Energy Efficient & Flexible Gigabit Optical Access Networks

Ph.D. Thesis

AMIT KUMAR GARG
(ID. No.2013REC9031)

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING
MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY, JAIPUR

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Amit Kumar Garg

ID-2013REC9031

Under the Supervision of

Dr. Vijay Janyani

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

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CERTIFICATE

This is to certify that the thesis entitled "**Energy Efficient & Flexible Gigabit Optical Access Networks**" being submitted by **Amit Kumar Garg** is a bonafide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Electronics & Communication Engineering, Malaviya National Institute of Technology Jaipur. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

Place: Jaipur

Date:

(Dr. Vijay Janyani)
Associate Professor
Dept. of Electronics and Communication
M.N.I.T., Jaipur

DECLARATION

I, Amit Kumar Garg, declare that this thesis titled, 'Energy Efficient & Flexible Gigabit Optical Access Networks' and the work presented in it are my own. I confirm that:

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(2013REC9031)

“Your hardest times often lead to the greatest moments of your life. Keep going. Tough situations build strong people in the end”

Roy T. Bennett

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ABSTRACT

With the continuously increasing bandwidth demand, optical access networks have emerged as a promising solution to support the next generation high bandwidth applications such as Video on demand (VOD), High-definition television (HDTV), Teleconferencing, E-Medicine, E-transactions and Social media etc. Due to continuously growing high data rate applications, energy consumption in Information and Communication Technology (ICT) is also increasing and is around 10% of the total of the industrial energy consumption. This energy consumption is increasing day-by-day exponentially with the expanding ICT applications. Since the earth has limited natural energy resources; available energy is not expected to fulfill the future energy demand. Also, higher energy consumption is responsible for the emission of larger Green-House Gases (GHGs) and carbon footprint; therefore producing global warming and deteriorating our friendly environment.

In this thesis, flexibility analysis of passive optical networks is done. Cost and energy efficient multiplexing techniques are identified for different network scenarios such as different fiber length, different users, and different data rates. Identified multiplexing combination requires the minimum number wavelengths for a given set of parameters for minimum cost and acceptable Quality of service (BER performance). After that, some flexible and energy efficient optical access network architectures are addressed that allow the best resource utilization and reduces energy consumption significantly for the varying traffic load networks. Our proposed architectures reduce the operational expenditure (OPEX) by utilizing the proper selection of transceivers (10 G/ 1G) and a minimum number of central office (CO) resources depending on the required load. Also, we propose an architecture which is capable of supporting dual rate broadcasting along with dedicated point to point (P2P) transmission to make the architecture multidimensional. In addition, proposed architecture also improves the reliability against any optical line terminal (OLT) module or transceivers (TRx) or line card failure. As traffic load is not

constant round the clock, proposed architectures allow bandwidth scalability, network extensibility to support next-generation optical access networks.

After that, we propose a flexible hybrid WDM-TDM passive optical network with pay as you grow deployment capability. This architecture is capable of providing up to 40Gbps, equal data rates to all optical distribution networks (ODNs) and up to 70Gbps asymmetrical data rate to the specific ODN. Pay-as-you-grow-deployment capability of the proposed architecture allows service providers to spend as they grow and reduces network energy consumption and OPEX significantly. This architecture also supports another important features like bandwidth scalability, broadcasting and reliability. Then we discuss another resilient, bandwidth scalable and energy efficient hybrid PON architecture. By utilizing proper OLT line cards and adaptive link rate mechanism, this architecture reduces significant access network power consumption in the presence of low traffic / underutilized network. This architecture also supports bandwidth scalability and provide network resiliency against LC/TRx or module failure.

Apart from energy efficiency, we further address some latency-aware direct inter- optical networking unit (ONU) communication architectures that may be utilized to support low latency applications among the peers located locally. Proposed WDM-PON architectures provide energy-efficiency, latency-awareness and direct ONU interconnection capabilities. Direct ONU interconnection reduces the requirement of complex routing mechanism of the inter-ONU signal at OLT and therefore increases the reliability of the system. By using proposed architectures, inter-ONU signal does not impose any extra burden on downstream bandwidth thus provide efficient bandwidth utilization.

Contents

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List of Abbreviations

APON:	ATM-PON
ATM:	Asynchronous Transfer Mode
AWG:	Array Waveguide Grating
BER:	Bit Error Rate
BPON:	Broadband PON
CM:	Cable Modem
CO:	Central Office
CW:	Continuous Wave
DB:	Duo-binary
DFB:	Distributed Feedback Laser
DPSK:	Differential Phase Shift Keying
DXC:	Digital Cross Connects
EAM:	Electro Absorption Modulator
EDFA:	Erbium Doped Fiber Amplifier
EPON:	Ethernet PON
FASN:	Full Service Access Network
FTTH:	Fiber to The Home
FTTx:	Fiber to The x
GEPON:	Gigabit Ethernet PON
GHG:	Green House Gas
GHz:	Gigahertz
HDTV:	High Definition Television
ICT:	Information and Communication Technology
IEEE:	Institute of Electrical and Electronics Engineers
IP:	Internet Protocol
ITU:	International Telecommunication Union

km:	Kilometer
LAN:	Local Area Network
LC:	Line Card
LED:	Light Emitting Diode
MLR:	Mixed Line Rate
MZM:	Mach-Zehnder Modulator
nm:	Nanometer
NRZ:	Non Return to Zero
OADM:	Optical Add-Drop Multiplexers
OAN:	Optical Access Network
ODN:	Optical Distribution Network
OLT:	Optical Line Terminal
ONU:	Optical Networking Unit
OOK:	On Off Keying
OPEX:	Operational Expenditure
OXC:	Optical Cross Connects
PC:	Power Combiner
PON:	Passive Optical Network
PS:	Power Splitter
RN:	Remote Node
Rx:	Receiver
RZ:	Return to Zero
SBS:	Stimulated Brillouin Scattering
SDH:	Synchronous Digital Hierarchy
SLR:	Single Line Rate
SMF:	Single Mode Fiber
SNR:	Signal to Noise Ratio
SOA:	Semiconductor Optical Amplifier
SONET:	Synchronous Optical Networking
SPM:	Self-Phase Modulation
SRS:	Stimulated Raman Scattering

TDM:	Time Division Multiplexing
THz:	Terahertz
TRx:	Transceiver
Tx:	Transmitter
VOD:	Video on Demand
WDM:	Wavelength Division Multiplexing
Wi-Fi:	Wireless Fidelity
Wi-Max:	Worldwide Interoperability for Microwave Access
WOBAN:	Wireless Optical Broadband Access Network
xDSL:	x Digital Subscriber Line

Dedicated to my Parents & Sisters for their endless support………………..

Chapter 1

1. Introduction

1.1 Introduction

With the necessity of transferring information, people have come across the various communication systems for sending information from one place to another place ranging distance of few meters to hundreds of kilometers (km). Optical communication had played a most significant role in the various developed technologies. From the ancient times, people are using light for the communication. Fire & smoke signals, semaphore flags were the most commonly used known techniques of that time [1-3]. For example, smoke signals as visual communication are used to transmit information to alert or invite people to the common areas [4]. With the advancement in technologies; methodologies of signal transmission are changed, but the concept remains same. Also with the requirement of high-speed communication and for longer distance transmission, optical communication have emerged as the most promising technology. In this chapter, we will see the overview of the optical communication system with its advantages. Then we discuss the need for optical access networks, and motivation of our Thesis work. Later part of the chapter presents the organization of the Thesis.

1.2 Overview of Optical Communication System

After the invention of the laser in the early 1960s, optical communication advances significantly. Coherent lasers used in optical communications are capable of generating the frequencies in the range of Terahertz (THz) which is approximately 10^5 times higher than the microwave frequencies. Therefore optical communication is responsible for providing much larger data transfer capacity than the other communication systems. During that period, it was also observed that optical fiber cables might be the one of the best and reliable communication channel [5]. However, at the initial stage of development of optical fiber, extremely high losses of the order of 1000 dB/km was the biggest challenge to utilize it in the real scenario. In 1966, Kao and Hockham observed that large losses were the mainly due to the material impurities of the fiber [6]. In 1972, highly pure low loss (20 dB/km) optical fiber was developed by Dr. Robert Maurer, Dr. Peter Schultz, and Dr. Donald Keck [7] and used for transmitting the signals for long distance. After that, optical communication system attracted worldwide. In the recent times, optical fibers having low losses (as low as 0.14 dB/km) have been developed [8], [9] which confirms the long distance transmission with least requirement of amplifiers or repeaters.

The electromagnetic spectrum in the near-infrared region ranging from 770 nm to 1675 nm is used for transmitting the light wave signals as it provides the low losses for the silica fibers. After 1990s, there was a demand for high bandwidth to service telemedicine, e-education, e-health, high definition videos etc. To fulfill the ever increasing bandwidth demand, transmission of multiple wavelengths in the same channel was also proposed [10], [11].

A basic optical communication system consists of three parts namely transmitter, channel and receiver. A generalized architecture of an optical communication system is shown in Fig. 1.1

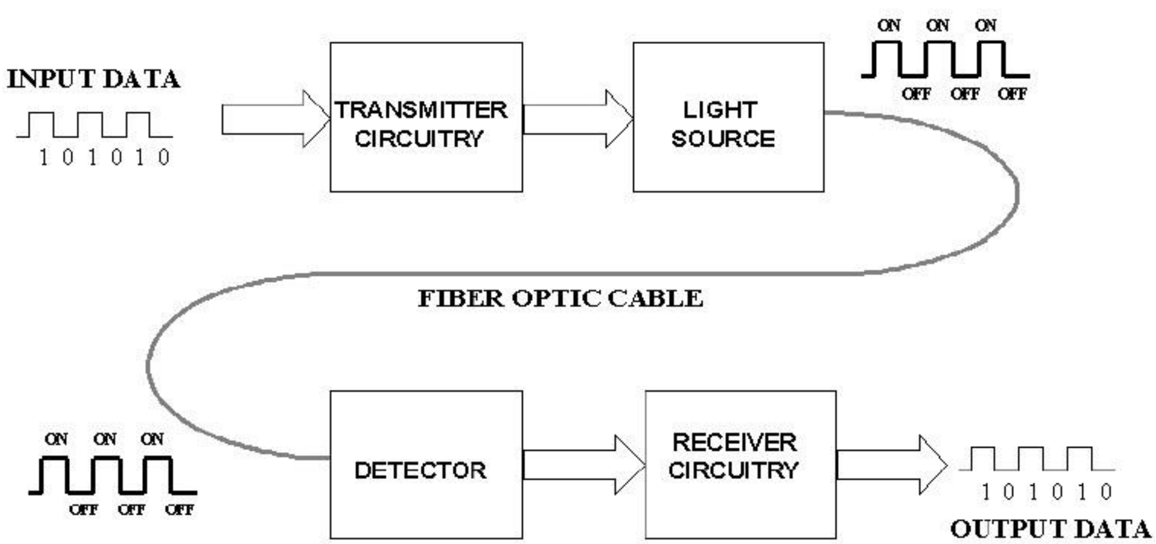

Fig. 1.1 A generalized architecture of an optical communication system [12]

1.2.1 Transmitter

At the transmitter side, information in the form of voice, data or video are first converted from the non-electrical form into electrical form. As an example, voice signals are first converted into the electrical form with the help of a microphone. For the short distance link as shown in Fig. 1.1, baseband signal (information) is directly modulated on the laser or LED. However, for long-distance links, baseband data may be impressed on the optical (electromagnetic) carrier with some external modulator. The optical carrier is often generated with the help of high-frequency stable CW laser or distributed feedback laser. However, for low distance transmission, low-cost LEDs may also be utilized. The modulated signal is then launched to the fiber optic cable by splicing it with the modulator. The main purpose of the splicing is to connect the optical signal and transfer it to the optical fiber cable efficiently.

1.2.2 Channel

Fiber optic cable serves as the channel for the optical signals and transmits them between the transmitter and receiver. Fiber optical cable is the dielectric waveguide that works at optical frequencies of the electromagnetic spectrum. Most widely used optical fiber cable is the cylindrical waveguide as shown in Fig. 1.2. The core of this cylindrical waveguide has the radius a and refractive index n_1 which is slightly greater than that of cladding and known as n_2. The main purpose of the cladding is to confine the light. If the mode is well confined, then scattering loss from the surface roughness can be smaller. It also shields the core from getting contaminated and provide mechanical strength to the fiber. Fiber is coated with buffer and bundled in a jacket to provide further strength to it. The material of the core is highly pure glass SiO_2. To create the refractive index difference between core and cladding, doping of various oxides are done either in the core or cladding. Oxides may be B_2O_3, GeO_2 or P_2O_5. The addition of GeO_2 or P_2O_5 increases the refractive index while the addition of B_2O_3 dopants reduces the effective refractive index [13].

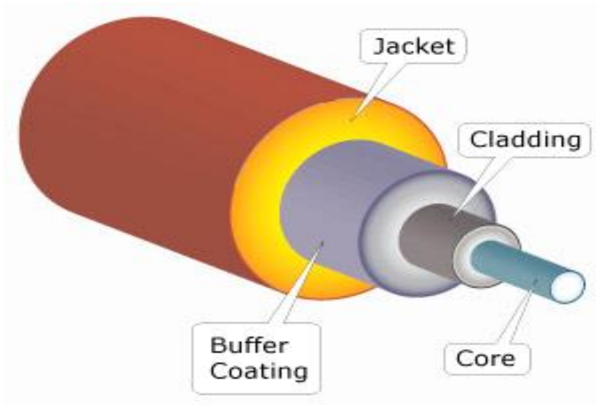

Fig. 1.2 Cylindrical silica fiber structure [14]

The combinations for the core and cladding may be any of the following [13];

1. Core GeO_2-SiO_2; Cladding SiO_2
2. Core P_2O_5-SiO_2; Cladding SiO_2
3. Core SiO_2; Cladding B_2O_3-SiO_2
4. Core GeO_2- B_2O_3-SiO_2; Cladding B_2O_3-SiO_2

Depending upon the fibers diameters and variation in the refractive index profile of the core, fibers may be categorized into three types as shown in Fig 1.3.

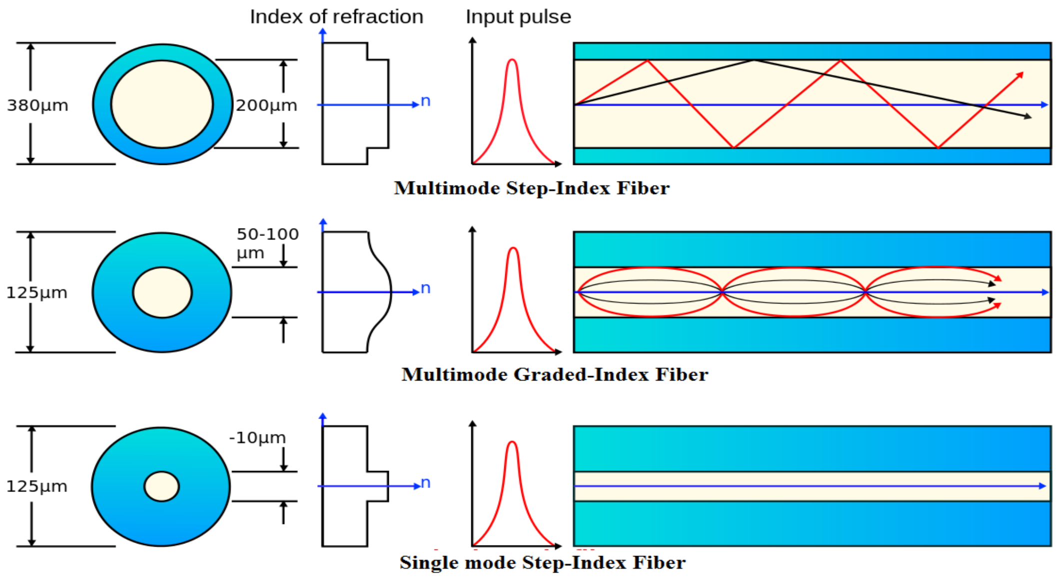

Fig. 1.3 Different types of fibers [15]

When the refractive index of the fiber core is made uniform throughout its radial axis and abruptly changes at the core-cladding interface, designed fiber is said to be the step index fiber. If the refractive index of the core of the fiber continuously varies with its radial axis than such fibers are known as graded index fiber [16]. According to the number of modes that allowed to travel in the fiber, it may be further categorized into two parts; single-mode fiber and multimode fiber. As the name suggests, when only one mode is allowed to travel in the single mode fiber while hundreds of modes are allowed to travel in multi-mode fiber [17]. Based on the number of modes and refractive index profile; three popularly used fiber combinations with their dimensions are depicted in Fig. 1.3.

Multimode fibers have several advantages and disadvantages over single mode fiber. Due to the larger core dimension, it may simultaneously transmit several modes. Also, multimode fibers may be launched with the low cost and simple light emitting diode (LED) source and may provide much larger bandwidth. However, multimode fibers face intermodal dispersion. As multiple modes travel, each mode propagates with the slightly different path and reaches at fiber end at slightly different times and therefore causing the pulse spread. Graded index fibers may be used to compensate the effect of intermodal dispersion in multimode fibers. As the refractive index of the core decreases with its radial distance, the rays close to the core axis (travel shorter path) travel slowly as compared to the rays travelling near to the core-cladding interface (travel longer path). Therefore, all the rays arrive at the fiber end almost at the same time [13], [18]. Intermodal dispersion is not present in single mode step index fiber as only one mode is allowed to travel. Therefore, single-mode fiber (SMF) is frequently used for larger distance transmissions. However, complex structured highly stable single frequency laser is highly desirable which is a challenging task for researchers, scientists and engineers.

1.2.3 Receiver

Before receiving the optical signal, sometimes especially for long distance transmission, it may be required to amplify the signal with the optical amplifiers to fulfill the minimum receiver sensitivities requirement as it gets weakened due to attenuation (absorption and scattering etc). The amplified optical signal is converted into the electrical signal with the help of PIN photodetector. The output photocurrent is filtered out to remove any DC biasing and unwanted frequency signals. It is required to design a receiver in such a way that it has high sensitivities (to detect the weakest signals), low thermal noise, low shot noise and low distortion. The filtered electrical signal is analyzed by the bit error rate (BER) analyzer to check the performance of the received signal. Generally, BER is synchronized with the input data and compares it with the received electrical signal. Therefore, BER analyzer gives the knowledge of a number of bits in error.

1.2.4 Advantages of Optical Communication System

Optical communication systems have several advantages as compared to the copper and coaxial cables. Transmission losses of pure silica fiber are very small (0.14 dB/km) as compared to the copper cable. Therefore data can be sent for the long distance without the requirement of frequent repeaters and amplifiers and reduce the overall cost and complexity of the channel [19]. Due to the higher bandwidth of optical fibers, more data can be transmitted on a single fiber cable and hence require less number of cables for the given data [20], [21]. Despite the high data rate and low channel losses, optical communication has other several advantages. Fiber cable is small in size and light in weight; it may be easily utilized in aircrafts and satellites for which low weight and compact cables are highly desirable. As fiber cables are made up of dielectric material, which does not get affected by electromagnetic interference such as copper cables. Optical fiber cables also provide a high level of data security as tapping of signals is not possible due to the well opaque coating over the fibers which enables the optical communication for the military, defense and financial applications [13].

Optical fiber communication also has some benefits over wireless communication. Bandwidth of optical communication is in GHz while it is limited upto only few MHz in wireless communication. Due to low losses, repeater distance is larger in optical communication as compared to the wireless communication. Reliability of optical communication is much higher as wireless transmission is much prone to weather conditions. However, deployment time, cost is less in wireless communication. Also, wireless communication is more ubiquitous to optical fiber communication. To avail the benefits of optical fiber along with wireless technology, the backbone network is supported with optical fiber, while the front end is provided with wireless access, this leads to hybrid wireless-optical broadband access network and radio over fiber technology [22].

1.3 Need for Optical Access Networks

For any telecom network, the access network is the part of the network which connects the end users with the rest of the network. Several access technologies have already been deployed such as asymmetric digital subscriber line (ADSL), cable modem (CM), coaxial cable, Wi-Fi and Wi-Max etc. [22]. But due to the maximum bandwidth and span limitation, these access technologies are not expected to be utilized in the far future.

Nowadays, with the increasing high-bandwidth applications such as video on demand (VOD), teleconferencing, social media, and other digital services; optical access technologies are the only left choice to support and fulfill the desired bandwidth. Provided bandwidth per user and maximum span for different access technologies are given in Table 1.1 [23].

Table 1.1: Access technologies with provided bandwidth and max span [23]

Technology	Bandwidth per user	Max span
ADSL	2 Mbps	5.5 km
Coaxial Cable	2 Mbps	0.5 km
Wi-Fi	54 Mbps	0.1 km
Wi-Max	28 Mbps	15 km
GPON	40 Mbps	20 km

Fig. 1.4 shows the Technology Future Inc (TFI) forecasting for the required nominal data rate for a household in U.S.. By the year 2025, it is expected that more than 90 % of the households will require broadband services and approximately 88% of the household will require the data rate more than 100 Mbps.

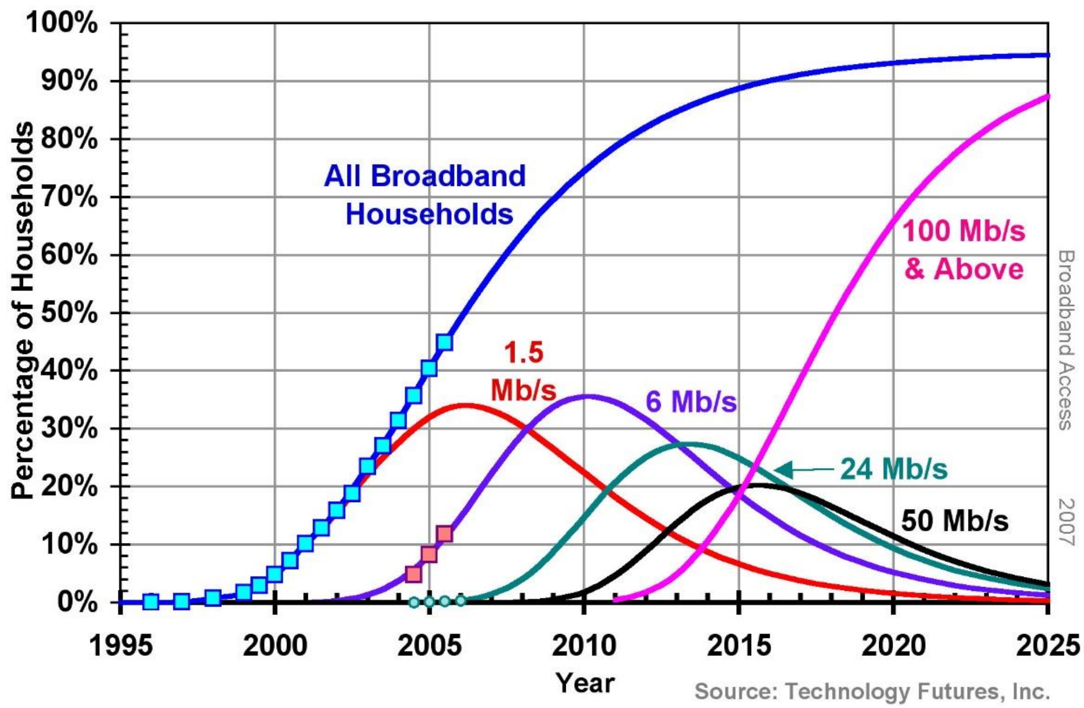

Fig. 1.4 Expected nominal data rate for U.S. households [24]

With ever-increasing bandwidth demand, it is apparent from the Table 1.1 that only optical access technology such as Gigabit Passive Optical Networks (GPON) are the only promising candidate to fulfill the bandwidth demand. As by the year 2025, each household is expected to require 100 Mbps data rates; optical technologies need further technological improvements. We will further discuss optical access technologies in detail in Chapter 2.

