals.

The Optical Carrier Suppression (OCS) modulation scheme is the desirable candidate in bidirectional optical wireless networks because of its superior spectral effectiveness and receiver sensitivity. RSOA is the most distinguished equipment employed in optical network units (ONUs) due to its several advantages. reflector, modulator, and amplifier simultaneously to achieve colorless uplink transmission, and it re-modulates the downlink signal with the uplink data, with the elimination of extra seeding sources at ONU, and system can be made simple and cost-efficient. Our new competent techniques for creating millimeter-wave signals do not necessitate costly high-frequency electrical utensils. The got results propose that the optical millimeter-wave creation, and up-change technique upheld outer force regulation and utilizing a single source with RSOA shows sensible advantages concerning the savvy basic setup and elite execution over significant distance correspondence. A WDM light wave conveying plan is an imminent contender not just for SMF-based optical fiber spine but also conjointly for RF/optical-remote-based feeder networks because of its colossal transmission capacity, high velocity information rate, intelligence, and inclusion range. Such a light-wave broadcast will be a delightful access for providing broadband-coordinated administrations, along with web, media transmission, and data correspondence administrations not only for wired and RF remote but rather likewise for optical remote clients inside the RF space. By applying dispersion compensated fiber and data recovery planner, the system may transmit more data over more distance with enough bandwidth.

5.2. Future Works

A few keys empowering advancements are distinguished and created in this exploration. There are as yet many issues that should be tended to. OFDM is an incredible decision for remote transmission, yet the OFDM-RoF strategy requires symmetry between subcarriers. One more significant point to explore for the functional execution of met MMW and WDM-PON is cross-talk between various optical channels. FSO correspondences have been turned into a capable substitute to remote systems for highlight point correspondence due to their low execution cost, high data transmission, high security, and unlicensed range in building, underground, and at rustic correspondingly as extending optical fibers is very simple.

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Gazili olmak ayrıcalıktır