1.4 Thesis Motivation

Energy consumption in Information and Communication Technology (ICT) is increasing with day-by-day increasing bandwidth demand. Energy consumed by ICT is almost 10% of the total industrial energy consumption [25], and the European Union’s carbon footprint is roughly 4% [26]. As the energy demand is increasing, available natural energy resources are not expected to support future energy demand. Two different approaches can resolve this problem. First, use of renewable energy resources as much as possible, like installation of servers and clouds in remote areas or wherever renewable energy is available [22]. This approach is not ubiquitous since renewable energy resources are not present everywhere. Due to this limitation, the second approach becomes more attractive and challenging to the researchers and scientists in which, new technologies must be developed that utilize the energy resources efficiently and give better mileage per user. That is, a similar level of functionality must be delivered with the least energy consumption. It not only reduces energy consumption but also reduces the Green House Gases (GHG) emission, a primary reason for global warming [22, 27]. In 2010, the worldwide energy consumption for telecom network was forecasted and given in Fig 1.5 [22]. It shows the exponential growth in telecom networks energy consumption and expected to grow more in future if new technologies and protocols will not be developed.

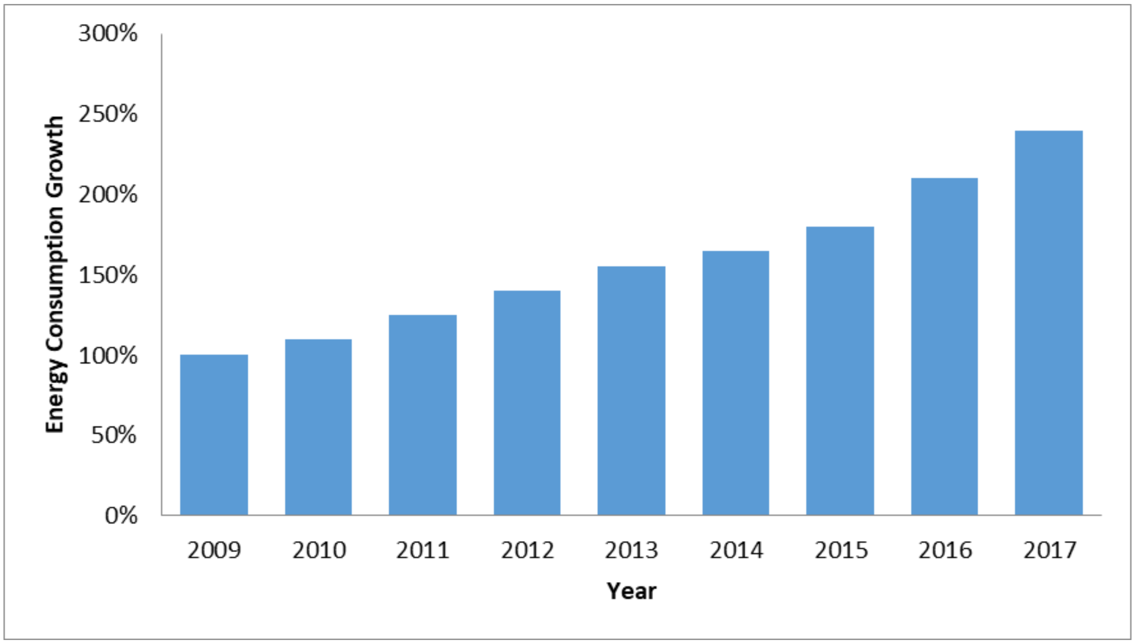

Fig. 1.5 Forecast of worldwide energy consumption in telecom networks [22]

There are several factors that affect the energy consumption of the telecom networks as given in Fig 1.6. Energy efficiency in the network may be achieved by efficient network processing, efficient electronic equipments, by proper dimensioning and planning of the network, or by installing the servers at the places where renewable resources are available and accessing them from the remote node.

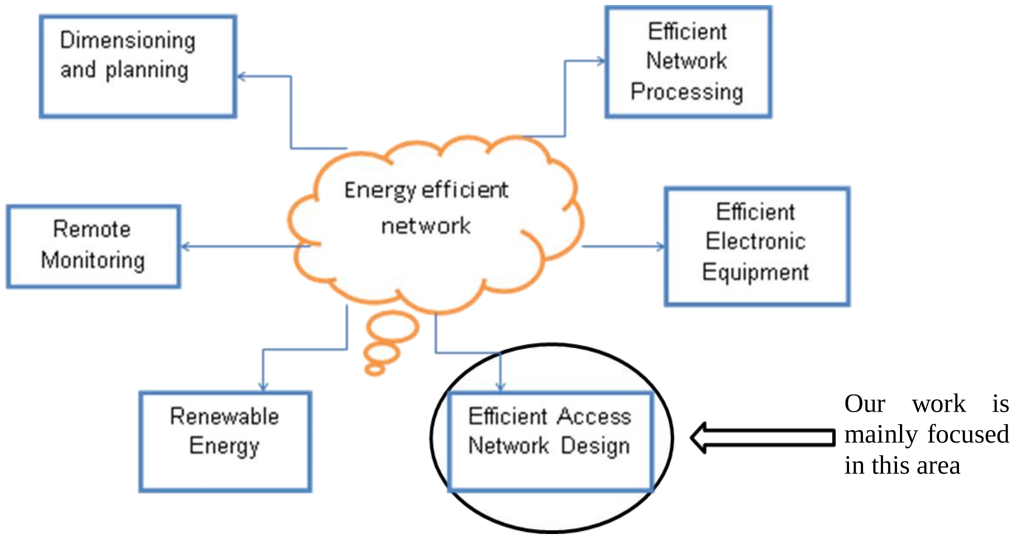

Fig. 1.6 Factor of energy efficient networks [28]

For various multimedia applications like high definition television (HDTV), video on demand, teleconferencing, telemedicine, online file sharing, very high bandwidth is required, going upto 500 Mbps- 1 Gbps per user for some applications. Such bandwidth demand can be fulfilled by deploying 10 G passive optical networks (10 G PONs) (ITU-T G.987 based XG-PON or IEEE 802.3av based EPON) [29]. Due to the presence of a large number of end users, access network consumes a substantial amount of energy. A significant amount of energy can be saved just by allocating the proper resources to the users and utilizing them efficiently [30]. As the optical access networks consume a significant amount of telecom network energy, by seeing such phenomenal energy consumption growth, we were motivated to reduce the energy consumption and started working towards this side since 2013. As given in Fig 1.6, energy efficiency may also be achieved by designing the access network efficiently. Our work is mainly focused on designing the efficient access networks to utilize the available resources such as transceivers, bandwidth, power etc effectively.

1.5 Major Thesis Contributions and its Organization

In this thesis, we develop some flexible hybrid WDM-TDM PON architectures to utilize the advantages of both TDM-PON and WDM-PON. Proposed hybrid PON architectures reduce energy consumption and operational expenditure (OPEX) significantly for low traffic loads. Moreover, the proposed schemes also provide additional desirable features simultaneously such as bandwidth scalability, reliability, resiliency and broadcasting etc.

We also propose some architectures for direct inter-ONU communication to reduce significant transmission latency among locally communicating users and give the opportunity to utilize various resources such as upstream and downstream bandwidth, central office transceivers and optical networking unit transceivers efficiently. This further reduces OPEX and energy consumption of the network.

Chapter 2 discusses the detailed description of the optical access networks. This chapter is started with telecom network hierarchy including core network, metro network and access network. After that, we discuss the optical access network technologies including fiber to the home (FTTH) network, GPON networks with different multiplexing techniques and their various standards. At the end of the chapter, we also discuss energy consumption of optical access networks.

Chapter 3 analyzes the flexibility of passive optical networks. Identified cost and energy efficient multiplexing techniques are presented for different network scenarios. After that, we describe the power budget improvement by using Duobinary coding over NRZ coding. Power budget improvement for any communication system is very essential to transmit data for longer reach or more users.

Chapter 4 deals with the adaptive bandwidth mechanism using dual rate OLT for energy efficient WDM-TDM PON architecture. This chapter discusses in detail about proposed architecture with its various significant advantages such as bandwidth scalability and resiliency to OLT TRx/ Line Card failure. After that, we discuss network extensibility and other illustrative examples of proposed architecture. Then, the verification of performance and feasibility of the proposed architecture with simulation setup is presented. At the end, the chapter is concluded with result and discussions.

Chapter 5 discusses flexible hybrid WDM-TDM Passive Optical Network with pay as you grow deployment capability. In this chapter, we first discuss proposed architecture and design setup and describe how the proposed architecture is providing up to 40 Gbps, equal data rates to all optical distribution networks (ODNs) and up to 70 Gbps asymmetrical data rate to the specific ODN. After that, working and operation of proposed architectures with Pay-as-you-grow-deployment, broadcasting capability and reliability is presented. At the end of the chapter, results are discussed.

Chapter 6 includes another resilient, bandwidth scalable and energy efficient hybrid PON architecture. First, we discuss conventional hybrid WDM-TDM PON architecture, and then we present our proposed hybrid WDM-TDM-PON architecture with its working. To utilize the bandwidth efficiently, module and line card switching is also discussed. At last, results and discussions are presented, and the chapter is concluded.

Chapter 7 presents direct Inter-ONU communication schemes in PON to reduce the latency between any communicating ONUs. First, we discuss various existing direct inter-ONU communication techniques. Then, our proposed overall/ subgroup ONU intercommunication based on two-stage flexible PON network architecture with its working and flexibility analysis is presented. After that another proposed WDM-PON architecture for dedicated and broadcasting downstream transmission is presented. Then, energy-efficiency and latency-aware ONU Interconnection capabilities with working and operation of proposed architecture is discussed. At the end, we concluded the chapter.

Chapter 8 concludes the work done in the thesis by giving a small discussion stating the fruitful contributions of the work. By keeping the current requirements, at the end of the thesis, we also give some recommendations for possible future work that could be done to extend our work.

Chapter 2

2. Optical Access Networks: A Detailed Description

The main focus of this chapter is to study in detail about the optical access networks (OANs) which are very popular nowadays for exchanging the information in various sectors such as finance, education, medical, and social media etc. The attraction of optical access networks become due to their large bandwidth capacity, low operational cost, low energy consumption and secure transmission. With the advancements of technologies, such as multiplexing of several wavelengths on a single fiber cable, OANs are capable of handling load up to few hundreds of Gigahertz (GHz). Before going in detail to the optical access network, an overview of telecom network hierarchy is presented in the following section 2.1. After going through the core, metro and access network; OAN and fiber to the x (FTTx) networks are discussed in section 2.2. Section 2.2 also describes the passive optical networks (PONs) with their various multiplexing techniques including their advantages and disadvantages. Section 2.3 covers the different PON standards defined by International Telecommunication Union (ITU-T) and Institute of Electrical and Electronics Engineers (IEEE). Section 2.4 illustrates the energy consumption in telecom optical networks with an overview of possible energy consumption reduction methods.

2.1 Telecom Network Hierarchy: An Overview

A telecommunication network may be categorized into three parts namely: core, metro and access network as depicted in Fig. 2.1. All the networks have their specific task and provide the connectivity the particular part of the network. The core network is the backbone of the telecom optical network. It is responsible for connecting larger distances such as one continental to another continental. Metro network provides the connectivity for the metropolitan areas. Metro network also connects the core network to the access network. Access networks are responsible for connecting the end users to the rest of the network i.e. the access networks provide the last mile connectivity.

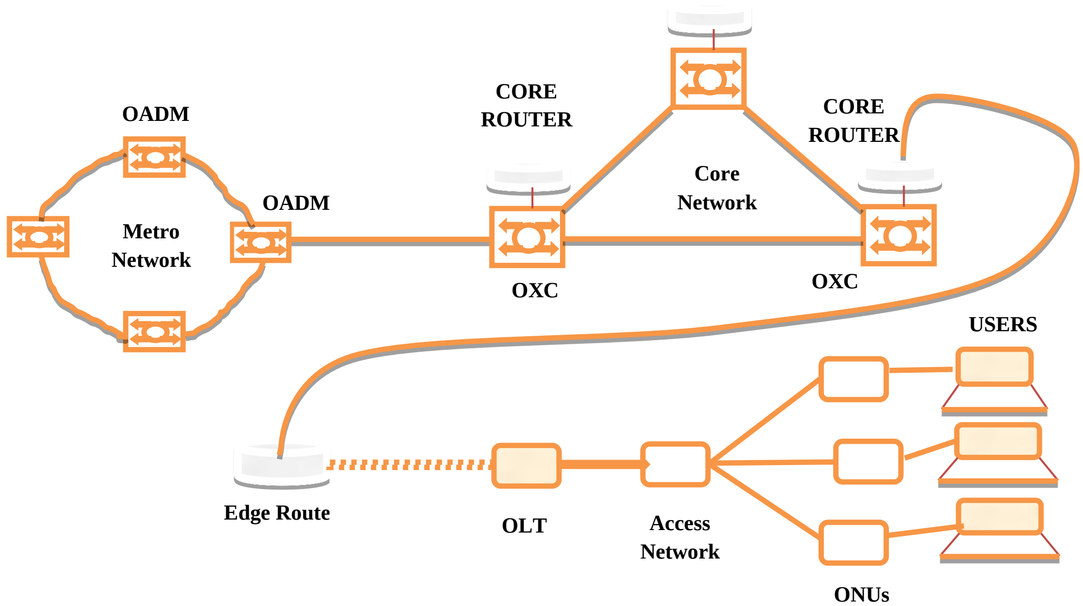

Fig. 2.1 Telecom network architecture

2.1.1 Core networks

Core network is a part of the telecom network, which is responsible for providing global or nationwide coverage of network nodes. In core network, the optical fiber links of hundreds to some thousands of kilometers are used to provide long distance communication i.e. core network is used to provide a connection between two main cities, continental or intercontinental distances. Core network employs mesh interconnection topology and gives an interface to metro and access networks. Core network also provide high speed, high capacity and scalability to the metro and access network.

To achieve high speed, high capacity and scalability in core network, various optical technologies such as IP (Internet Protocol) over SONET (synchronous optical networking) / SDH (Synchronous Digital Hierarchy) [31], IP over WDM (Wavelength Division Multiplexing) and IP over SONET / SDH over WDM [32] have been developed which control and manage the optical networks intelligently.

In IP over WDM network, the energy consumption of its network elements mainly occurs in routing/switching and transmission level. For switching electric signal, the significant energy is consumed by Digital Cross Connects (DXC) and IP routers, while for optical signal energy is consumed by Optical Cross Connects (OXC). From the surveys, it is observed that the energy consumption in the electronic layer is much larger than optical layer i.e. optical switching is more energy efficient than the electronic switching [33].

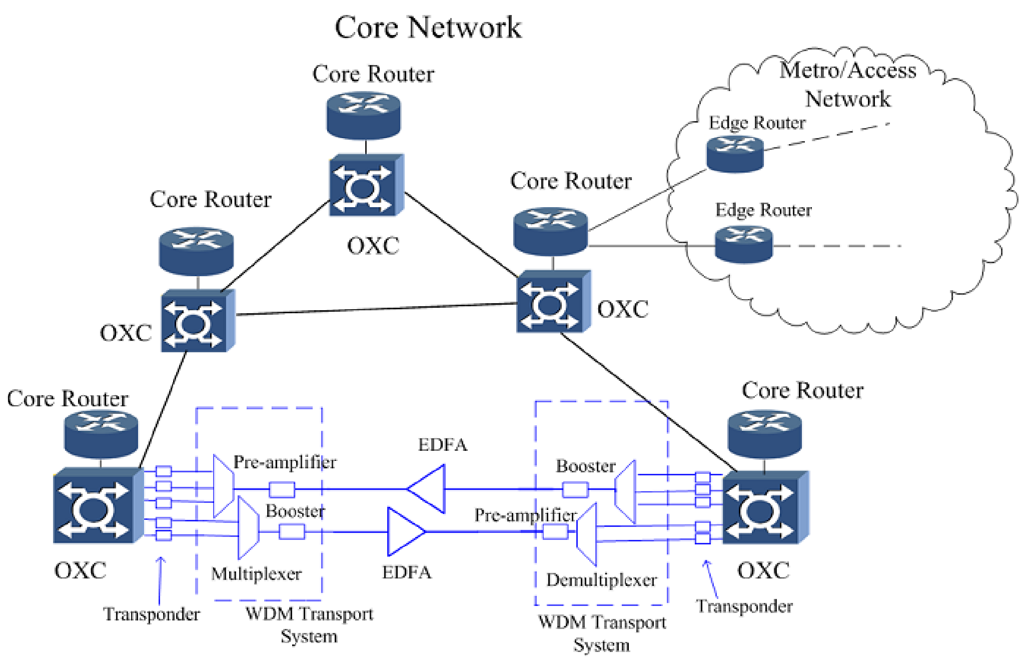

Fig. 2.2 Core network architecture [22]

For transmitting a WDM signal, a transport system requires multiplexers to combine different wavelength signals at transmitter and de-multiplexers at receivers to separate the signals [34, 35]. WDM system also needs some amplifiers such as Erbium Doped Fiber Amplifiers (EDFAs), power amplifiers and pre-amplifiers to amplify the signals for different purposes. The energy consumed at transmission level is mainly due to multiplexers, de-multiplexers, amplifiers, transmitters, receivers and transponders. Traffic volume of core network is growing at very high speed, and in next 10 to 15 years, energy consumption of this network will be very high if new approaches are not applied to reduce energy consumption. There are several methods to reduce energy consumption and get efficient core network. Some of them are given as follows [22]: -

Switching off idle network elements: Traffic load conditions for any network do not remain same for the day, i.e. traffic load is more at daytime, and decreases at night, so it is not advisable to keep all the network elements on when there is low traffic. This approach is called selectively turn off the network elements; the elements may be a node or a link. The node can be switched off when the node is unused or when the traffic load is smaller than a given threshold. Similarly, a link can be turned off when there is no load on the link or when the load is below a given threshold. Due to turning off the intermediate nodes or links, sometimes signals have to travel longer route, and this may create delay or congestion at receiver and degrade the network performance and Quality of Service [34].

Energy efficient network design: To save energy and get energy efficiency, efficient network architecture can be designed during the device installation in the network, i.e. energy efficiency can be achieved at an early stage of the network design by energy awareness of optical core network design. For any network, the energy consumption of routers, amplifiers, and transponders may be jointly minimized. This approach is also known as a holistic approach in which the whole network is optimized rather than separate components. In core network, line cards and chassis of core routers are also higher energy consumers. In [36], authors say that if the fill level of chassis is high, the network is more energy efficient. The chassis with lower fill levels consumes more energy per bit than the chassis with higher fill level. One more network design issue is that recently bandwidth demands are varying from 10-100 Gbps. Therefore the future optical network should support Mixed Line Rates (MLR) rather than Single Line Rates (SLR) to get better energy efficiency [37].

Green routing: As we already discussed that in core network, the energy is mainly consumed in routing/switching and transmission. Since line cards and chassis are the major consumer of energy in the core network, if we employ energy aware routing schemes, then it is expected to reduce a significant amount of energy consumption. As the traffic growth of core network is increasing day by day, new energy efficient technologies only will be able to serve the energy requirement in distant future. Therefore, renewable energy sources must be incorporated in the network. This will not only reduce the carbon footprint but also decrease the energy cost. For this, installations of core routers, switches, servers, and data centers are required at locations where renewable energy is available [38].

2.1.2 Metro networks

Metro network generally covers the distance of a few kilometers to a few hundreds of kilometers i.e. metropolitan regions are covered by the metro networks. This network provides the interface to distributed access networks such as Digital Subscriber Line (xDSL) and Fiber-to-the-x (FTTx) networks by connecting it to the core network. These networks are typically based on SONET/SDH optical ring topology. WDM ring, SONET and Metro Ethernet are most commonly used optical technologies in metro networks. Metro Ethernet relies on Ethernet Standard and consists of Edge Routers, SONET Add-Drop Multiplexers (ADM), Optical Add-Drop Multiplexers (OADM), Network Gateway, Ethernet Switches etc. Above these components are the major energy consumers of the metro network. For higher speed and scalability, WDM ring is proposed [39] as shown in Fig. 2.3. OADMs are the main component that consumes energy in metro WDM-ring. SONET ring based metro networks are also widely deployed to aggregate low traffic of metro network to the high bandwidth of the core network [34].

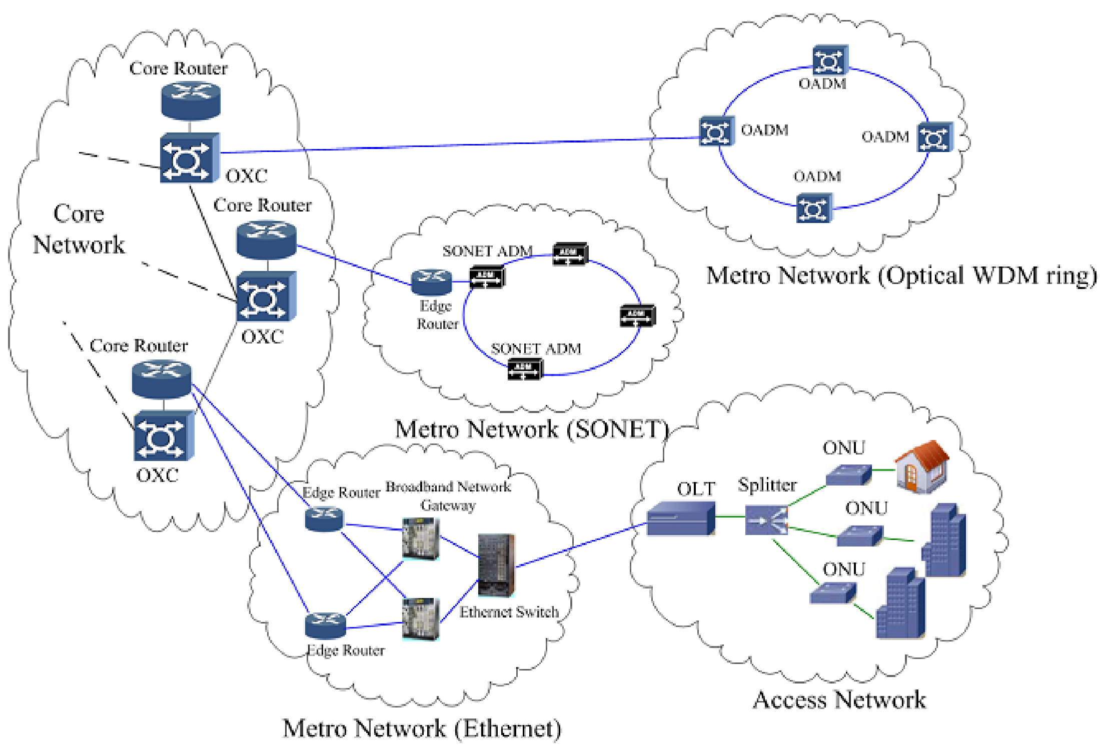

Fig. 2.3 Access and Metro network architecture [34]

For SONET-based network, SONET ADMs and edge routers are the major energy consumable components. Ethernet-based metro network is also used for connecting the core network to the access networks. Its major energy is consumed by broadband network gateways, edge routers and ethernet switches etc. [34].

2.1.3 Access networks

Access networks are responsible for connecting the central office (CO) resources to the local area networks (LAN) at the user end i.e. access networks connect rest of the network to the end users. LAN allows the several users to utilize the shared resources such as printers, data centers or other expensive equipments. Access networks typically cover a distance of approximately 20 kilometers while LAN connects users residing within few kilometers (approx 1 km) such as a university or hospital etc. Usually, access networks are based on tree-based point to multipoint topology.

Over the past years, several network access technologies have been developed such as xDSL, Cable Modem (CM), FTTx, Wireless Optical Broadband Access Network (WOBAN) etc. As our main focus is on optical access networks, we are not going in detail of other access technologies. Optical access networks are being discussed in the following section.

2.2 Optical Access Networks

Due to the emergence of fiber to the home (FTTH) infrastructure, and to support high bandwidth demand applications such as video on demand (VOD), teleconferencing, e-commerce and high definition television (HDTV), optical access network (OAN) have become imperative across the globe. To support the ever-increasing bandwidth demand, other access technologies mentioned in previous sections are not expected to support the present and future bandwidth needs.

Recently, Passive Optical Network (PON) is the major choice for the fiber access network as PON is responsible for providing maximum data transmission capacity for longer reach. PON is also attractive as it consists of only passive components between the Optical Line Terminal (OLT) and Optical Networking Units (ONUs). Commonly used passive components are array waveguide gratings (AWG), power splitters (PS), interleavers, and filters etc. which do not require any power to operate. Due to the utilization of above mentioned passive components, PON consumes very less power than any other access technology. However, PON provides the wired access that is less ubiquitous in nature; wireless access network is responsible for providing more flexible and universal communication. For this, nowadays WOBAN is used as a powerful tool of optical backhaul and wireless at the front end to provide flexible and high-speed communication [40]. Due to the large volume of end users, access networks are the major consumer of energy in telecommunication network [41]. It is very necessary and challenging job for researchers to design most energy efficient access network technology. PONs are usually based on tree topology as shown in Fig. 2.4.

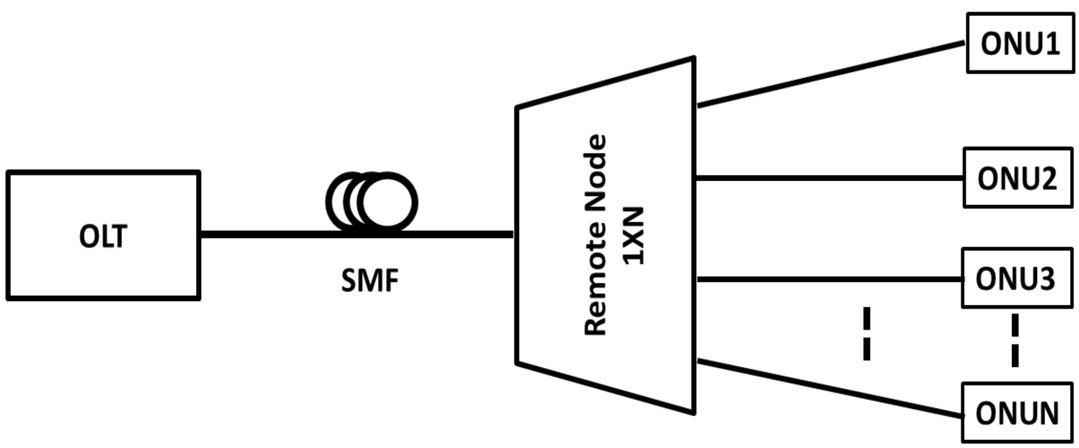

Fig. 2.4 Basic PON architecture

It consists of three main parts namely OLT at the central office, remote node (RN) at the mid-path and optical networking units at the user end [42]. At OLT, the information signal is modulated on optical carrier. For downstream transmission, OLT transmits voice, video or data by modulating different type of signals on various wavelength signals [43]. Modulated signals are transmitted to the single mode fiber (SMF). For upstream transmission, receivers at OLT receives the signals coming from different users. OLT may also transmit multiple wavelengths signals at different data rates simultaneously by combining them itself at OLT [44]. Multiplexing of multiple signals is performed by the AWG multiplexers [45]. Such type of transmission is known as WDM-PON, will be discussed in more detail in section 2.2.2. If transmission rates for downstream transmission and upstream transmission are same than PON is known as symmetric PON otherwise known as asymmetric PON.

At remote node, a passive component either PS or AWG is used to distribute the signal at multiple ports for serving multiple users. PS just split all the data stream to its all the output ports [45] while AWG demultiplexes the incoming data stream and transmit an individual wavelength to its each output port [44], [46]. The transmission of wavelengths depends on the central frequency of the AWG. At the user end, various ONUs are available. The main purpose of the ONUs is to provide the interface between the end user and PON. Sometimes, received optical signal is split into two parts. One part is used to serve the end users while another part of the signal is re-modulated at the ONU to utilize it for upstream transmission.

Depending on the transmission and sharing of central office wavelengths, any PON may be categorized into three types. TDM-PON, WDM-PON and Hybrid WDM-TDM-PON. Each type of PON with their merits and demerits are being discussed below.

2.2.1 Time Division Multiplexed Passive Optical Network (TDM-PON)

In TDM-PON, a power splitter is incorporated at the remote node. The main purpose of this power splitter is to transmit the stream of incoming wavelengths to its multiple output ports. i.e. all transmitted wavelengths from the OLT are split to each output port of the splitter, from where each ONU is receiving the signals [42-45].

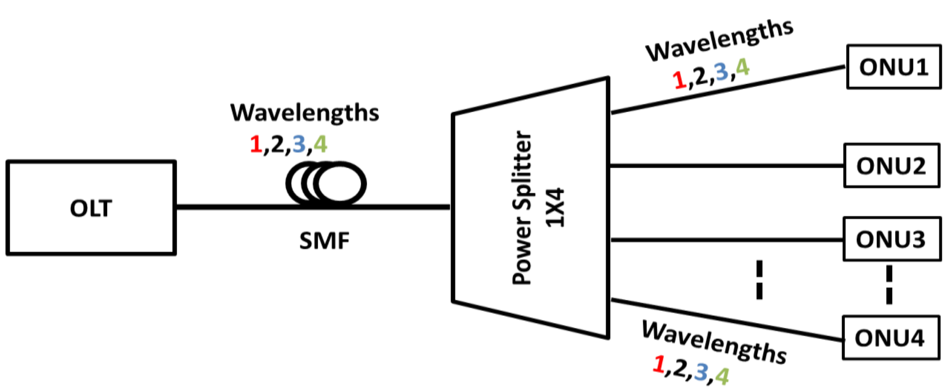

Fig. 2.5 Basic TDM- PON architecture

Fig. 2.5 illustrates the basic example of TDM-PON architecture. In which four wavelengths 1,2,3,4 are transmitted from the OLT. Power splitter distributes each signal to its each output port. Any ONU can receive any wavelength.

TDM-PON has several advantages over WDM-PON [45]. As all OLT wavelengths are transmitted to all the ONUs, TDM-PON is fully flexible and for lower traffic loads only one wavelength may serve the purpose. On failure of any wavelength, service may be continued on other wavelengths until the recovery of primary wavelength. Also, it utilizes the low-cost power splitter thus TDM-PON is cheaper [47]. However, TDM-PON also has some challenges. The number of served ONUs in TDM-PON are limited because for a larger number of splitting ports, insertion losses of the splitter become significant and power budget of the system is mismatched. The insertion loss of the power splitter depends on the relation $3.5\text{Log}_2(N)$ [48], where N being the number of splitter ports. As all wavelengths in TDM-PON are shared with all ONUs whether these are intended for them or not, security issue is also present. For higher splitting ports, effective received power and signal to noise ratio (S/N) at each ONU is reduced. According to the Shannon's channel capacity theorem $C=B.\text{Log}_2(1+S/N)$, effective channel capacity is also reduced [49-51]. Here, C is the maximum channel capacity, B is the bandwidth of the channel. Therefore, TDM-PON is not expected to support next generation high bandwidth applications. For supporting high bandwidth applications, WDM-PON has already been proposed which is being discussed in next section.

2.2.2 Wavelength Division Multiplexed Passive Optical Network (WDM-PON)

In WDM-PON, instead of power splitter, an AWG is incorporated at the remote node. The main purpose of the AWG is to separate the stream of incoming wavelengths and transmit an individual wavelength to its each output port from where each ONU can receive an individual wavelength. Fig. 2.6 illustrates the example of basic WDM-PON architecture. In which four wavelengths 1,2,3,4 are transmitted from the OLT. Due to the cyclic property of AWG, it separates all four wavelengths and transmit a particular wavelength at it each output port. Wavelength routing property of the AWG is explained in detail in the later part of this section. The insertion loss of AWG is almost fixed and ranging from 5-7 dB [52]. Nowadays with the advancements of new technologies, AWG with low insertion losses (as low as 3 dB) is also available [53]. Like TDM-PON, WDM-PON also has some merits and demerits. In WDM-PON, a dedicated wavelength is transmitted to the each ONU. Therefore it provides larger bandwidth capacity and data transmission security. However, as a dedicated wavelength is transmitted to the each ONU regardless the traffic load, wavelength utilization is poor for lower traffic loads [45-47].

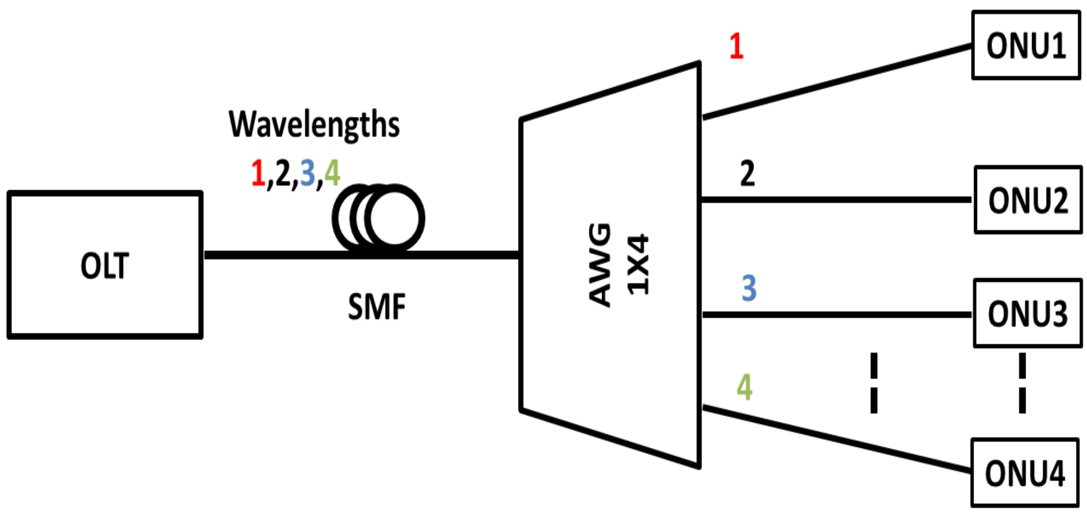

Fig. 2.6 Basic WDM-PON architecture

A number of required wavelengths are also higher for larger ONUs even each ONU has very low traffic. Due to the requirement of larger number of wavelengths and costlier AWG [47], the cost of the WDM-PON system is much higher as compared to the TDM-PON. To utilize the advantage of both TDM-PON and WDM-PON, Hybrid WDM-TDM PON architecture has already been proposed in several literatures [29], [54-57] which is being discussed in the next section.

Wavelength routing property of the AWG:

The routing property of AWG having M number of input ports and M number of output ports is based on the equation 2.1 [58].

$$j = 1 + \left(i - 1 + \left\lfloor \frac{f-1}{C} \right\rfloor \right) \bmod M \text{..(2.1)}$$

$$i, j \in [1, M] \; and$$

$$f \in [1, \infty]$$

where *i*,*j* and *f* represent the input port, output port, and wavelength number respectively, *M* is the size of AWG and *C* denotes the coarseness factor which represents the number of contiguous wavelengths passing at a time. In our case, the value of coarseness factor is unity hence equation (2.1) can be reduced to equation (2.2).

$$j = 1 + \left(i - 1 + \left(f - 1 \right) \right) \bmod M \text{.......................................(2.2)}$$

To understand the routing property of the AWG in a better way, let us consider an example of 8×8 AWG. AWG as Multiplexer is explained in Fig. 2.7(a) and Fig. 2.7 (b). 100 GHz spaced eight wavelengths 193.1, 193.2……………..193.8 THz are applied to the input port 1, port 2 ………port 8 respectively. Consecutive two ports of AWG also have the frequency spacing of 100 GHz. As the center frequency of the AWG is 193.1 THz, the input wavelength 193.1 THz is transmitted to the output port number same as input port number. 193.2 THz is applied to the input port 2 which is 100 GHz spaced apart from 193.1 THz, since frequency spacing between port 1 and port 2 is also 100 GHz, 193.2 THz is also transmitted to the port 1 of the AWG. Similarly, other wavelengths are also transmitted to the port 1 of the AWG and therefore all the incoming wavelengths are multiplexed at port 1 of the AWG.

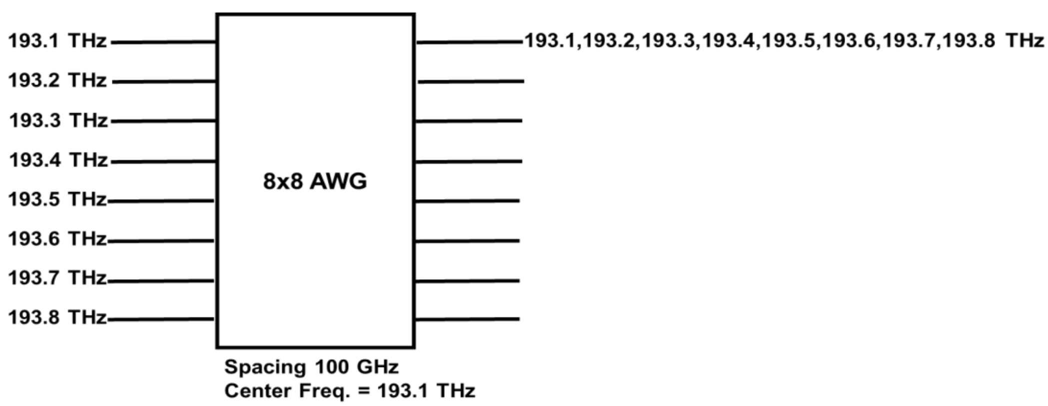

Fig. 2.7 (a) 8x8 AWG as MUX having center frequency of 193.1 THz

In Fig. 2.7 (b), the center frequency of the AWG is changed to the 193.2 THz. Now, all the incoming wavelengths are multiplexed at output port 2 of the AWG.

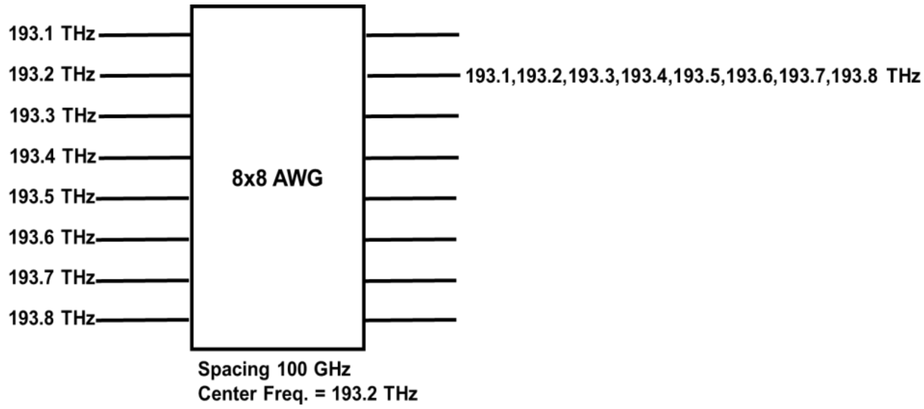

Fig. 2.7 (b) 8×8 AWG as MUX having center frequency of 193.2 THz

Fig. 2.7 (c-h) shows the de-multiplexing property of the AWG, In Fig. 2.7 (c), eight wavelengths 193.1, 193.2……………..193.8 THz are applied to the input port 1 of the AWG. Center frequency of the AWG is 193.1 THz, therefore input wavelength 193.1 THz is transmitted at the output port 1 of the AWG. Since output port 1 and port 2 has the frequency spacing of 100 GHz, input wavelength 193.2 THz at input port 1 will be transmitted at output port 2 of the AWG. Similarly, other wavelengths are transmitted as shown in Fig. 2.7 (c).

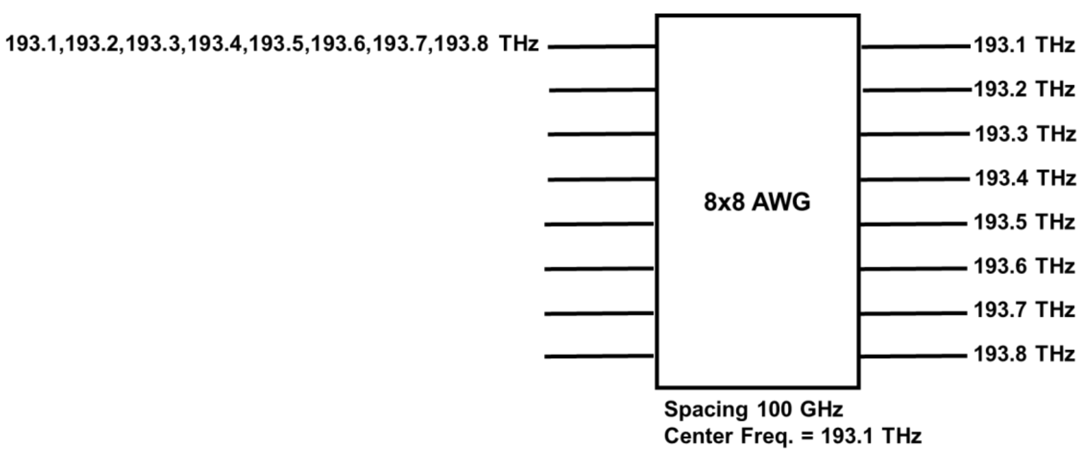

Fig. 2.7 (c) 8×8 AWG as De-MUX having center frequency of 193.1 THz and input wavelength at port 1

If all wavelengths are applied at input port 2 of the AWG, then input wavelength 193.1 THz will be transmitted at the output port 2 of the AWG. Other wavelengths will be transmitted in a cyclic manner as shown in Fig. 2.7 (d).

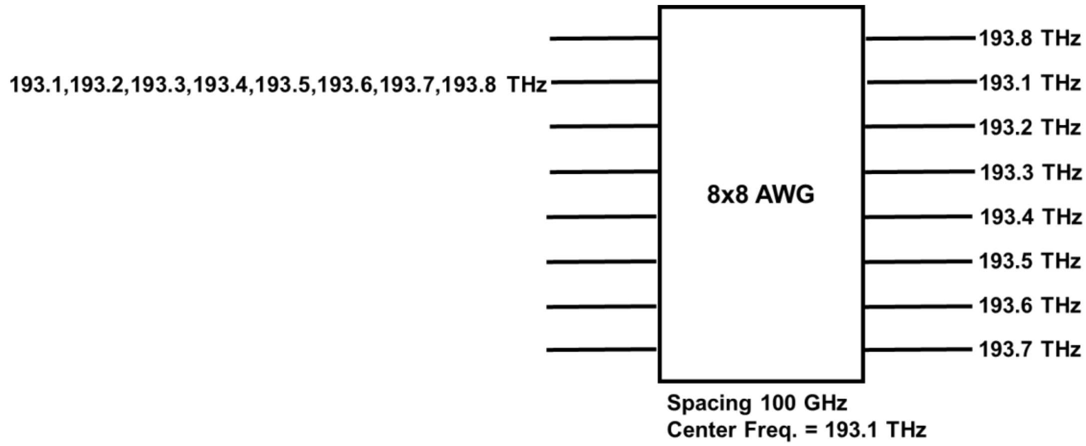

Fig. 2.7 (d) 8×8 AWG as De-MUX having center frequency of 193.1 THz and input wavelength at port 2

If all input wavelengths are applied at input port 1 of the AWG and center frequency of the AWG is changed to 193.2 THz, then input wavelength 193.2 THz will be transmitted at the output port 1 of the AWG. Other wavelengths will be transmitted in a cyclic manner as shown in Fig. 2.7 (e).

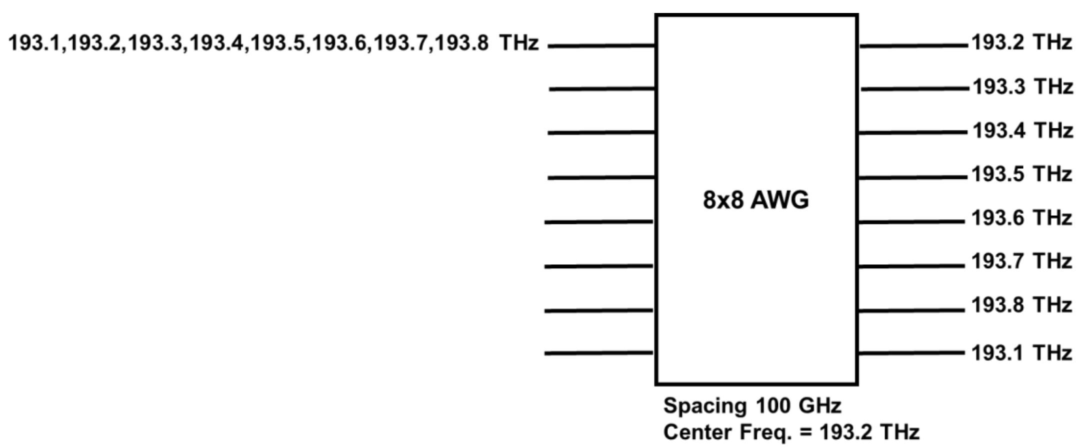

Fig. 2.7 (e) 8x8 AWG as De-MUX having center frequency of 193.2 THz and input wavelength at port 1

In Fig. 2.7 (f-h), the size of the AWG is reduced as 4×4 and input wavelengths are kept same. Now as there are total eight input wavelengths which have to be transmitted at four output ports, therefore each output port will receive total two wavelengths. In Fig. 2.7 (f), all input wavelengths are applied to the input port 1 and center frequency of AWG is kept 193.1 THz. Output ports will receive wavelengths 193.1, 193.2, 193.3 and 193.4 THz. Due to cyclic property, input wavelengths 193.5, 193.6, 193.7 and 193.8 THz will start repeating the output ports port 1, port 2, port 3, and port 4 respectively.

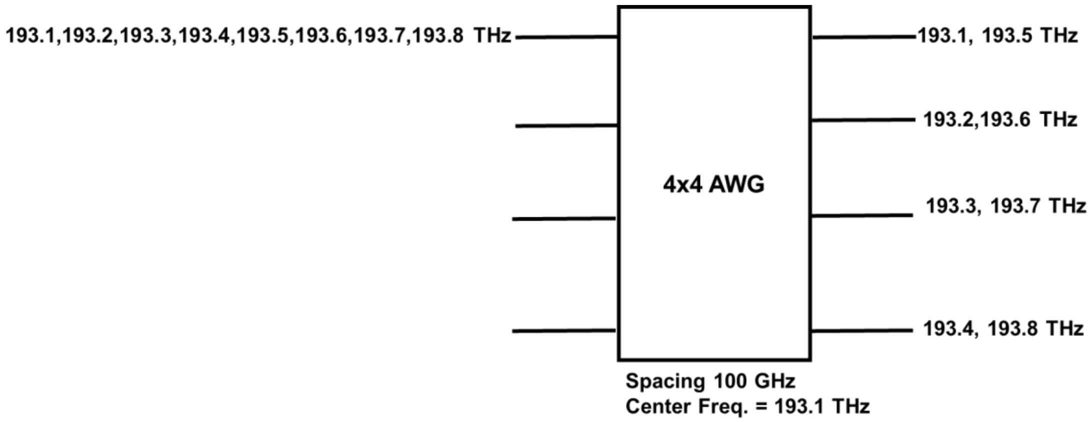

Fig. 2.7 (f) 4x4 AWG as De-MUX having center frequency of 193.1 THz and input wavelength at port 1

If center frequency of the AWG is changed to 193.2 THz, and other parameters kept same as the previous case then output port 1 will receive 193.2 THz instead of 193.1 THz. Due to the cyclic property, output ports port 1, port 2, port 3, and port 4 receive a set of wavelengths (193.2, 193.6 THz), (193.3, 193.7 THz), (193.4, 193.8 THz), and (193.1, 193.5 THz) respectively as shown in Fig. 2.7 (g).

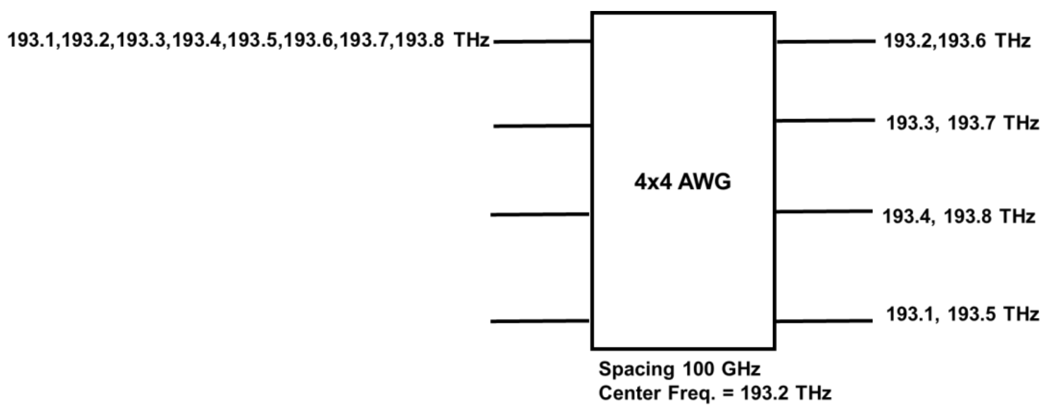

Fig. 2.7 (g) 4x4 AWG as De-MUX having center frequency of 193.2 THz and input wavelength at port 1

If center frequency of the AWG is kept 193.2 THz, and all input wavelengths are applied to port 1 then output ports port 1, port 2, port 3, and port 4 receive a set of wavelengths (193.1, 193.5 THz), (193.2, 193.6 THz), (193.3, 193.7 THz) and (193.4, 193.8 THz) respectively as shown in Fig. 2.7 (g).

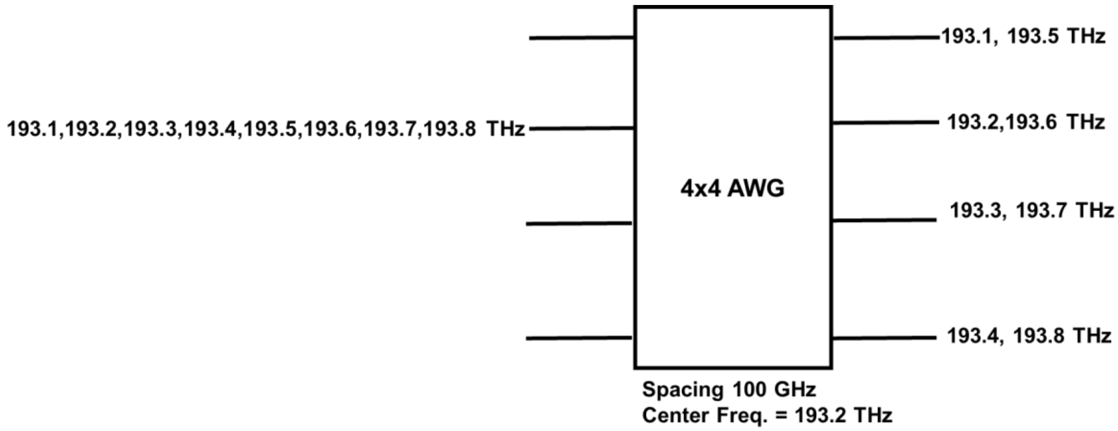

Fig. 2.7 (h) 4x4 AWG as De-MUX having center frequency of 193.2 THz and input wavelength at port 2

2.2.3 Hybrid WDM-TDM PON

A Hybrid WDM-TDM PON is the combination of both WDM-PON and TDM-PON [29]. Two cascaded remote nodes are employed for designing of such architectures. At one remote node, AWG is incorporated to implement WDM-PON while on another remote node, power splitter is incorporated to implement TDM-PON [54-57]. An example of basic hybrid WDM-TDM PON architecture is shown in Fig. 2.8. Transmitted wavelengths from OLT are separated by AWG to its each output port. After that, each wavelength is given to a different PON branch, and each PON branch is known as optical distribution network (ODN). The distance between the AWG and ODN is normally up to 2 km. However, it may slightly change depending upon the different network setups. Power splitter is placed at remote node which enables a single wavelength to serve multiple ONUs [59]. The distance between power splitter and different ONUs is normally few hundred meters.

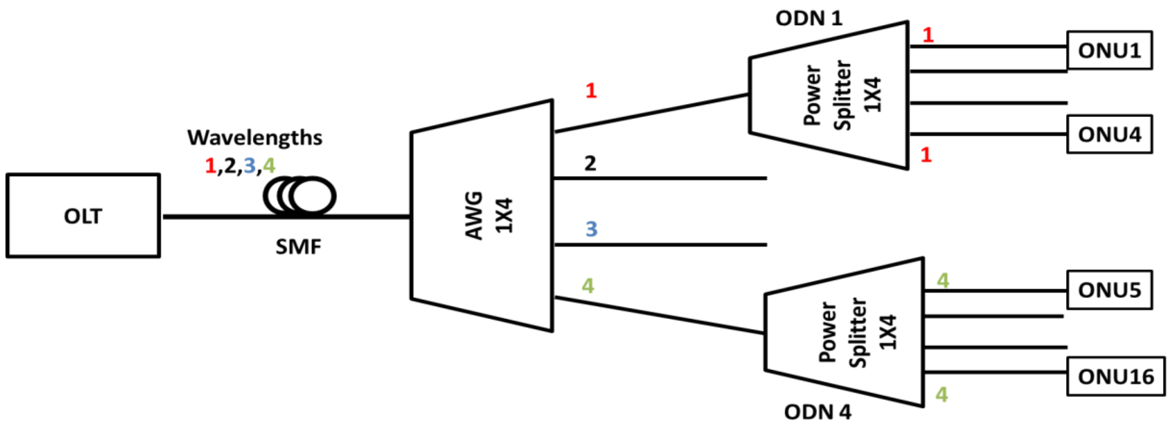

Fig. 2.8 Hybrid WDM-TDM PON architecture

Hybrid WDM-TDM PON utilizes the advantages of both WDM-PON and TDM-PON. This combination is responsible for providing sufficient data rates at reasonable cost and energy. The combination also offers efficient OLT resource utilization regardless of the traffic load throughout the duration. More detailed description of various multiplexing techniques is discussed in chapter 3.

2.3 Various Passive Optical Network Standards

There are various standards that have been proposed for the passive optical networks. In this section, Various PON standards are described below-

2.3.1 Broadband Passive Optical Network (BPON)

BPON is the first type of TDM-PON architecture developed by full service access network (FASN). BPON is based on the ITU-T G.983 Asynchronous Transfer Mode (ATM) protocol, and hence BPON is also known as APON (ATM-PON). According to the ITU-T G.983.1 recommendation, the basic data rates supported by BPON are [60], [61]:

- For downstream transmission: 622 Mbps
- For upstream transmission: 155 Mbps

With the refinement of ITU-T recommendations, revised transmission rates are [62]:

- For downstream transmission: 1.24 Gbps
- For upstream transmission: 622 Mbps

2.3.2 Gigabit Passive Optical Network (GPON)

For the next generation passive optical networks, FASN developed a gigabit passive optical network (GPON), which supports bandwidth in gigabits. In 2003, GPON is defined in the G.984 recommendation. According to the ITU-T G.984.2 recommendation, supported data rates by the GPON are 2.488 Gbps for both downstream and upstream transmission [63]. Though, in current practice, only 1.244 Gbps data rates are used for upstream transmission [64].

2.3.3 Ethernet Passive Optical Network (EPON)

In 2004, Institute of Electrical and Electronics Engineers (IEEE) proposed an Ethernet-based PON (E-PON) which is standardized by IEEE 802.3ah standard. EPON supports 1.24 Gbps symmetric data rates for both downstream and upstream transmission [65], [66]. Due to 8/10-line coding, the effective data rates for EPON is normally considered as 1Gbps for both downstream and upstream transmission [67]. As EPON is capable of handling gigabit of data rates, sometimes EPON is also referred as Gigabit Ethernet PON (GE-PON).

With the increment in high bandwidth band demand, in 2009 IEEE further proposed new standard IEEE 802.3av to support next-generation optical access networks. IEEE 802.3av standardized PON is referred as 10 G Ethernet PON (10 G-EPON). It supports the data rates of 10 Gbps for both downstream and upstream transmission [68].

2.3.4 10-Gigabit Next-Generation Passive Optical Network (XG-PON)

In 2009, ITU-T standardized another ITU-T G.987 standard for 10 G-PON and known as XG-PON [69]. Where X is the roman number just denotes decimal number 10. It supports 10 Gbps for downstream transmission and 2.5 Gbps for upstream transmission respectively. In 2015, ITU-T proposed XG-PON2, which is capable of supporting symmetric 10 Gbps data rates for both downstream and upstream transmission [70]. A brief comparison of BPON, EPON, and GPON is given in Table 2.1.

Table 2.1: A brief comparison of various PON Standards

	BPON	***GPON***	***EPON***
Standard	ITU-T G.983	ITU-T G.984	IEEE 802.3ah, IEEE 802.3av
Protocol	ATM	GEM	Ethernet
Max downstream data rate	1.24 Gbps	2.48 Gbps for GPON, 10 Gbps for XGPON	1.24 Gbps for IEEE 802.3ah, 10 Gbps for IEEE 802.3av
Max upstream data rate	622 Mbps	2.48 Gbps for GPON & XGPON, 10 Gbps for XG-PON2	1.24 Gbps for IEEE 802.3ah, 10 Gbps for IEEE 802.3av
downstream wavelength	1490 nm, 1550 nm	1490 nm	1490 nm, 1550 nm
Upstream wavelength	1310 nm	1310 nm	1310 nm
Max users	32	64	16

2.4 Energy Saving Approaches in PON

Energy efficiency in Optical Access Network: A report on energy consumption says that 70% of the overall internet energy is consumed by the access networks [41]. This is due to the large volume of the end users. Hence it is important to minimize the consumption of power of the access network. Recently FTTx has become the most popular access network technology in which direct fiber cable is laid down to end users. In FTTx, different underlying technologies are used such as direct fiber, shared fiber, and the most used is PON. PON is the responsible candidate to provide high bandwidth services such as IP-TV, video conferencing, telemedicine etc.

In North America, the fiber-to-the-home (FTTH) subscribers have crossed 9.7 million in April 2013, which is increased more than 20% from April 2012 [71]. According to FTTH conference 2014, Stockholm, In China and Japan, there are 37 million and 24.7 million FTTB/H subscribers respectively. It was expected that by 2015, the total number of worldwide FTTB/H subscribers would reach 197 million [72].

GPON and GEPON (Gigabit Ethernet PON) are more energy efficient optical access technology than copper access technology. PONs still consumes a lot of energy. Number of ONUs (Optical networking units), OLTs (Optical line terminals), and EAs (Ethernet aggregators) are 512, 16, and 1 respectively in [73] and energy consumed by them is 60%, 7%, and 14% respectively [73]. From the above data it is very clear that in access networks, the most of the energy is consumed by ONUs. According to "Code of conduct on energy consumption of broadband equipments" published by European Commission in 2006 to encourage the progress of energy efficient equipment, the targeted power consumption of GPON and GEPON ONUs was 5.5 W and 4.0 W for 2011-2012, and 4.0 W and 3.5 W for 2013-2014 respectively, and for OLTs it was 8 W and 7 W for 2013-2014 respectively.

Power saving methods for ONU: There are four basic approaches to save the ONU power: power shedding, dozing, sleep, and cyclic sleep. In power shedding mode, the ONU maintains the transmission and receiving functions on while powering off the nonessential and unusual functions. Due to nonessential functions off, a lot of energy can be saved.

In dozing mode, the transmitter of ONU is made off while the receiving function of ONU is on. In case of sleep state, both the transmitter and receiver of ONU is put off. In sleep mode, some loss of downstream signal may be possible; to overcome this problem, cyclic sleep is addressed. In cyclic sleep mode, ONUs awake the sending and receiving functions periodically to get downstream signals [74]. By using dozing and cyclic sleep, GPON ONU power consumption is reduced down to 1.7 W and 1.3 W respectively [75].

By optimizing the traffic flow and scheduling, power saving can be maximized. Authors in [76] gave an idea to plan the appearance of downstream and upstream traffic at the same time in each ONU, so that sleep time is maximized. Another idea to save power is Adaptive Link Rate (ALR) Control, ALR is used to change or select the link according to traffic load conditions. By using ALR, 10-G PON can be utilized for both 1 GBPS and 10 GBPS downstream links. Links can be switched between 1 GBPS and 10 GBPS according to actual traffic, and a significant amount power can be saved [77]. In [78], Authors proposed the bit interleaved PON (BI-PON), in which multiplexing of downstream signals to all ONUs is done bit-by-bit in place of packet-by-packet. So at ONU receiver, low-speed clipper can extract the bits, by eliminating the use of high-speed devices, power consumption can be decreased.

Power saving methods for OLT: Power consumed by the ONU is approximately 60% of the total power consumption in access network but 21% of the power is also consumed by OLT and EA, so it is also important to minimize the power consumption of OLT and EA. For this, an IEEE 802.3az standard is adopted for OLT-EA links as well as links between EA and core network. The basic idea of power saving is to suppress the power consumption of PHY transmitter and receiver when it sends or receives idle frames. Combining of several packets further minimize the power consumption; this is due to the fact that power consumption is proportional to the link utilization [79].

Link aggregation is an additional approach to reduce power consumption. For managing aggregated links, link aggregation control protocol (LACP) is specified by IEEE 802.3ad. For this, the number of working links are managed according to total available traffic [80].

In [81], Authors divide the EA into two parts and put secondary EA to sleep mode when the total available traffic is much less than the half. This architecture not only saves power but also provides resiliency, traffic can be diverted on the remaining EA in case of failure of primary EA. It is estimated and shown in Fig. 2.9, that the total power consumption of OLTs and EAs is reduced to 60% by applying EA-OLT links and selective EA sleep when total traffic is low [82].

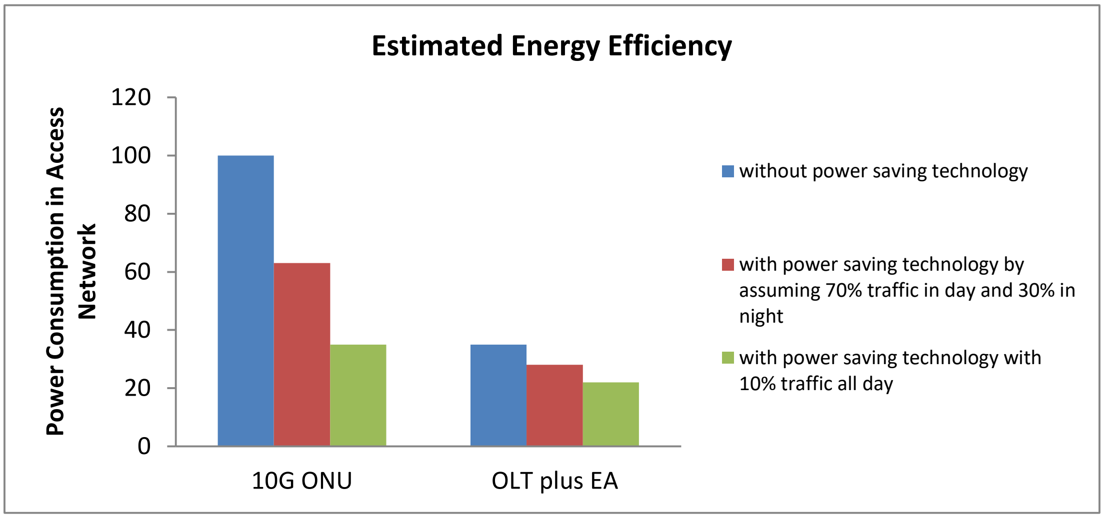

Fig. 2.9 Estimated energy efficiency for ONU and OLT plus EA for different load conditions [82]

2.5 Summary

This chapter presented an overview of telecom network hierarchy including core network, metro network and access network. Core network provides the global or nationwide coverage of network nodes over hundreds to some thousands of kilometers fiber links. Core network employs mesh interconnection topology and gives an interface to metro and access networks. Metro network generally covers metropolitan regions for the distance ranging from a few kilometers to a few hundreds of kilometers. This network provides the interface to distributed access networks such as Digital Subscriber Line (xDSL) and Fiber-to-the-x (FTTx) networks by connecting it to the core network. Metro networks are typically based optical ring topology. Access networks provide the connectivity between central office and end users covering a distance of approximately 20 kilometers. Normally, access networks are based on tree-based point to multipoint topology.

Then we discussed passive optical networks with different multiplexing techniques. TDM-PON, WDM-PON and Hybrid WDM-TDM PON have been discussed with their advantages and disadvantages. Various passive optical access network standards including BPON, GPON, and EPON with their maximum supported downstream and upstream data rates have also been discussed. At the last of the chapter, some existing ideas to save energy at ONU and OLT have been discussed. At ONU, power can be saved by power shedding, dozing, sleep, and cyclic sleep. In power shedding mode, the ONU maintains the transmission and receiving function on while powering off the nonessential and unusual functions. In dozing mode, the transmitter of ONU is made off while the receiving function of ONU is on. In sleep mode, both the transmitter and receiver of ONU is put off. In sleep mode, some loss of downstream signal may be possible; to overcome this problem, cyclic sleep is addressed. In cyclic sleep mode, ONUs awake the sending and receiving functions periodically to get downstream signals. Power saving at OLT can be achieved by utilizing the central office resources such as transceivers, links or bandwidth etc. efficiently.

Chapter 3

3. Flexibility Analysis of Passive Optical Networks

This chapter first identifies the cost and energy efficient multiplexing techniques including TDM-PON, WDM-PON and hybrid WDM-TDM PON with their merits and demerits. We study how the cost and required number of wavelengths change with changing different multiplexing techniques. Multiplexing techniques are modified just by altering the remote nodes.

For any PON network, power budget becomes the challenging issue for the larger split ratio or larger span. In the later part of the chapter, we also analyze the power budget improvement in passive optical network by using Duobinary as compared to the simplest NRZ coding.

3.1 Identification of Cost and Energy Efficient Multiplexing Techniques for PON

In this section, we analyze and identify the most appropriate remote node combination for different network scenarios for different fiber reach and subscribers. We cascade the power splitter and arrayed waveguide grating (AWG) at remote to give hybrid TDM-WDM-PON. Hybrid multiplexing provides efficient use of optical line terminal (OLT) resources and reduces the required number of wavelengths and transceivers. Reduction in wavelength and transceivers results in designing energy and cost-effective access network. This study will help the network operators to choose the most appropriate remote node architecture to give economic and environmental friendly services for different network scenarios.

3.1.1 Introduction

Passive optical network (PON) due to its large capacity, easy upgradability and extensibility, is considered as the ideal candidate to support voice, video and data services together with better quality of service (BER performance) [83]. Legacy PON network is capable of supporting up to 20 km (OLT to subscriber) fiber span, and up to 1:32 splitting ratio [84]. Nowadays transmission reach has been increased up to hundreds of kilometers by using amplifiers and advanced transmission technologies such as coherent detection techniques or highly sensitive receivers [85]. But coherent detection techniques are still not preferred over direct detection due its high cost and complexity. A PON is a point to multipoint architecture having OLT at the central office (CO) and ONU at receiver end with no active elements between them. Active components may be only at OLT and ONU [86]. There are various multiple access techniques, but time division multiplexing (TDM) and wavelength division multiplexing (WDM) are most preferred access techniques. In order to support economic and environment-friendly network, a PON system must deliver high quality of service (better (BER performance)) with low cost and energy requirement.

TDM-PON utilizes the advantages of a broadcasting feature of the power splitter, in which two or more ONUs shares the single channel in time domain and reduce the required number of interfaces [87]. Multiple users are using the single channel, and there may be a collision if more than one of multiple users sending the upstream signal same time. To avoid the collisions, time division multiple access (TDMA) is controlled by the medium access control (MAC) protocol at OLT. Due to the sharing of OLT resources and low-cost power splitter, TDM-PON is cost effective, but there are some challenges associated with it. TDM-PON requires the burst mode transmitter and receivers at optical networking unit (ONU) and high data rate burst mode transceivers are still not at matured stage [88]. TDM-PON doesn't provide the higher level of data security as whole downstream data is shared by all users can be accessed by all whether intended for them or not. The power budget in TDM-PON is also a serious concern as insertion losses of power splitter become significant at higher port numbers and losses are given by 3.5 $\log_2(X)$, where X is the number of output ports. Due to the sharing of the channel, effective data rate offered by TDM-PON is very low and not expected to support required data rate by the year 2020 [89].

To support the future data rates various next generation PON [NG-PON] solutions has been proposed. Currently, WDM-PON is deployed worldwide and has the capacity to transmit several wavelengths on a single channel. WDM-PON is responsible for providing higher data rates to the customers by using the dedicated wavelengths for each customer [46]. In other words, WDM-PON offers point to point access using dedicated wavelength for each user. The use of dedicated wavelength in WDM-PON provides more security and better quality of service (BER performance) to the customers. WDM-PON uses arrayed waveguide grating (AWG) at its remote nodes to combine and separate several wavelengths. The insertion losses of AWG are low and remain almost fixed regardless the number of output ports and approximately given by 5 dB. However, the use of WDM-PON is not always suggested because it requires more number of wavelengths and resulting need of more transceivers at OLT that increases the overall cost and energy consumption of the system. For future bandwidth demands, WDM-PON is only the available choice while for current bandwidth demands, combination of both TDM-PON and WDM-PON seems to be satisfactory.

There is a tradeoff between the QoS/security and cost/energy consumption of the network. To minimize the total number of required wavelengths to reduce cost and energy consumption in the network, TDM must be employed along with WDM technology. A brief comparison of all three schemes is given in Table 3.1.

Table 3.1: A brief Comparison of various PON architectures

	Pure TDM-PON	***Pure WDM-PON***	***Hybrid PON***
Insertion loss	High	Low	Moderate
Security	Low	High	Moderate
Flexibility	Flexible	Static	Partial
Resource Sharing	Yes	No	Partial
Cost	Low	High	Moderate
Wavelength required	Minimum	Maximum	Moderate

The cost associated with AWG is given by $500+70*\log_2(X)$$ while for power splitter it is approximately $200+50*\log_2(X)$$ [47, 48]. These costs are based on the year 2014, and may change in future. Cost for individual splitter and AWG for the different port number is given in Table 3.2.

Table 3.2: Splitter and AWG cost for different port numbers [47, 48]

Splitter Ports : Cost($)	***AWG Ports : Cost($)***
4:300$	4:640$
8:350$	8:710$
16:400$	16:780$
32:450$	32:850$

3.1.2 Hybrid PON Architecture

TDM-PON is cost and energy efficient, but the BER performance cannot be guaranteed for higher split ratios as power budget, effective data rates and signal to noise ratio at receiver are deteriorated. WDM-PON is responsible for providing higher data rates with better BER performance, but cost of the system is comparatively higher due to the use of costly AWG and more wavelengths. So the best way is to use the hybrid multiplexing to utilize the benefits of both TDM-PON and WDM-PON. Hybrid WDM-TDM PON provides the flexibility to use more wavelengths and share them among multiple users to reduce the total number of required wavelengths. Hybrid WDM-TDM PON is capable of fulfilling the required data rates and utilizing network resources efficiently. Fig. 3.1 shows the basic PON architecture having OLT at CO and ONU at the user end. Remote nodes (RN) are placed between OLT and ONUs. The architecture has two stages of RN and can be supposed as primary RN (RN1) and secondary RN (RN2). We consider the splitting ratio of RN1 as $1\times M$ and RN2 as $1\times N$ [48]. The effective splitting ratio of given PON architecture is $1\times MN$. Here, MN represents the total number of supported ONUs.

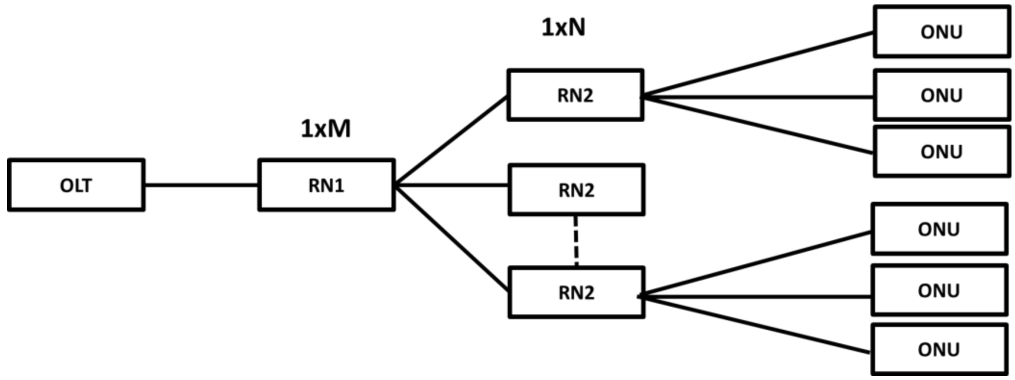

Fig. 3.1 Basic remote PON architecture with remote node in cascade [48]

If all the remote nodes are power splitters, then designed architecture is pure TDM-PON and if all RNs are AWGs then architecture is pure WDM-PON. Hybrid WDM-TDM PON can be designed by cascading the power splitter and AWG at two remote nodes. For different network scenario, we considered different output ports of splitter and AWG to support a different number of ONUs as given in Table 3.3.

Table 3.3: remote node scenario and supported ONUs

M	***N***	***Supported ONU***
8	4	32
16	4	64
16	8	128
32	8	256

Required cost and power budget for the different multiplexing technologies with different port numbers is shown in Fig. 3.2 and Fig. 3.3 respectively. Total remote node cost is calculated by adding the cost associated with different remote node components e.g. power splitter and AWG. The cost is changing with the change in the output ports of power splitter and AWG. i.e. remote node cost increases with increasing number of users as output ports of remote node is increased. Also, shifting from pure TDM multiplexing to pure WDM multiplexing increases the remote node cost as low-cost power splitters need to be replaced with high cost AWGs. Required power budget is calculated by considering the losses of splitter/AWG and standard single mode fiber loss 0.2 dB per km. 6 dB extra power loss is also considered for compensating connector losses and safety margin.

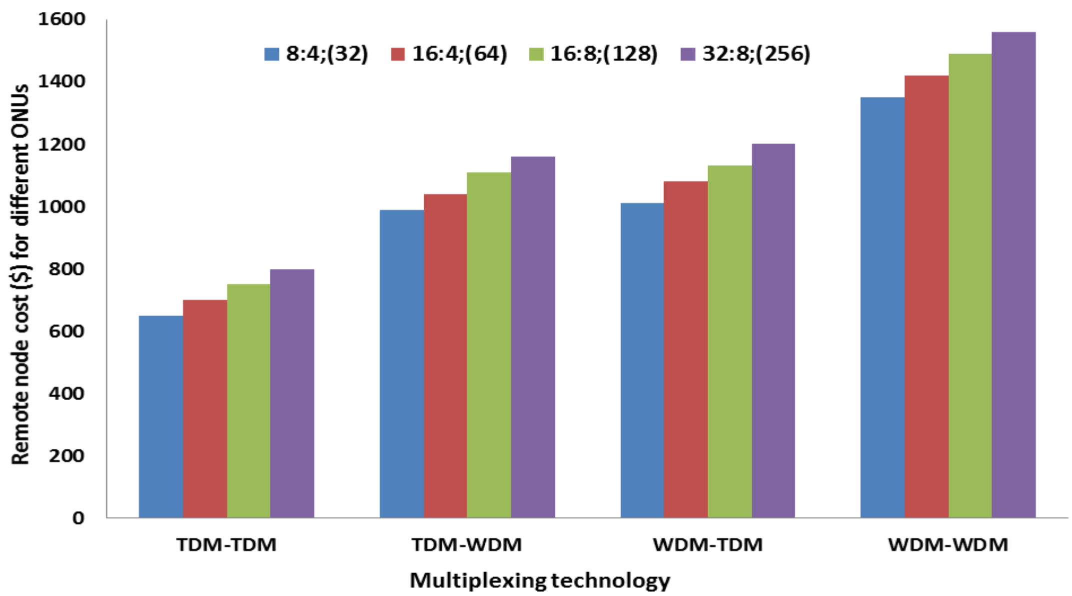

Fig. 3.2 Remote node cost (in $) for different scenarios (based on year 2014)

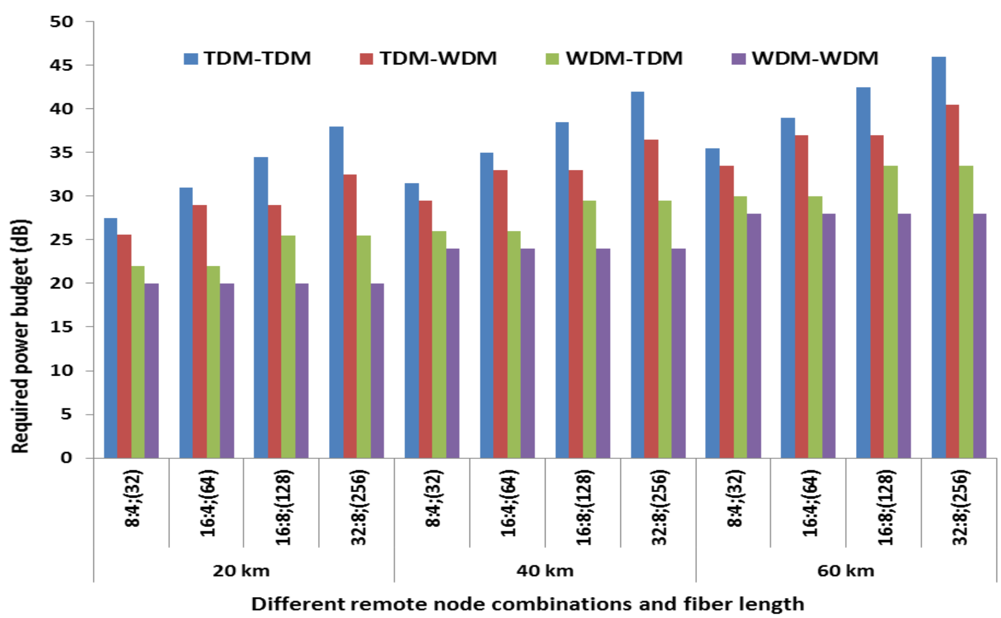

Fig. 3.3 Required power budget (in dB) for different multiplexing combination for different fiber length

Pure TDM-PON (TDM-TDM multiplexing technology) is the cheapest technology but require maximum power budget. Pure WDM-PON (WDM-WDM multiplexing technology) requires least power budget but increases the cost. Required power budget increases as the fiber length increases, and in the case of LR-PON, it becomes significant. An appropriate combination of remote nodes must be used to meet the power budget condition otherwise complicated and costly coherent detection techniques or modulation techniques would be required for getting the acceptable bit error rate performance of the received signal at the receiver.

3.1.3 Proposed Multiplexing Techniques

In a practical scenario, the traffic demands are heterogeneous in nature for all types of services; different ONUs are expected to support various types of service such as residential, business and cellular. For a particular network scenario, suppose 50% of ONUs are used to provide service to residential users at aggregated traffic of 5 Gbps per ONU, 20% are for business users at 7.5 Gbps per ONU and 30% for cellular services at 10 Gbps per ONU. For this network, on average maximum load per ONU is 7 Gbps and for low peak hours the effective traffic is very low. For some instants 1 Gbps or 2.5 Gbps per ONU is sufficient. Since more power is consumed at larger bitrates, so it is not necessary to use full capacity links all the times. We assume three traffic categories for low, medium and high bandwidth demands and supposed 1 Gbps, 2.5 Gbps and 10 Gbps link rates are sufficient for low, medium and high bandwidth demands respectively. By incorporating a varying optical attenuator before photodetector and varying it, receiver sensitivities for OOK modulation for 1 Gbps, 2.5 Gbps and 10 Gbps are measured and depicted in Fig. 3.4. At a bit error rate (BER) of 1×10^{-9}, observed receiver sensitivities are -38.25 dBm, -36.44 dBm and -33.91 dBm respectively. We kept only single optical transmission power (at 0 dBm) to identify the suitable remote node combinations.

Minimum required wavelengths for different multiplexing technologies are given in Fig. 3.5. Pure TDM-PON technology requires the least wavelength (only one wavelength for low traffic) and pure WDM-PON needs maximum wavelengths (equivalent to the number of ONUs) regardless of the traffic. This is due to the fact that WDM-PON uses a dedicated wavelength for each ONU. Hybrid PON technology uses more than one wavelength and enables them to share between multiple ONUs thus this technology utilizes the wavelengths efficiently.

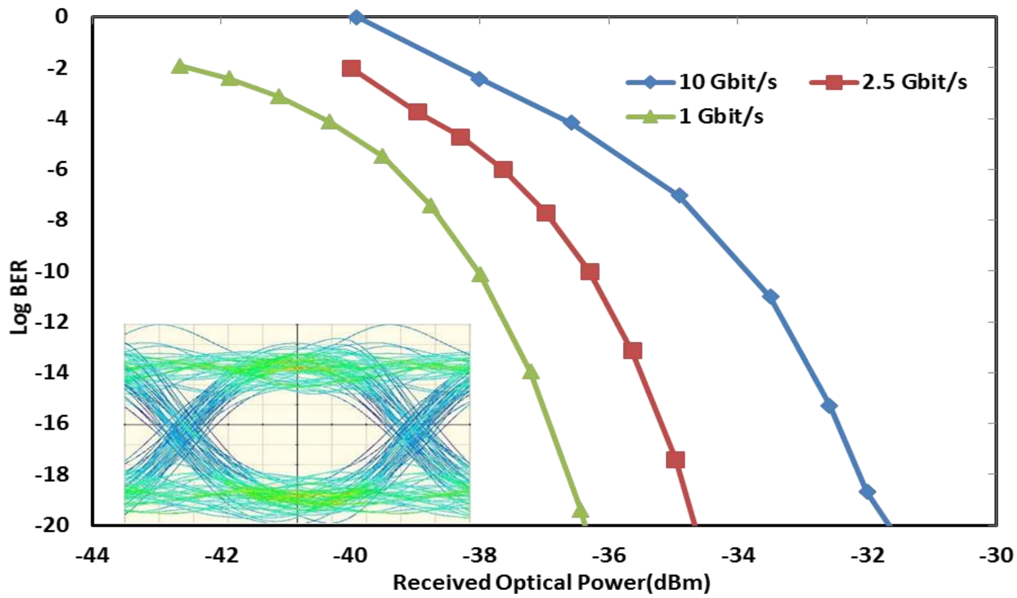

Fig. 3.4 Optical receiver sensitivity at 1, 2.5 and 10 Gbps for 1×10^{-9} BER

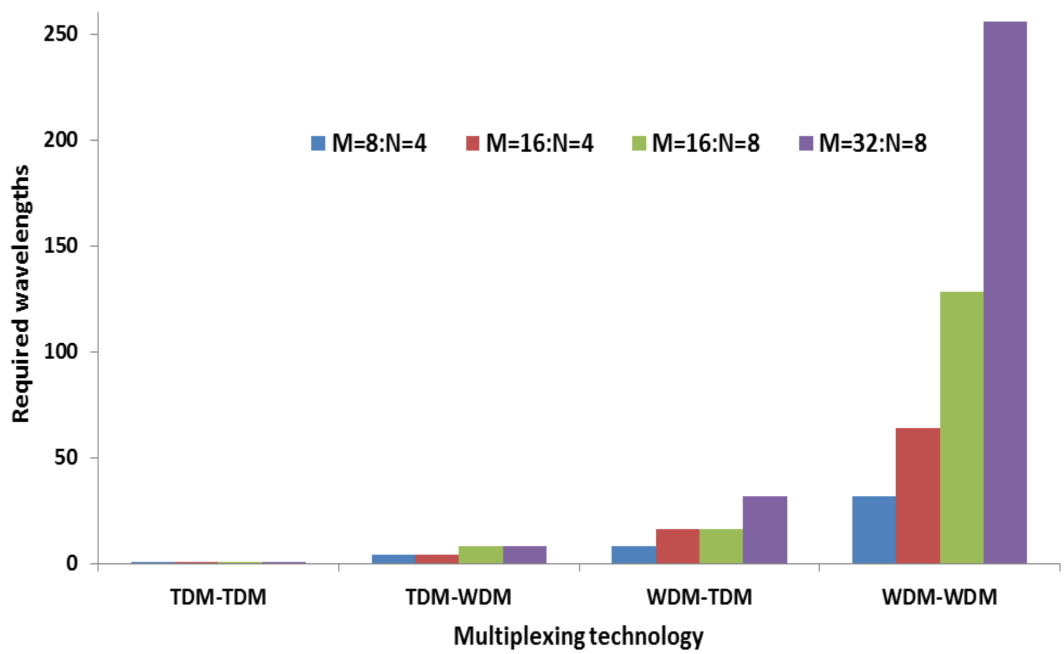

Fig. 3.5 Minimum wavelength required for different multiplexing technologies

Tables 3.4, 3.5, and 3.6 give the identified multiplexing combination at 1 Gbps, 2.5 Gbps and 10 Gbps respectively for a different number of users for different fiber lengths ranging from 20 km to 60 km with acceptable BER performance. The number in brackets with each multiplexing combination shows the number of wavelengths utilized for that combination. As this thesis more concerned about cost and energy saving, we preferred TDM technology (conditioned to power budget fulfillment) to reduce the number of required wavelengths and line cards. Each 10 G line card requires approximately 3.5 W (35.44 dBm) power whereas each 1 G line cards requires 0.5 W (27 dBm) [90]. Our identified multiplexing combination reduces the required number of line cards and demands less cost and energy. Required numbers of wavelength increases as the number of ONUs or fiber reach increases. A number of wavelengths also increases when traffic load increases.

Table 3.4: Selected remote node combination at 1 Gbps

Length v/s No. of ONU	***20km***	***40km***	***60km***
8:4;(32)	TDM-TDM (1)	TDM-TDM (1)	TDM-TDM (1)
16:4;(64)	TDM-TDM (1)	TDM-TDM (1)	TDM-WDM(4)
16:8;(128)	TDM-TDM (1)	TDM-WDM(8)	TDM-WDM (8)
32:8;(256)	TDM-TDM (8)	TDM-WDM (8)	WDM-TDM (32)

Table 3.5: Selected remote node combination at 2.5 Gbps

Length v/s No. of ONU	***20km***	***40km***	***60km***
8:4;(32)	TDM-TDM (1)	TDM-TDM (1)	TDM-WDM (4)
16:4;(64)	TDM-TDM (1)	TDM-WDM (4)	WDM-TDM (16)
16:8;(128)	TDM-WDM (8)	TDM-WDM (8)	WDM-TDM (16)
32:8;(256)	TDM-WDM (8)	WDM-TDM (32)	WDM-TDM (32)

Table 3.6: Selected remote node combination at 10 Gbps

Length v/s No. of ONU	***20km***	***40km***	***60km***
8:4;(32)	TDM-TDM (1)	TDM-TDM (1)	WDM-TDM (8)
16:4;(64)	TDM-TDM (1)	TDM-WDM (4)	WDM-TDM (16)
16:8;(128)	TDM-WDM (8)	TDM-WDM (8)	WDM-WDM(128)
32:8;(256)	TDM-WDM (8)	WDM-TDM(32)	WDM-WDM(256)

3.1.4 Summary

Our identified multiplexing combination gives the Hybrid PON architecture that requires minimum number wavelengths for a given set of parameters such as users, transmission reach and required data rates for minimum cost and acceptable BER. As the required number of wavelengths reduced, need of transceivers at central office also reduced and that helps to reduce the line cards requirement as well as cost. Reduction in each line card reduces power consumption by up to 3.5 W. Multiplexing combination given in the top row and left most box consumes least cost and energy while multiplexing combination given in the down row and rightmost box consumes maximum cost and energy consumption. This is due to the fact if we move from top to down or left to right, the number of users and transmission length is increasing and therefore power penalty of the system is increasing. To compensate the power penalty, lower excess loss component may be utilized i.e. PS must be replaced with AWG. As AWG is used, more number of wavelengths (transceivers) are used that increase the cost and energy consumption of the system. Cost and energy saving becomes significant especially when low data rates are required or small users are available in the network.

3.2 Power Budget Improvement for Energy Efficient Long Reach PON

Effective power consumption at the central office (CO) in passive optical network can be reduced by sharing the central office resources to the maximum number of underutilized users. However, resource sharing in the system is limited by the power budget. The choice of modulation format is very important to improve the power budget and to allow larger splitting in the system.

In this section, nonlinear effects for Duobinary and NRZ modulation format are analyzed with the behavior of BER performance for different launched powers. For a fixed BER, Duobinary modulation format decreases the required launched as compared to NRZ thus improves the power budget. This power budget improvement can be used to increase the splitting ratio to enable single OLT to serve more number of low load or underutilized ONUs to reduce the CO resource requirement in order to give energy and cost-efficient access network.

3.2.1 Introduction

Pure WDM-PON system is not energy efficient especially when the network is not fully utilized or have low load for which a dedicated wavelength is really not required. By combining both TDM-PON and WDM-PON, network can use the benefits of resource sharing of TDM-PON to make system cost and energy efficient and high bandwidth of WDM-PON to serve future bandwidth demand satisfactorily [91]. Hybrid WDM-TDM PON enables each wavelength to serve a group of subscribers by cascading the power splitter with AWG at remote node [92]. To reduce the power consumption of hybrid PON architecture, CO resource sharing must be maximized by utilizing higher splitting ratio power splitters [93].

For hybrid WDM-TDM PON, choice of proper modulation format is very important to optimize the power budget for allowing multiple users in access network [94]. As the input power increases, fiber nonlinearities such as stimulated Brillouin scattering (SBS) and self-phase modulation (SPM) occurs in the system and start to degrade the signal quality thus increases the required optical signal to noise ratio (OSNR) or receiver power.

Due to the high dispersion tolerance and high SBS threshold, optical Duobinary signal is suitable at high power levels as compared to NRZ signal [95]. In this section, we simulate the PON for 80 km reach for Duobinary and NRZ signal and the behavior of BER for different fiber inputs has also been analyzed.

3.2.2 Simulation Setup of Proposed Architecture

The schematic simulation diagram is shown in Fig. 3.6. DFB laser is externally modulated by using Mach-Zehnder Modulator (MZM). Generated three level Duobinary encoded electrical signal drives the MZM. Levels 1 and -1 produces 100% transmission while level 0 produces 0% transmission hence the optical output signal is of two levels. The optical power output of MZM varies according to launched powers and for large distances this power can be amplified using erbium-doped fiber amplifier (EDFA). Output power is given to arrayed waveguide grating (AWG) to multiplex the different signals. These multiplexed signals are transmitted through SMF.

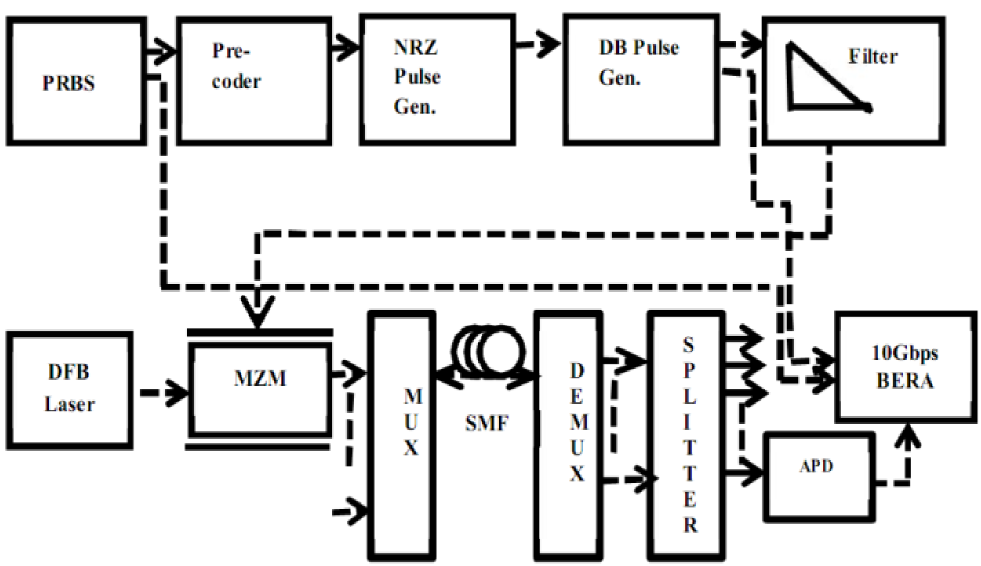

Fig. 3.6 Simulation setup for duobinary modulated passive optical network

At remote node, signals are demultiplexed and separated in wavelength domain. Each wavelength signal is used to serve a group of ONUs with the help of optical power splitter. The system performance is studied by measuring the reflected power from the fiber and BER at receiver for different launched powers. At the receiver, received optical signal is directly detected by using APD. BER analyzer (BERA) is used to analyze the BER of detected electrical signal. For this BER analyzer is synchronized with input.

3.2.3 Result and Discussion

To handle the larger networks, passive optical network requires larger input power along with amplifiers. After a certain threshold if launched input power increases, nonlinear effects such as SBS, SPM occur in the system thus limiting the launched power. Fig. 3.7 indicates the measurements of BER for different launched power. BER improves as the launched power increases. After a certain threshold BER degrades due to nonlinear effects occurring in the system. Duobinary format reduces the nonlinear effects and increases the SBS threshold or power budget that can be used for supporting larger network or more number of ONUs. SBS threshold is higher in Duobinary modulation format as carrier is suppressed by biasing the modulator at null.

For the Duobinary modulation format, received BER is less as compared to NRZ, which clearly indicates that Duobinary signal format provides better power budget in system than NRZ that can be used to handle more number of networking units.

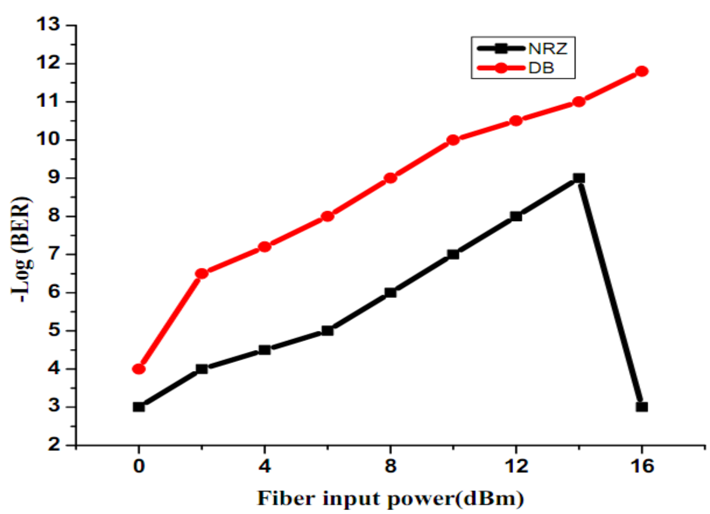

Fig. 3.7 Input power v/s. BER curve

For calculating the maximum split ratio, the power budget is calculated in such a way that the receiver receives a bit correctly. For $1x10^{-9}$ BER, required fiber input powers for NRZ and Duobinary is 14 dBm and 8 dBm respectively i.e. Duobinary signal format require 6 dB less input power as compared to the NRZ signal. This 6 dB power can be used for increasing the split ratio or fiber reach. By considering the splitter losses of $3.5Log_2$ (K), where K being the port numbers, more than twice users can be supported as compared to the NRZ coding.

3.2.4 Summary

To reduce the power consumption of access network hybrid WDM-TDM PON architecture is used in which CO resources are shared among underutilized ONUs by using power splitter. Resource sharing is limited due to insertion losses of power splitter occurring in the system. These insertion losses are compensated by improving the power budget. To improve the power budget and to maximize the resource sharing, Duobinary modulation is used. By using Duobinary modulation, supported optical networking units are more than twice in number as compared to the NRZ and allow to save half of the power consumption at CO under low load by switching off half of the unused OLTs and line cards.

Chapter 4

4. Adaptive Bandwidth Mechanism Using Dual Rate OLT for Energy Efficient WDM-TDM PON

This chapter reviews various energy efficient approaches in existence and proposes a Hybrid WDM-TDM PON architecture that allows the adaptive bandwidth allocation mechanism to reduce central office (CO) power consumption with acceptable performance. Proposed architecture in this chapter allows sending two signals, one broadband and other narrowband to each optical networking unit (ONU) so an appropriate signal can be utilized according to the traffic demand.

In case of very low traffic, only narrowband signal is used and a significant amount of energy consumption and OPEX is reduced by turning off the broadband signals. By using 2xN power splitter (PS) and interleaver, proposed architecture provides broadcasting at both broadband and narrowband signal depending on the required link rate. This further reduces energy consumption and OPEX by avoiding the transmission of same signal from multiple sources. Offered data rates to the optical distribution networks (ODNs) may also be varied by doubling the wavelength spacing of remote node AWG so that two contiguous wavelengths can be transmitted at each port or ODN. This provides the geographical dynamic bandwidth allocation. Proposed architecture also support simultaneous transmission of both broadband and narrowband signals to the ODN to provide bandwidth scalability and network extensibility for supporting future access network in terms of new users and data rates. As two signals are reaching to any ODN, resiliency against OLT TRx and line card failure is also achieved.

4.1 Introduction

Nowadays, energy efficiency in the optical access networks has become a serious concern as the energy consumption is increasing exponentially with increasing broadband services. Natural energy resources on earth are not expected to serve the energy demand for distant future. With increasing energy consumption, emission of CO_2 and Green-House Gases (GHGs) is also increasing which is a leading cause of global warming and deteriorating the environment.

Energy efficiency for tree-based 10 G EPON and ring based hybrid TWDM-PON network is evaluated in [13], and it is observed that for 2, 4, 8 & 16 wavelengths, ring topology based TWDM PON is more energy efficient than tree topology based EPON. TWDM PON with 4 wavelengths provides the maximum energy efficiency and reduces maximum up to 58.7% energy consumption as compared to EPON [13]. In ring based TWDM PON, energy efficiency is achieved by forming a ring of the different remote nodes (RN), and redistributing the signal to multiple ONUs with the help of splitters. In this, only one wavelength may handle all ONUs available in the network [96]. However, due to the ring nature, latency is higher for the ONUs which are connected to the last node.

By employing a channel combine/split (CCS) module at the remote node (RN), required number of OLTs at the central office are reduced. CCS module is a combination of power splitters (PS) and switches (SW) and used for aggregating the load of different ONUs so that minimum number of OLTs are required. For example, for downstream transmission, with the help of splitter and switch, minimum OLTs are used to serve all active subscribers [97]. As the active subscribers in network increases, and if the working OLT is out of capacity, another OLT is used. For upstream, power splitters act as combiners and consolidate the traffic of several PONs to the single OLT. All active ONUs are tuned to the same upstream wavelength (say λ_1) thus upstream traffic is aggregated to one OLT (OLT 1). This architecture provides invest-as-customer-comes approach. Effective take-up rate (ratio of subscribed customers to the portion of system capacity utilized) of the system is increased by this architecture, and up to 35% and 20% power can be saved at the time of minimum traffic demand and full operating stage respectively [97]. Using two OLT and MUX at the central office, wavelength routing is done to reduce the power consumption. For achieving the wavelength routing, different optical networking units (ONU) are employed with tunable transmitters. By changing the ONU upstream wavelength and with the help of the wavelength router, load of upstream signals can be routed to any one of the two OLTs thus allowing other OLT to sleep during traffic below a certain threshold [98]. However, resiliency against OLT TRx and/or line card failure is not provided. The complexity of the system is also much higher for real-time routing and aggregation of numerous wavelengths.

At the central office, a wavelength selective switch (WSS) is used instead of static AWG to allocate the wavelength dynamically according to the immediate traffic demand [54]. By incorporating WSS switch to connect OLT and different ODNs, the number of assigned wavelengths are also changed depending upon the load of particular ODN. This provides the dynamicity in the resource sharing and routes the wavelengths towards the high traffic load of the network for load balancing. By reducing effective number of required wavelengths, up to 60% of the OLT energy is reduced [54]. However, dual rate and broadcasting features are not available in the schemes proposed in [97-99].

In the presence of narrowband (1G) traffic, the use of wideband (10G) resources are avoided to reduce significant energy consumption. The power consumption of each 10 G LC in OLT is approximately 3.5 W while for 1G LC it is around 0.5 W [90]. In this work [90], an (n+1)×(n+1) AWG is used at RN, whose first input port is connected to (n+1) line cards (n 10G and remaining one 1G) through an ((n+1)×1) coupler. n output ports of this AWG is used for connecting it to n ODNs and remaining one output port is used to loopback the narrowband signal to its n input ports with (1×(n+1)) coupler. Due to the cyclic property of AWG, (n+1) wavelengths transmitted from OLT are distributed to (n+1) output ports. n broadband wavelengths are reaching to n ODNs directly. Remaining narrowband wavelength is looped-back and broadcasted to n input ports. Broadcasted narrowband wavelength is transmitted at its n output ports and thereby reaching all ODNs. For low traffic broadcasting, all 10 G line cards are switched off to reduce power consumption. To receive dual rate wavelengths, each ONU is equipped with a dual rate (1G/10G) tunable transceiver [90]. However, dual rate broadcasting is not considered in this work.

A flexible TWDM PON architecture has been proposed [29], [55] in which hybrid AWG/splitter module is used between the OLT and ODNs. Hybrid module constitutes a 4x4 AWG with a 4x4 power splitter connected in parallel. A 100 GHz optical interleaver is inserted before as well as after the hybrid module. The purpose of the first interleaver is to divert the 100 GHz tuned wavelengths towards splitter. OLT transmitter module transmits a set of downstream wavelengths with 200 GHz spacing. Each 200 GHz spaced incoming wavelength is passed through the interleaver towards AWG for transmitting dedicated wavelengths to ONU. The second set of wavelengths shifted by 100 GHz with respect to the first set of wavelengths can also be transmitted from the OLT transmitter module. 100 GHz shifted wavelengths are diverted by intreleaver towards splitter for broadcasting the wavelengths. At the receiver side, second interleaver combines the wavelengths coming from splitter and AWG. Hence in this architecture, each OLT transmitter can be used for one to one service, one to many services or many to many services according to the traffic load [29], [55].

A comparison of different hybrid WDM TDM PON architectures discussed above is summarized in Table 4.1, along with the features of our proposed architecture. As can be seen, the proposed architecture permits broadcasting only at 1 G and/or 10 G, and the maximum capacity of the network is limited upto 44 Gbps.

Table 4.1: Comparison of different hybrid WDM TDM PON architectures

Paper	Max energy saving	Bandwidth scalability at particular node	Resiliency to TRx / Line card failure	Geographical network scalability	Limitations
J. Song et al. [96]	58.7%	No	No	No	Only Fixed Rate, No broadcasting, latency is higher for the ONUs connected to the last node of the ring.
H. Feng et al. [97]	35%	Yes	No	No	Only Fixed Rate, No broadcasting
J. Kani et al [98]	-	No	No	No	Only Fixed Rate, No broadcasting
A. Dixit et al [54]	60%	Yes	No	Yes	Only Fixed Rate, No broadcasting
M. Tadokoro et al [90]	75%	No	No	No	Dual rate, No broadcasting at 10Gbps
N. Cheng et al [29], [55]	-	Yes	No	No	Fixed rate, No broadcasting at 1Gbps
Proposed	61.2%	Yes	Yes	Yes	Broadcasting only at 10G and/or 1G, Maximum capacity limited upto 44Gbps.

Dual rate mechanism have been utilized for saving energy in other type of access networks such as hybrid fiber-coaxial (HFC) access networks [99-102]. Master-slave line card (LC) based traffic scheduling algorithm has been proposed to provide the energy efficiency in the HFC networks. Based on traffic load, reported algorithm dynamically transfers packets to either master or slave LC and idle LC is toggled to sleeping mode to save energy [99]. To support DOCSIS (Data Over Cable Service Interface Specification) 3.0 standard in HFC network, traffic aware algorithms have been reported [100] that change the operation status of two primary network elements cable modem (CM) and cable modem termination system (CMTS) dynamically. At CM side, reported algorithm optimizes its energy consumption and provides 37.5%–42.2% energy saving as compared to the conventional static CM operation. At CMTS side, by supporting CM connections with least numbers of CMTS ports, 31.08%–32.61% energy saving is achieved as compared to the conventional CMTS [100], [101]. Channel bonding algorithms are also proposed for both network side and customer side [101], [102]. These algorithms could be utilized by cable operators to allow a CM to tune for numerous channels parallel to provide energy efficiency of cable access network. The operation mode of CM and CMTS are adjusted dynamically based on traffic fluctuations and other channels are switched off to achieve energy saving. Proposed scheduling algorithm in [102] achieved up to 75% power saving as compared to normal operation in which TRs are always active [102].

Nowadays, elastic optical networks (EON) are also becoming much popular due to their distinctive characteristics like bandwidth segmentation, bandwidth aggregation, traffic grooming and arrangement of variable data rates to develop energy efficient architectures [103-106]. Routing and spectrum allocation policies may be utilized to allocate the spectrum in the form of different number of narrow slots according to the traffic load [103], [104]. Bandwidth variable transponders (BVT) and sliceable bandwidth variable transponders (SBVT) can be used for providing multiple data rates to the networks. Therefore, spectrum utilization efficiency and energy saving could also be improved by using EON. Detailed unique characteristics of EON with its architecture and operational principle are provided in [103-106].

The rest of the chapter is organized as follows. Section 4.2 presented the proposed network architectures. While section 4.3 covers the bandwidth scalability and network resiliency against OLT TRx and line card failure. Network extensibility is discussed in section 4.4. Other illustrative examples of proposed architecture are discussed in section 4.5. Section 4.7 presents the simulation setup and results of the proposed network.

4.2 Proposed Architecture

In this chapter, we propose a network architecture using two cascaded stages of AWG to provide flexibility, energy efficiency, OPEX efficiency and resiliency to TRx and line card failure. Also, we use a 2×N PS in parallel to enable the broadcasting capability at both broadband and narrowband transmission in the same architecture. Before discussing the proposed architecture (as Case 2), conventional architecture is discussed first as Case 1.

Case 1: When the number of input ports of CO AWG and that of the output ports RN AWG are equal (M=N) [24], then designed network works as a conventional WDM-PON network in which, a set of M wavelengths are provided to 1×N AWG as shown in Fig. 4.1. As M and N are equal, each output port of RN AWG receives only one dedicated wavelength irrespective of load. Due to the dedicated wavelengths reaching at individual port, this architecture is not suitable for varying traffic load environment. When traffic load is small, WDM-PON is not energy efficient since wavelengths are not fully utilized, and when the network is overloaded, the quality of service (BER performance) may not be guaranteed as dynamic bandwidth/wavelength allocation is not possible. In the case of any particular transmitter/line card failure, resiliency is also not provided. To add the flexibility in the network, we proposed an architecture as discussed in case 2.

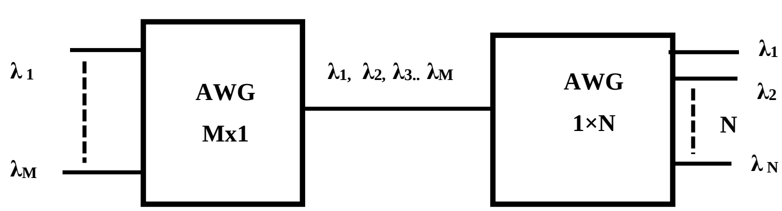

Fig. 4.1 Conventional hybrid WDM-TDM PON architecture (M=N)

Case 2: To make the conventional architecture flexible, energy efficient, OPEX efficient and resilient to OLT TRx/ line card failure, we designed a tree-topology based network as shown in Fig. 4.2. Proposed architecture is also capable of supporting narrowband as well as broadband traffic along with dual rate broadcasting capability. The architecture is designed in such a way that it satisfies M/2 = N for CO and RN AWG ports. To utilize the bandwidth efficiently and to reduce the power consumption in the network, OLT is equipped with first (M-N) line cards with 10 Gbps (10 G LCs) to support broadband traffic and remaining N line cards with 1 Gbps (1 G LCs) for narrowband traffic. RN AWG (1×N AWG) separates the set of M incoming wavelengths at its N output ports. As in proposed architecture, M/2 = N, due to the cyclic property of AWG; two wavelengths (one 10 G and one 1 G) are transmitted at each output port of RN AWG. Incoming wavelengths of 1×N AWG start repeating its output port after the free spectral range (FSR) [107][108].

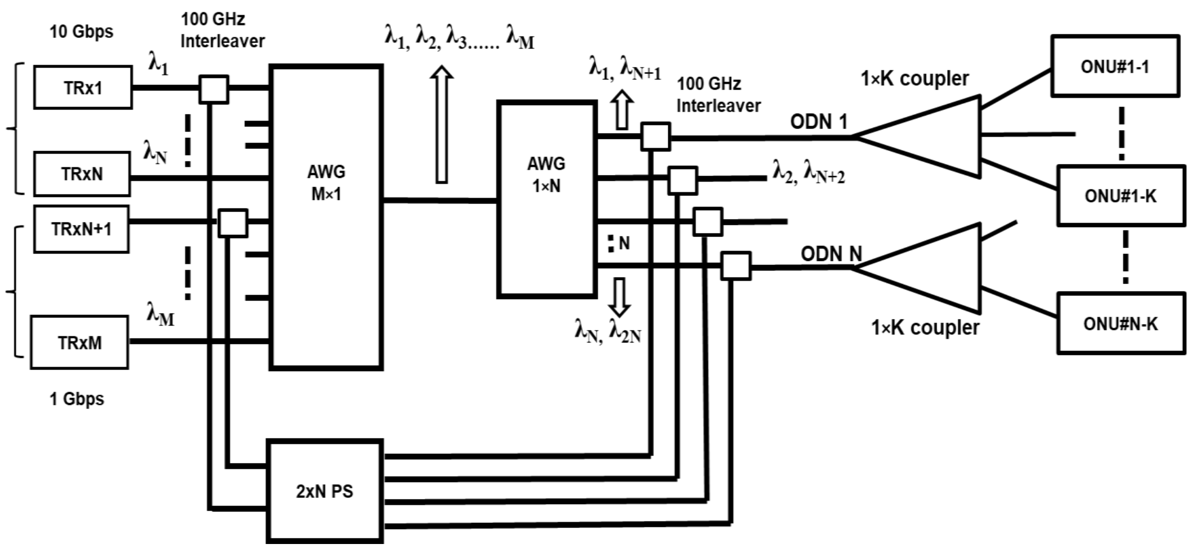

Fig. 4.2 Proposed hybrid WDM-TDM PON architecture (M/2=N)

OLT line cards and tunable ONU is shown in Fig. 4.3. The energy efficiency of this architecture can be achieved both at higher as well as lower traffic loads. In normal case, when OLT has to send high data rate downstream signals, all 10 G LCs transmit data at wavelengths $\lambda_1, \lambda_2, \lambda_3 .... \lambda_N$ and all 1 G LCs are switched off. For low traffic load at ONU, all 1 G LCs send narrowband signals at wavelengths $\lambda_{N+1}, \lambda_{N+2}, \lambda_{N+3} .... \lambda_{2N}$ and all 10G LCs are switched off. Each ONU must be equipped with one 1 G/10 G dual rate tunable transceiver so that it can receive the downstream signal at both 1 Gbps and 10 Gbps data rates at any wavelength. To achieve the broadcasting at both 10 Gbps and 1 Gbps in proposed architecture, a 2×N PS is inserted between OLT and ODNs by connecting it's I/O and O/P ports to 100 GHz interleavers. Its two input ports are connected to one 10 Gbps and one 1 Gbps transmitter to broadcast at dual rates. For broadcasting the signal, transmitted wavelengths are 100 GHz shifted from the main downstream wavelengths. 100 GHz interleavers divert these wavelengths towards 2×N PS. After that, broadcasted wavelengths are combined at each ODNs with the help of other N 100 GHz interleavers. Each ODN is distributing the broadcasted signal to K ONUs with the help of another 1xK coupler. The designed architecture supports bandwidth scalability, resiliency to OLT TRx/ line card failure, and network extensibility and described in following sections.

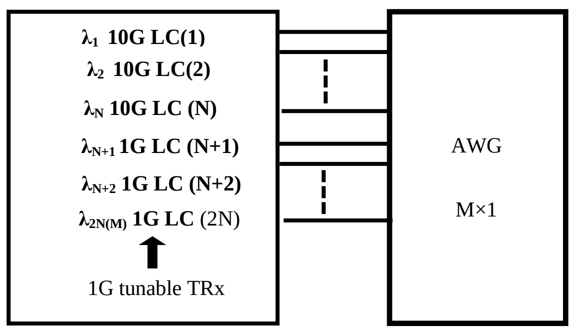

Fig. 4.3 Line Cards connections at OLT

4.3 Bandwidth Scalability and Resiliency to OLT TRx/ Line Card Failure

Bandwidth scalability is to increase the offered bandwidth to some ODN whenever required. Bandwidth is an important parameter as its demand is growing continuously and expected to increase more and more in future. Offered bandwidth per ODN can be increased by increasing the data rates, but this is not a cost-effective and viable approach since all the ONUs needs to adopt the new data rates. Our proposed system can offer comparatively more bandwidth by using all OLT transmitters (1G and 10G) simultaneously. One major advantage of the proposed system is added resiliency to the network thus in case of any transmitter or line card failure; the network will continue to serve because each ONU is receiving two wavelengths. In this case, ONU is tuned to an alternative working wavelength until the recovery of failed wavelength. This unique feature is neither available in TDM PON nor in WDM-PON systems. However, offered bandwidth will depend on working transmitter/line card.

By using the proposed architecture (Fig. 4.2), dynamic geographical bandwidth scalability is also possible i.e. allocation of more bandwidth to any particular network segment depending upon the user demand is also possible. This can be performed by using special parameter coarseness factor (C) of RN AWG where C represents the number of contiguous wavelength channels allocated to the same port of AWG [109]. C can be adjusted by changing the frequency spacing of AWG. For C=2, frequency spacing of RN AWG is kept twice than the input frequency spacing to pass two contiguous wavelengths. Now as case depicted in Fig. 4.4, output wavelengths of RN AWG changes from the previous one shown in Fig. 4.2.

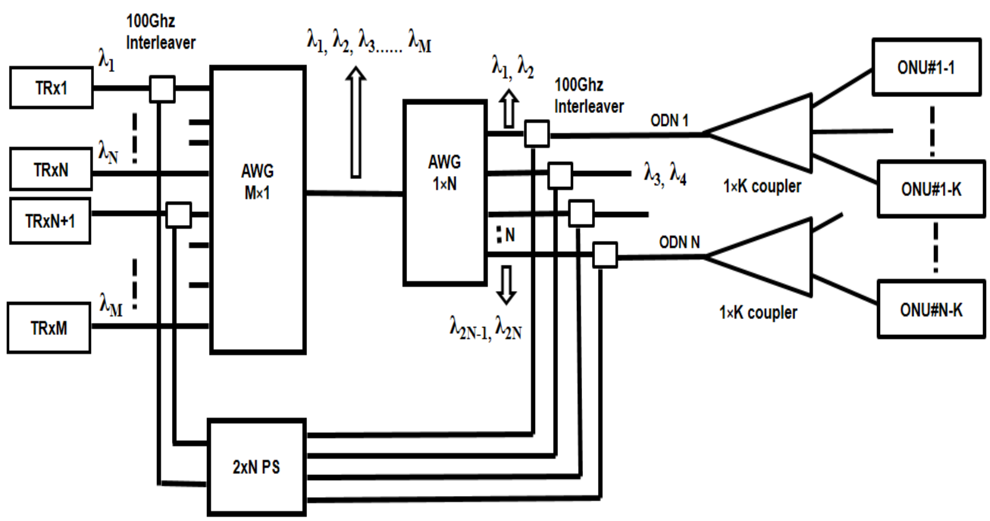

Fig. 4.4 Proposed Network architecture with coarseness factor (M/2=N, C=2)

By designing such architecture, first half ports of RN AWG can support extremely high bandwidth (capable of supporting 20 Gbps data rates). This part of the network can also be used for serving the extended network (new users added in the network). The remaining half ports of remote node AWG support low bandwidth applications. The offered bandwidth to different ports can be changed dynamically by changing the center frequency of remote node AWG as wavelength routing of AWG depends on its center frequency.

4.4 Network Extensibility

Network extensibility is to support the newly added users in the already deployed network with acceptable performance to support the future generation optical network. As the proposed system is bandwidth scalable, by allocating multiple broadband wavelengths to a specific part of the network (distribution network), it can easily support the newly added users within the power budget matching conditions. New users can be served by inserting extra remote AWG or power splitter in cascade before the individual PON branch. If all ports are scaled with 1×2 power splitter, then the network can support twice of previously supported users. Insertion losses of AWG are about 5-6 dB regardless of the output ports, and for power splitter, it is about to $3.5\log_2(n)$. Where n is the number of output ports of power splitter. So to employ AWG having four ports or more gives superior power budget than the power splitter. To verify the performance of the proposed architecture, results are validated with the help of simulations.

4.5 Other Illustrative Examples of Proposed Architecture

OLT is equipped 8 LCs out of which four are 10G and remaining four are 1G. 10G LCs provide the output wavelengths λ_1, λ_2, λ_3 and λ_4 and 1G LCs provide the output wavelengths λ_5, λ_6, λ_7 and λ_8. Due to the cyclic property, CO AWG multiplexes λ_1, λ_2, λ_3…. λ_8 wavelengths and outputs to the signal output port. At remote node 1x4 AWG separates all these wavelengths at different ports. Each output port of remote node AWG supports 32 ONUs with the help of 1x32 power splitter. The power consumption of each 10 G LC is 3.5 W while for 1 G LC it is approximately 0.5W. Hence, the total power consumed by 10 G LCs is 14 W and by 1 G LCs is 2 W. Input wavelengths have the wavelength spacing of 200 GHz and are considered to be 193.1, 193.3, 193.5 and 193.7 THz respectively at 10 Gbps and 193.9, 194.1, 194.3 and 194.5 THz respectively at 1 Gbps, as shown in Fig. 4.5.

We assumed that for traffic load above the certain threshold, 10 Gbps lines are used otherwise 1 Gbps lines are used i.e. for higher traffic load 1 Gbps line cards are switched off and for lower traffic load 10 Gbps line cards are switched off. For providing up to 11 Gbps to each ODN, both the line cards (10 G and 1 G) are kept switched ON. Since all the ONUs are tunable, ONUs having load above threshold are tuned at 10 G wavelength and ONUs with load lower than threshold are tuned at 1 G wavelength. For example, ODN1 has 32 ONUs, out of which 20 ONUs have load below threshold and remaining 12 have load above threshold. In this case, 20 low load ONUs are tuned at 1 G wavelength and remaining 12 ONUs are tuned at 10 G.

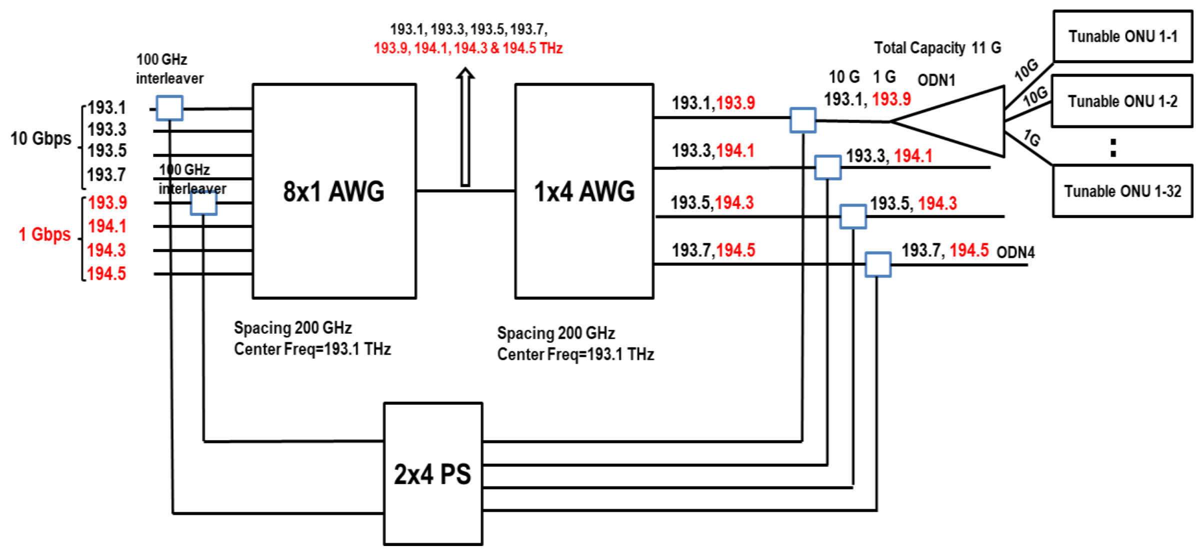

Fig. 4.5 Dual rate OLT for efficient wavelength utilization

In the architecture shown in Fig. 4.6, two 100 GHz interleavers, one for 10 Gbps and one for 1 Gbps are used at the central office to separate out the even multiple of 100 GHz and odd multiple of 100 GHz wavelengths.

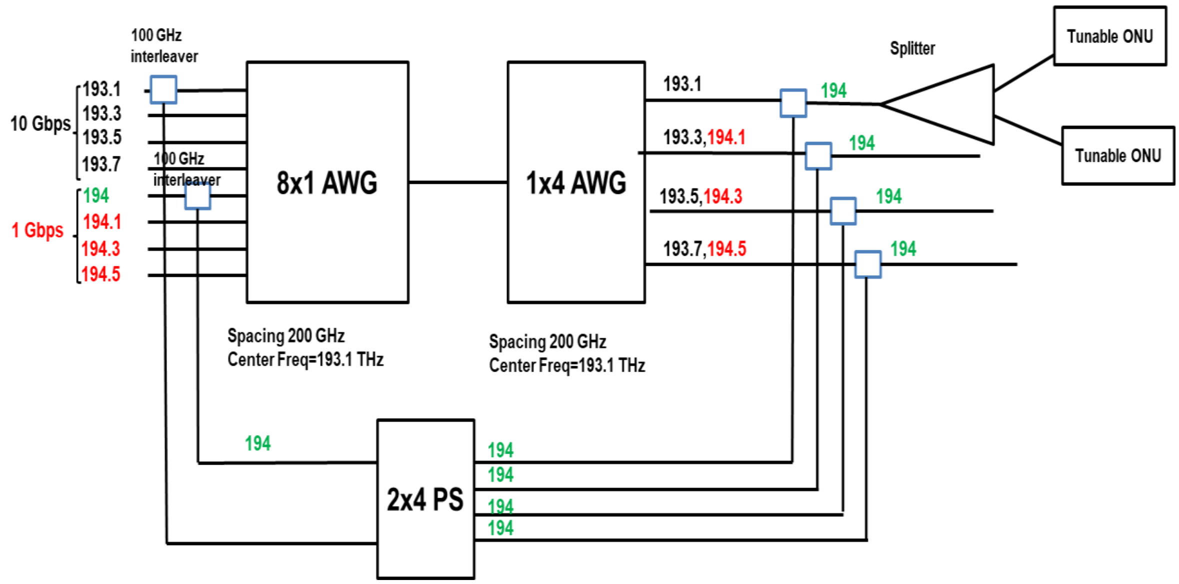

Fig. 4.6 Broadcasting at 1 Gbps

Even multiple of 100 GHz wavelength is transmitted by the interleaver and reached at 8x1 AWG. While 100 GHz shifted wavelength from the original (odd multiple of 100 GHz) is separated and diverted by the interleaver towards 2×4 PS for broadcasting. Broadcasting can be done at 10 G or 1 G or both depending upon the shifted wavelength. At the optical distribution network (ODN), four 100 GHz interleavers are used as wavelength combiners to combine the broadcasted wavelengths with downstream wavelengths. As all the ONUs are equipped with a dual rate and tunable transceivers, each ONU can receive any wavelength within the network.

Broadcasting at 1 G and 10 G are shown in Fig. 4. 6 and Fig. 4.7 respectively. If active users are less but demand high data rate, broadcasting is to be done at 10 Gbps by shifting the 10 Gbps wavelength and vice versa. In both the cases, a significant amount of energy and operational expenditure (OPEX) is saved by turning off all transmitters except the broadcasting one. Another advantage of this architecture is reliability. When a particular transmitter fails, data can be transmitted on broadcasted wavelength and services remain continue on broadcasted wavelength until the recovery of failed transmitter.

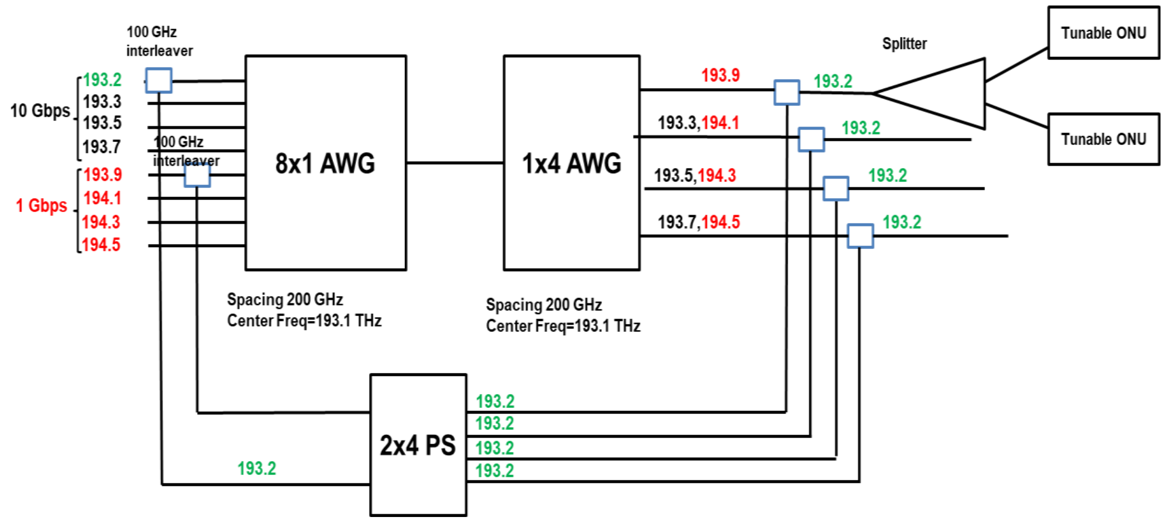

Fig. 4.7 Broadcasting at 10 Gbps

In Fig. 4.8-a, data rates provided to ODN1, ODN2, ODN3 and ODN4 are 20 Gbps, 20 Gbps, 2 Gbps and 2 Gbps respectively. By changing the center frequency from 193.1 to 193.3 THz, the data rate provided for different ODNs change as shown in Fig. 4.8-b. Data rates provided in this case are 20 Gbps, 11 Gbps, 2 Gbps and 11 Gbps at ODN1, ODN2, ODN3 and ODN4 respectively. Likewise, changes take place as shown in Fig. 4.8-c and Fig. 9-d when changing the center frequency to 193.5 THz and 193.7 THz respectively. To increase the AWG channel spacing or to shift the AWG central frequency, electro-optical tunable AWG [110-111] or thermo-optical tunable AWG [112-114] can be used. Thermo-optic tunable silicon-based AWG using TiN heater has already been demonstrated in [113]. Effective refractive index n_{eff} of silicon AWG is highly sensitive to the temperature variations. As wavelength spacing of AWG depends on its effective refractive index spacing, changing n_{eff} by means of temperature, wavelength spacing of AWG can be achieved [112-114] and given by $\Delta\lambda=\Delta n_{eff} \bullet \lambda_{0/} n_g$. where $\Delta\lambda$ is the frequency spacing of the AWG, λ_0 is AWG wavelength. Δn_{eff} is the effective refractive index of the AWG. n_g is the group index. Center frequency of AWG also depends upon n_{eff} and given by $\lambda_c = 2n_{eff} \bullet \Lambda$ [111]. Just by changing the n_{eff} by means of above-mentioned techniques, central frequency can also be easily changed. As both wavelength spacing and central frequency of AWG are dependent on n_{eff} (temperature), for a desired frequency spacing $\Delta\lambda$, λ_0 may be chosen such that its final central frequency should be λ_c.

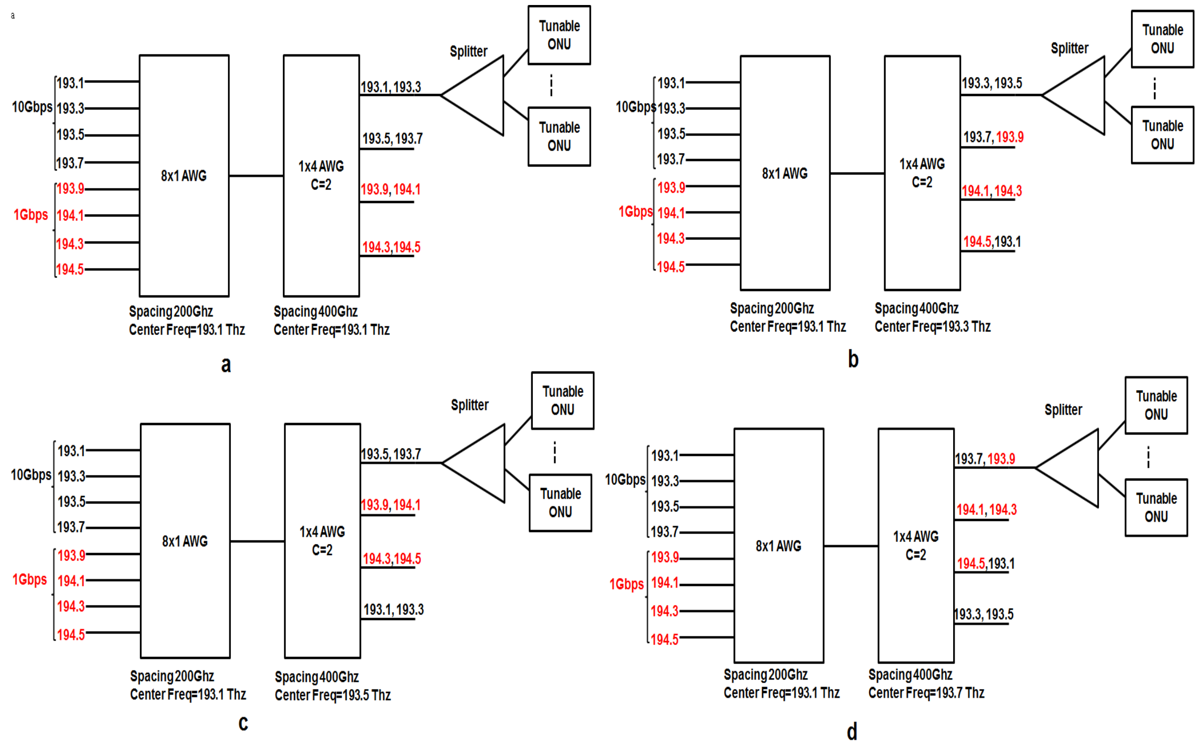

Fig. 4.8 Dynamic wavelength allocation for different center frequency

To support extended network or to provide bandwidth scalability to any specific part of network, proposed architecture is used with interleaver and coarseness factor C=2 as shown in Fig. 4.9. In this architecture, the wavelength spacing of RN AWG is kept twice the CO AWG (coarseness factor C=2). At each output port of RN AWG, two contiguous wavelengths are transmitted, thus providing up to 20 Gbps data rate. The 100 GHz interleavers separate the 1 G/10 G wavelength for broadcasting at wavelength 1 G/10 G. Here, Fig. 4.9 shows only 1 G broadcasting at 194 THz. This provides a significant amount of energy saving by turning off all other wavelengths/ transmitters whenever traffic load goes below a certain threshold.

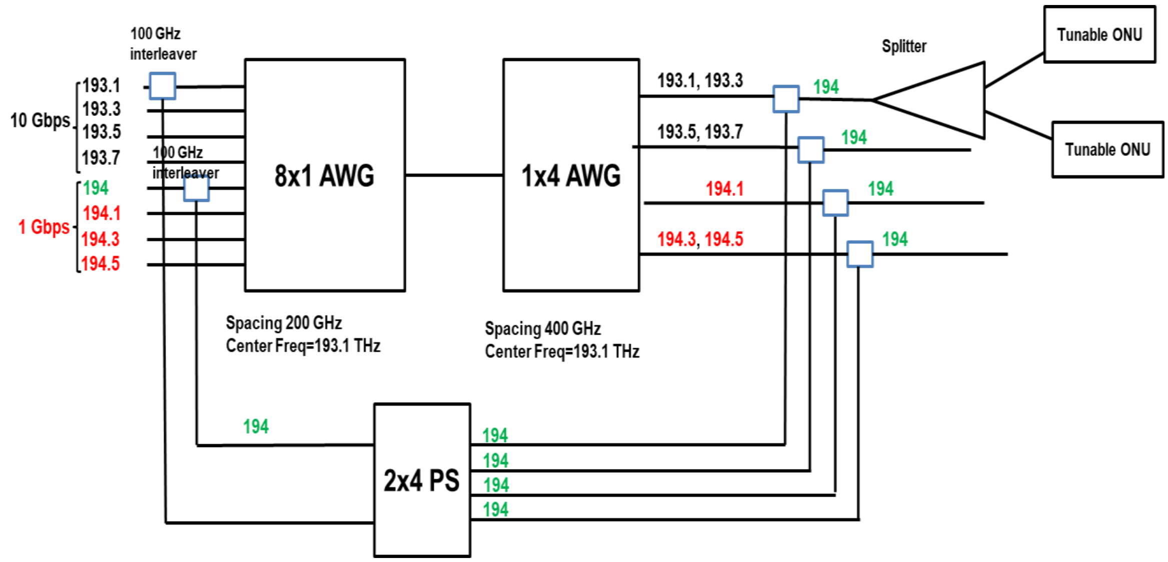

Fig. 4.9 Broadcasting at 1 Gbps with coarseness factor C=2

4.6 Simulation Setup with Results & Discussions

To demonstrate the system characteristics and capabilities of proposed tree topology based hybrid WDM-TDM PON, we simulated it with the help of a system level simulator Optisystem 13.0 as depicted in Fig. 4.10.

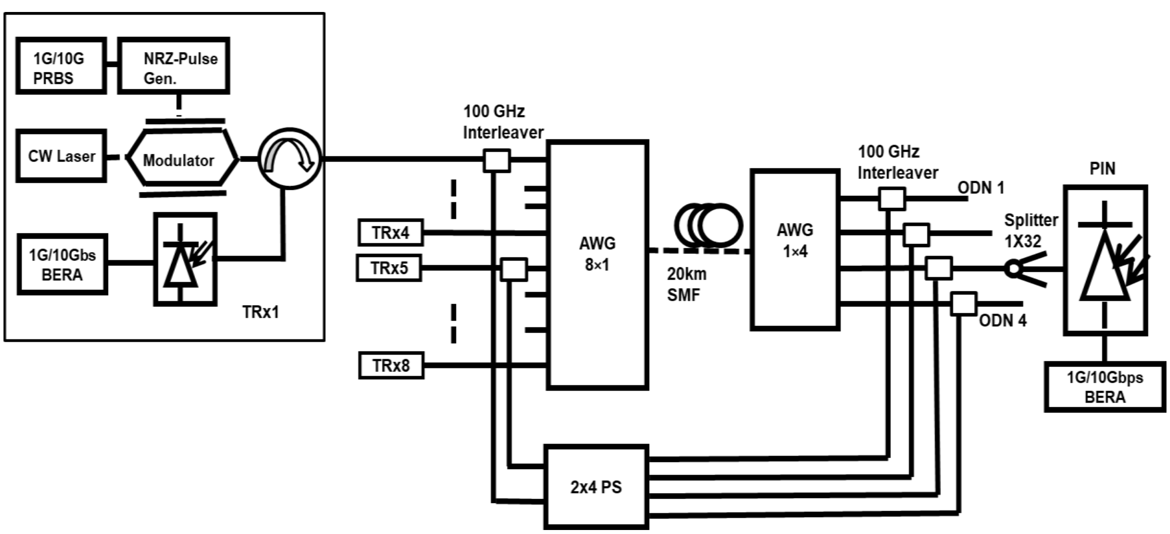

Fig. 4.10 Simulation setup of proposed network architecture

OLT consists of laser sources along with 1 G and 10 G pulse generator that generates the pseudo-random binary sequence (PRBS) data of 2^{31}-1 length. Due to low driving power and broadband property [115], $LiNbO_3$ Mach-Zehnder modulator is used to modulate the signal externally. The extinction ratio of MZM is kept 30 dB.

OLT sends four 10 G and four 1 G downstream wavelengths to 8×1 CO AWG (M=8) located at CO. This AWG has the channel spacing of 200 GHz (1.608nm) and center frequency of 193.1 THz. Output wavelengths of 8×1 CO AWG is transmitted through 20 km single mode fiber. Fiber attenuation and dispersion losses are considered to be 0.2 dB/km and 16.75 ps/nm/km respectively; fiber output signal is applied to 1×4 RN AWG located at the remote node. Channel spacing and center frequency of RN AWG are kept same as that of CO AWG. Again downstream data is shared among multiple ONUs through the 1×32 optical splitter. We assumed the insertion losses of 3 dB for both CO AWG and RN AWG. 16.5 dB losses are also considered for the splitter [116]. At ONU, output optical signal is filtered out by a tunable optical filter to pass the desired signal and remove all other unwanted signals. Operating frequency of this filter depends on required narrowband or broadband signal. PIN photoreceiver with a responsivity of 1A/W and dark current of 10 nA is used to detect the optical signal. The output electrical signal is filtered by the electrical filter with cutoff frequency of 0.75 × bit rate. ONU is installed with a dual rate receiver so that it can receive both 1 G and 10 G downstream signals.

The performance of the proposed architectures (Fig 4.2) is evaluated with and without broadcasting for both 1 Gbps and 10 Gbps transmission. BER v/s received optical power for all the cases are observed and plotted in Fig. 4.11 and Fig. 4.12 which show the clear reception of transmitted signals at the receiver.

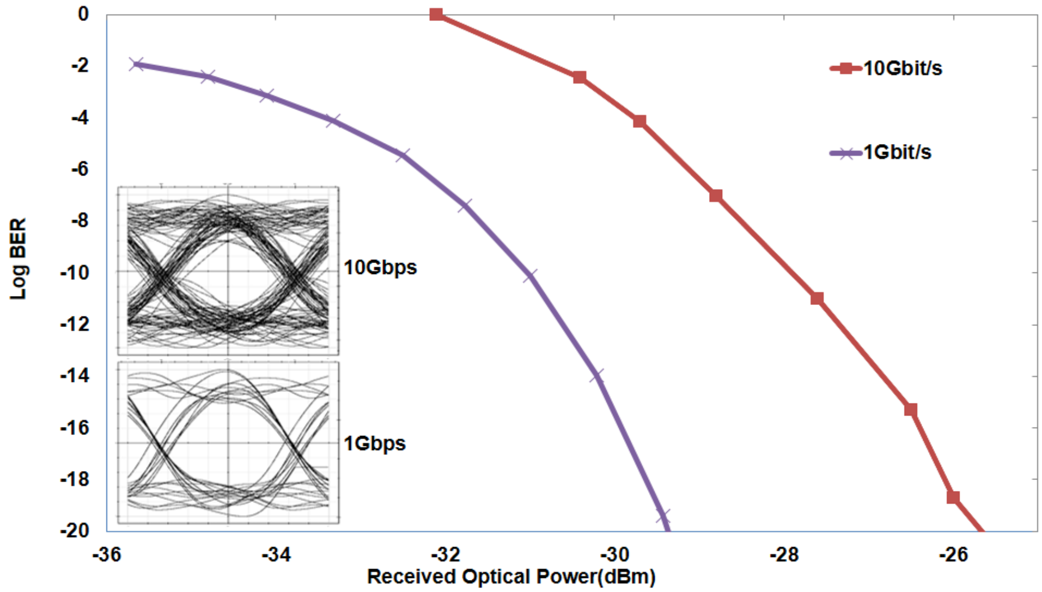

Fig. 4.11 Received optical power (dBm) v/s BER for 20 km fiber without broadcasting

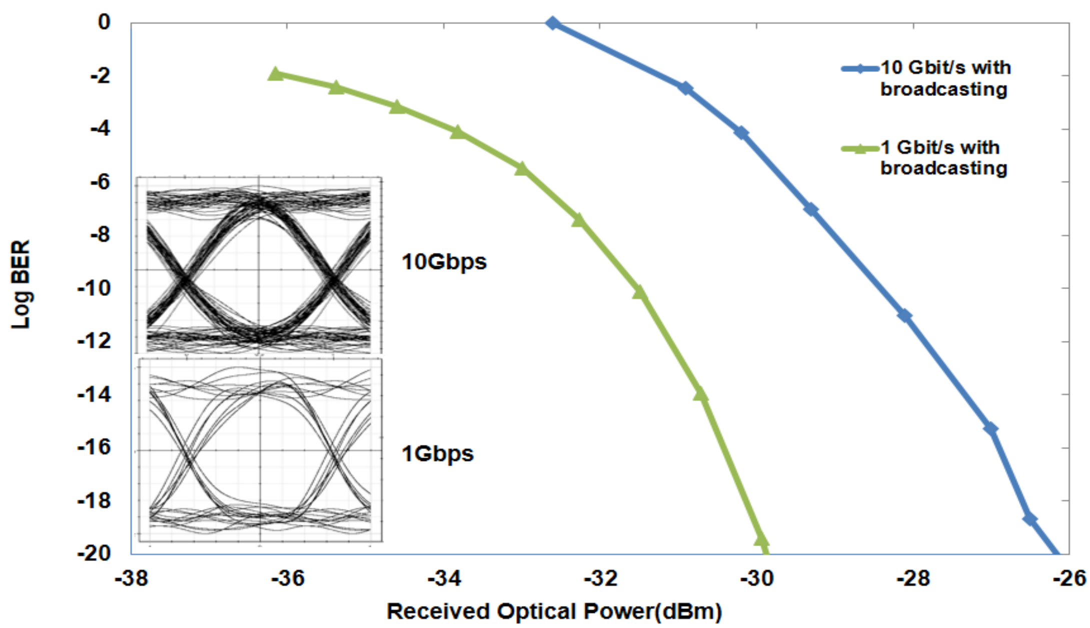

Fig. 4.12 Received optical power (dBm) v/s BER for 20 km fiber with broadcasting

Power received at the receiver is given by equation (4.1) and equation (4.3):

$$P_{Rx} = P_{Tx} - L_{Ch} \quad \text{..........(4.1)}$$

$$L_{Ch} = L_{Interleaver} + L_{AWG} + L_{Fiber} + L_{AWG} + L_{Interleaver} + L_{1\times K.PS} \quad \text{..........(4.2)}$$

$$P_{Rx} = P_{Tx} - L_{Interleaver} - L_{AWG} - L_{Fiber} - L_{AWG} - L_{Interleaver} - L_{1\times K.PS} \quad \text{..........(4.3)}$$

where P_{Tx} and P_{Rx} are the transmitted and received power in dBm. L_{Ch} is the total loss occurring in the channel and given in dB. Channel losses are depending upon the various passive components utilized in the path and for downstream transmission, losses are given by equation (4.2). For the broadcasting path, losses due to CO and RN AWGs are saved. However, it faces losses of 2×4 PS. Losses and received power with broadcasting are given by equation (4.4) and equation (4.5) respectively.

$$L_{Ch} = L_{Interleaver} + L_{2\times 4.PS} + L_{Fiber} + L_{Interleaver} + L_{1\times K.PS} \quad \text{..........(4.4)}$$

$$P_{Rx} = P_{Tx} - L_{Interleaver} - L_{2\times 4.PS} - L_{Fiber} - L_{Interleaver} - L_{1\times K.PS} \quad \text{..........(4.5)}$$

Total losses occurring for 20 km reach in the system for downstream and broadcasting system are 27.5 dB and 28 dB respectively. 3 dB insertion losses occur due to each CO AWG and RN AWG. Insertion losses of each interleaver and 2×4 power splitter are 0.5 dB and 6.5 dB respectively. Broadcasting architecture suffers 0.5 dB more insertion losses, and this power margin can be used for supporting additional users without increasing input power. By providing 0 dBm optical power, received optical powers are -27.5 dBm and -28 dBm respectively and at these received optical powers, observed BER is reasonably good.

Since proposed network (Simulation set up fig 4.10) utilizes total eight wavelengths out of which four are used for transmitting signals at 10 Gbps and remaining four for 1 Gbps, the total capacity of the network is to support up to 44 Gbps. To analyze the power saving capability of proposed architecture, we have assumed the representative traffic pattern for different days of a week for 24 hours as shown in Fig. 13.

We have some assumptions as follows: The traffic is assumed to be random in nature and varying randomly up to 44 Gbps for the duration of 24 hours on each day. Also traffic has different loads for different days from Monday to Saturday. Each particular day will follow the same traffic pattern in upcoming weeks.

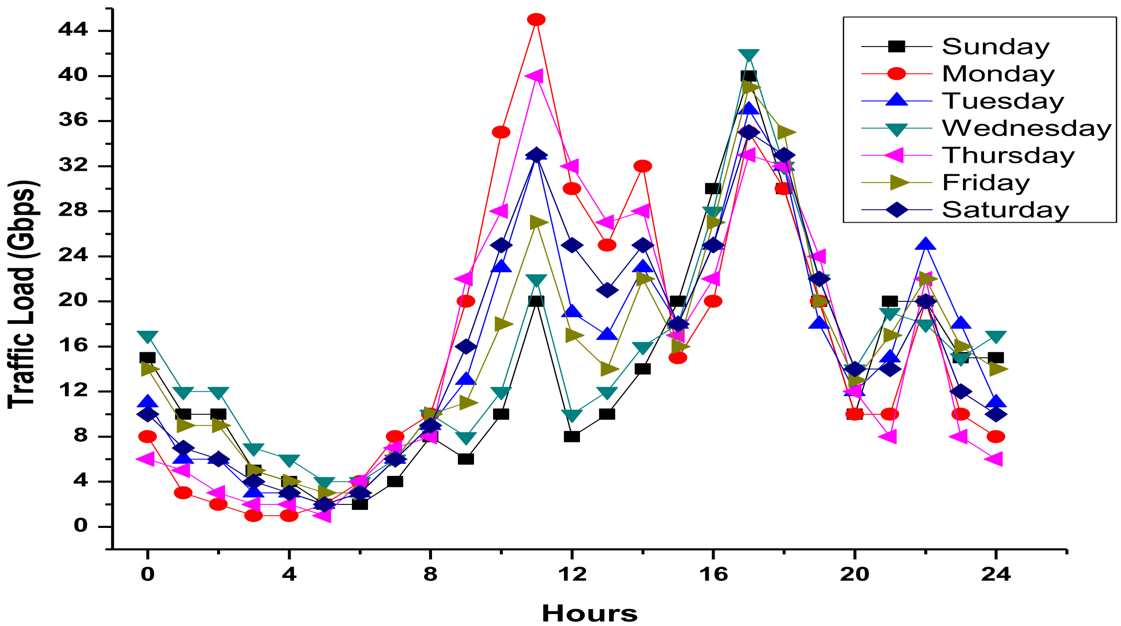

Fig. 4.13 Representative traffic pattern for one week

By using the proposed architecture with broadcasting (Fig 4.2) as compared to conventional architecture (Fig 4.1), power saving in percentages at a particular day will be given by equation (4.6):

$$1-\frac{[\sum_{n=1}^{4} h_{10,n} n_{10G} \times P_{10G} + \sum_{n=1}^{4} h_{1,n} n_{1G} \times P_{1G}]}{[HN_{10G} \times P_{10G}]} \qquad \text{.......................................(4.6)}$$

where n_{10G} and $h_{10,n}$, denote the number of working 10 G transmitters and duration of n working 10 G transmitters respectively, while the terms n_{1G} and $h_{1,n}$ are the respective terms for the 1 G transmitters. P_{10G} and P_{1G} denote the power consumed by each 10 G and 1 G transmitters respectively. H, N_{10G} and N_{1G} denote the total duration, total number of 10 G transmitters and total number of 1 G transmitters respectively. The numerator part shows the power consumed by the proposed architecture on a particular day and denominator part represents the power consumed by the conventional architecture as shown in Fig. 4.1.

Based on the above calculations, energy efficiency of the proposed architecture (Fig. 4.2) as compared to conventional architecture discussed in case 1 (Fig. 4.1) is analyzed for different days and is depicted in Fig. 4.14, which clearly shows the up to 61.2% energy can be saved by using proposed architecture.

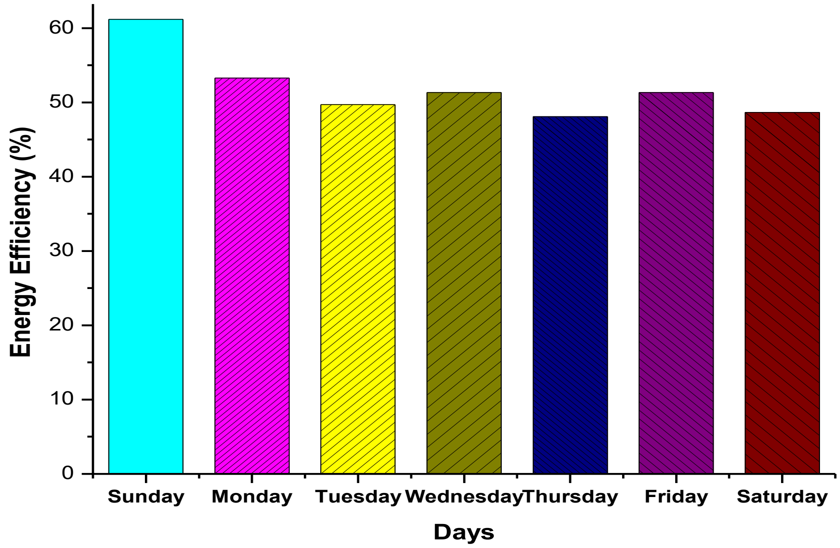

Fig. 4.14 Power saving for one week

Confidence interval (in %) of the reported results are 51.94 ± 3.1 and 51.94 ± 4 for 95% and 99% confidence level respectively. The confidence interval is calculated based on equation (4.7):

$$\bar{X} \pm Z\frac{\sigma}{\sqrt{n}} \qquad (4.7)$$

where $\bar{X}$, σ and n indicate the mean, standard deviation and sample size respectively. Z is the value of a variate for a given confidence level. It has the values 1.96 and 2.57 for confidence level 95% and 99% respectively. Though, the cost of the proposed architecture is increased as compared to conventional architecture because it requires additional four 1 G transceivers. The cost of Hilink 10 G transceiver is approximately $320.00 [117] while it is approximately $86.00 [117] for 1 G transceiver. Thus overall CAPEX of architecture is increased about 26.87%. One USA's premier internet provider "US Internet" costs approximately $298.00/ month for 10Gbps upstream/ downstream [118] and $65.00/ month for 1Gbps upstream/ downstream transmission [118]. By considering these costs, the reduction in OPEX for the assumed traffic pattern is given by equation (4.8):

$$1 - \frac{[\sum_{n=1}^{4} h_{10,n} n_{10G} \times B_{10G} + \sum_{n=1}^{4} h_{1,n} n_{1G} \times B_{1G}]}{[HN_{10G} \times B_{10G}]} \qquad (4.8)$$

where B_{10G} and B_{1G} denote the 10 G and 1 G bandwidth cost respectively. The numerator part shows the OPEX of proposed architecture on a particular day and denominator part represents the OPEX of conventional architecture. Effective OPEX reduction on different days for assumed traffic in given in Fig. 4.15.

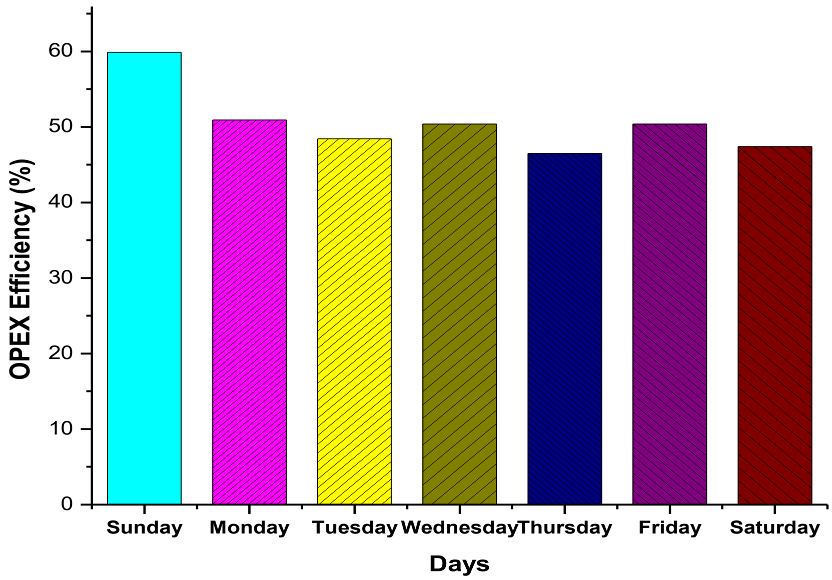

Fig. 4.15 OPEX reduction on different days of a week

Based on equation (7), the confidence interval for OPEX efficiency are 50.56 ± 3 and 50.56 ± 4 for 95% and 99% confidence level respectively.

4.7 Summary

In this chapter, we discussed our proposed energy-efficient hybrid WDM-TDM PON architecture which allows the dual rate 1 G/10 G transmission depending upon the traffic load. At the central office, this efficient bandwidth utilization provides an opportunity to reduce a significant amount of energy consumption and OPEX. In the proposed architecture, two wavelengths are reaching to the same ODN. Therefore it provides the resiliency to the OLT TRx and line card failure. Under low load scenario, services may remain continued on an alternative wavelength until the recovery of failed wavelength. By tuning the transmitted wavelength by 100 GHz, broadcasting at 10 G and/or 1 G is also achieved simultaneously to support various applications like HDTV, e-education services etc. By allocating two contiguous wavelengths, proposed architecture also supports bandwidth scalability to any specific geographical part of the network. For the considered representative traffic, using proposed broadcasting architecture, maximum energy consumption, and OPEX is reduced up to 61.2% and 59.9% respectively. When operating at full capacity, the proposed architecture is capable of providing up to 44 Gbps data rates to the network. Finally, the proposed architecture is more flexible, resilient to OLT TRx and line card failure, bandwidth scalable, OPEX and energy efficient to support next-generation optical networks.

Chapter 5

5. Flexible Hybrid WDM-TDM Passive Optical Network with Pay as You Grow Deployment

This chapter discusses a novel Flexible Hybrid WDM-TDM-PON architecture that allows sending dual rate signals at 1 Gbps and 10 Gbps to each optical networking unit (ONU) depending upon the traffic load. Proposed design allows wavelength allocation dynamically with pay-as-you-grow deployment capability. This architecture is capable of providing up to 40 Gbps, equal data rates to all optical distribution networks (ODNs) and up to 70 Gbps asymmetrical data rate to the specific ODN. Proposed design handles broadcasting capability with simultaneous point to point (P2P) transmission which further reduces energy consumption. In proposed architecture, each module is sending a wavelength to each ODN thus making the architecture fully flexible; this flexibility allows network providers to use only required OLT components and switch off others. The design is also reliable to any module or TRx failure and provides services without any service disruption. Dynamic wavelength allocation and pay-as-you-grow deployment support network extensibility and bandwidth scalability to handle the future generation access networks.

5.1 Introduction

Various hybrid multiplexed PON architectures have already been proposed in [29], [54-57], [119]. WDM based conventional PON architecture does not provide efficient resource and bandwidth utilization. As an example, consider a network having four optical distribution networks (ODNs), and each ODN is having a certain number of users as shown in Fig. 5.1. OLT has four modules, and each module contains four 10 G TRxs. Transmitted wavelengths from modules are multiplexed and given to the 4×4 AWG. AWG transmits four wavelengths to its each output port. These wavelength signals are given to the optical fiber and a 1×4 AWG is used to separate these wavelengths. Finally, each wavelength is responsible for serving K number of users.

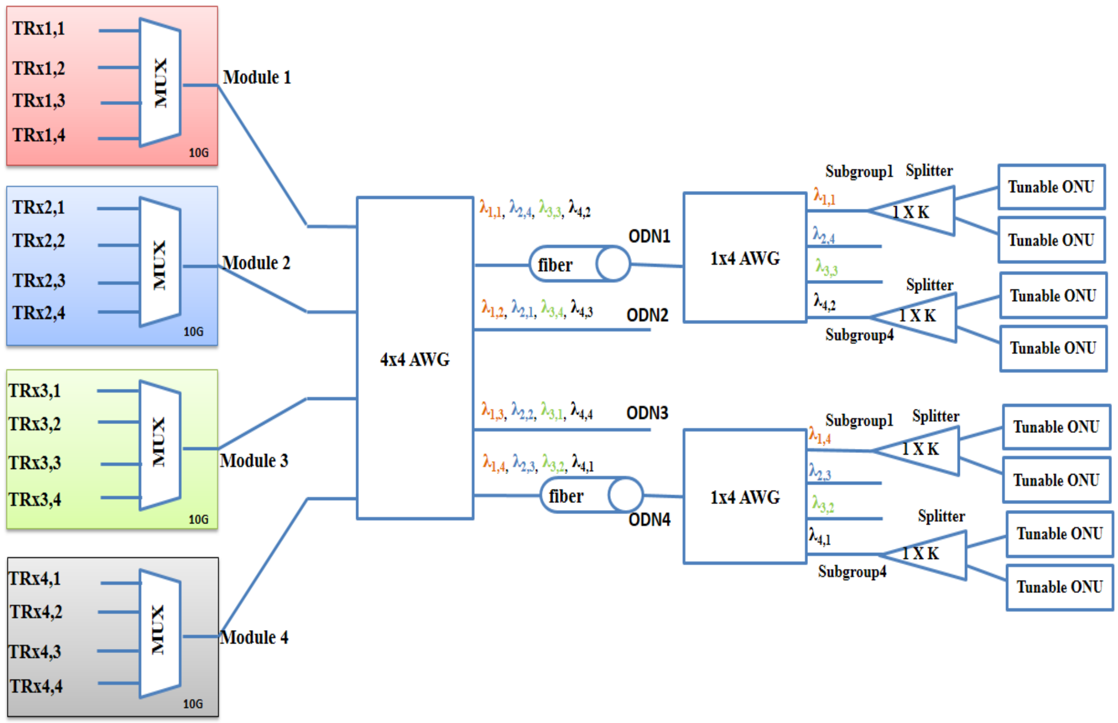

Fig. 5.1 Hybrid WDM-TDM PON architecture based on conventional WDM scheme

At some time instant, suppose an ODN has low traffic load that can be handled by a single wavelength, but due to the architecture inflexibility, the wavelength cannot be accessed by other ONUs located within that ODN. Therefore all the OLT TRxs need to keep ON regardless of the traffic load of each ONU. Also, an ODN in this architecture cannot be provided more than 40Gbps. Thus such type of architectures do not provide efficient resource utilization.

5.2 Proposed architecture and design setup

Due to the inflexibility and limitations of the architecture shown in Fig. 5.1, we have proposed an architecture as shown in Fig. 5.2; it has four modules located at CO. Each module consists of four 10 G transceivers (TRx) and one 1 G TRx. 10G TRxs are denoted by $TRx_{m,n}$ and 1 G TRxs are denoted by TRx_m, where m and n indicate module number and TRx number respectively. For each module, one optical switch is used for routing the transmitted wavelengths towards either 4x4 AWG or directly to combiner located at ODN. Wavelength transmitted from TRx1 (1 G) is passed through WDM drop filter. The purpose of this WDM drop filter is to make 1 G transceiver usable for either point to point transmission or broadcasting transmission.

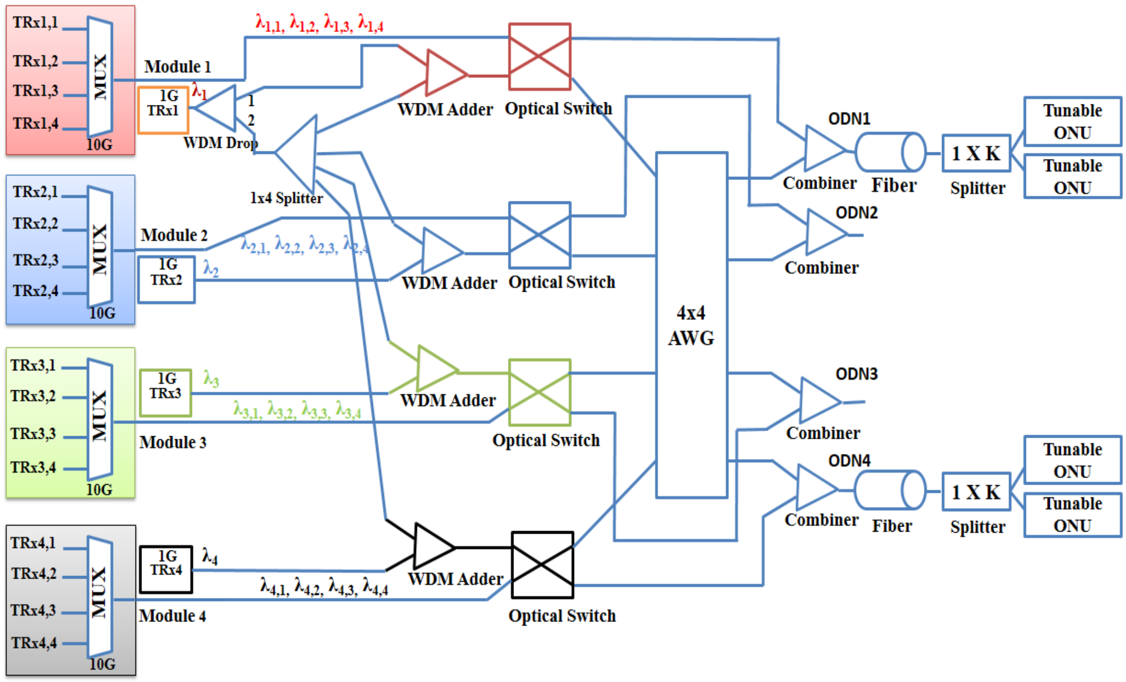

Fig. 5.2 Proposed flexible and energy efficient hybrid WDM-TDM PON architecture

This is achieved by transmitting the received signal at its either port1 or port2. When WDM drop filter wavelength is same as 1G TRx transmitted wavelength, transmitted wavelength will be dropped at port2. For any other WDM drop filter wavelength, same transmitted wavelength will be dropped at port1. Received wavelength at port1 is used for point to point transmission by directing it to WDM adder while received wavelength at port2 is used for broadcasting by giving it to 1×4 power splitter. Received signals are further applied to optical switch from where these signals can be further transmitted through 4×4 AWG or can be transferred directly to combiner of each ODN. A combiner is used following the AWG to combine the signals coming directly or through AWG. Transmitted signals are applied to single mode fiber of 20 km length having 0.2 dB/km attenuation losses and 16.75 ps/nm/km dispersion losses**.** At the user end, transmitted signal is passed through the 1×K power splitter to serve K (up to 32) ONUs simultaneously. Insertion losses of 1×K power splitter are considered to be $3.5\mathrm{Log}_2K$. Insertion losses for WDM drop, WDM adder and combiner are kept 3.5 dB each while for 1x4 power splitter, calculated losses are 7 dB. 1 dB loss of optical switch is also considered [120]. Each ONU has a tunable filter to select the desired signal and designed with dual rate transceivers to operate with both 1 G and 10 G signals. Received optical signals are detected by PIN photo receiver having responsivity of 1 A/W and dark current of 10 nA.

5.3 Working and operation

The full operation of the proposed hybrid WDM-TDM PON architecture is illustrated in Fig. 5.3. Transmitted 10 G wavelengths of each module are first combined at OLT located at CO and then applied to the optical switch. Depending on the phase shift of the switch, incoming wavelengths are diverted towards either AWG, or to the combiner directly.

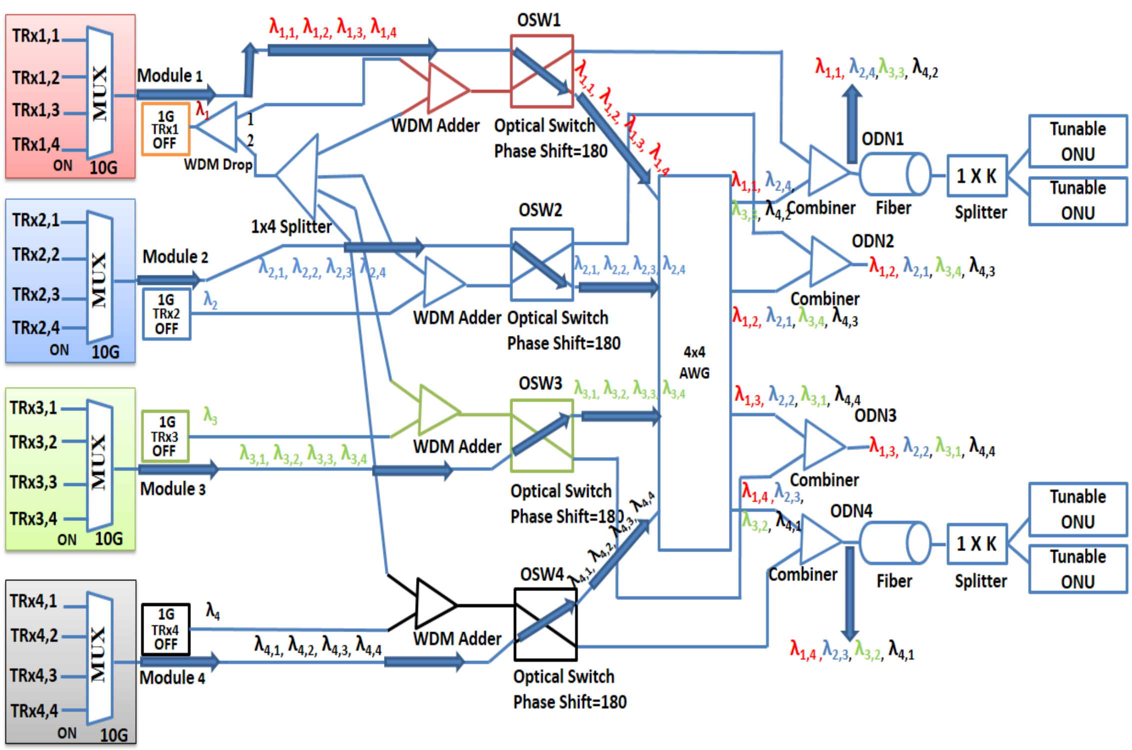

Fig. 5.3 10 G Architecture with 180-degree phase shift; symmetrical network

When the phase shift of switch is kept 180 degree, all incoming wavelengths are diverted to AWG input ports. Each input port of AWG receives four wavelengths and due to the cyclic property of AWG, incoming wavelengths are distributed to its different output ports and each output port receives one wavelength from each module i.e. the wavelengths $\lambda_{1,1}$, $\lambda_{1,2}$, $\lambda_{1,3}$, $\lambda_{1,4}$ coming from module1 are distributed in such a way that $\lambda_{1,1}$, $\lambda_{1,2}$, $\lambda_{1,3}$, $\lambda_{1,4}$ exit from port1, port2, port3 and port4 of the AWG respectively. The wavelengths $\lambda_{2,1}$, $\lambda_{2,2}$, $\lambda_{2,3}$, $\lambda_{2,4}$ from module2 exit from port2, port3, port4 and port1 respectively. Finally, wavelength sets ($\lambda_{1,1}$, $\lambda_{2,4}$, $\lambda_{3,3}$, $\lambda_{4,2}$), ($\lambda_{1,2}$, $\lambda_{2,1}$,$\lambda_{3,4}$, $\lambda_{4,3}$), ($\lambda_{1,3}$, $\lambda_{2,2}$,$\lambda_{3,1}$, $\lambda_{4,4}$) and ($\lambda_{1,4}$, $\lambda_{2,3}$,$\lambda_{3,2}$, $\lambda_{4,1}$) exit from port1, port2, port3 and port4 respectively. Thus, it is clear that each module is sending one wavelength to each ODN or each ODN receives one wavelength from each module. This makes the proposed architecture fully flexible. Total four wavelengths are received at each output port, and hence at the input of each ODN; i.e. each ODN is capable of supporting up to 40 Gbps simultaneous data rates. These received wavelengths are transferred to 20 km SMF for transmission. At the user end, these received signals are applied to 1x32 optical power splitter to support up to 32 ONUs simultaneously. At receiver, each ONU receiver is receiving four wavelengths, so each ONU is tuned to a particular wavelength at which its data is intended. For some cases, if bandwidth demand from a group of ONUs exceeds the bandwidth capability of the wavelength, then some of the ONUs may be tuned to some other underutilized wavelength. This mechanism is controlled by medium access control (MAC) layer at OLT. Another important feature of this architecture is that it provides reliability to any module or any TRx failure. For example, if the network is working at 20 Gbps with two modules switched ON, and suddenly any working module or its TRx is failed; any of the other two reserved modules is switched ON to continue service till the original module is recovered as any modules can route its wavelength to any ODN.

5.4 Pay-as-you-grow-deployment

Initially, there is no need to turn ON all the modules as only one module is capable of serving all four ODNs, as the active number of users increases, bandwidth demand also increases and pay-as-you-grow technique can be applied in which, reserved modules are switched ON one by one as the number of users/ bandwidth demand grows. When the number of active users increases, bandwidth demand also increases and at instant, when the module1 becomes out of capacity, module2 is turned ON. As module2 goes out of capacity, module3 is turned ON and so on. The pay-as-you-grow deployment provides bandwidth scalability and not only provides the opportunity to reduce OPEX but also reduces energy consumption during underutilized network which will further reduce the OPEX as required energy is decreased.

For upstream transmission as shown in Fig. 5.4, the function of splitters and combiners are reversed. Data for module1 is transmitted at $\lambda^u_{1,1}$, $\lambda^u_{1,2}$, $\lambda^u_{1,3}$, and $\lambda^u_{1,4}$ from ODN1, ODN2, ODN3 and ODN4 respectively. This upstream data is split by the combiner (working as a splitter) into two parts, to be transmitted towards AWG and optical switch respectively. Due to the cyclic property of AWG, all the upstream wavelengths coming from different ODNs are combined at a single port and reach at optical switch (OSW1). Since the phase shift of optical switch is 180 degree, all these upstream wavelengths coming from AWG are received by 10 G TRxs at module1, while wavelengths coming directly from combiner are transmitted towards 1 G TRx and discarded as 1 G TRx is switched off. For simplicity, discarded wavelengths are not drawn.

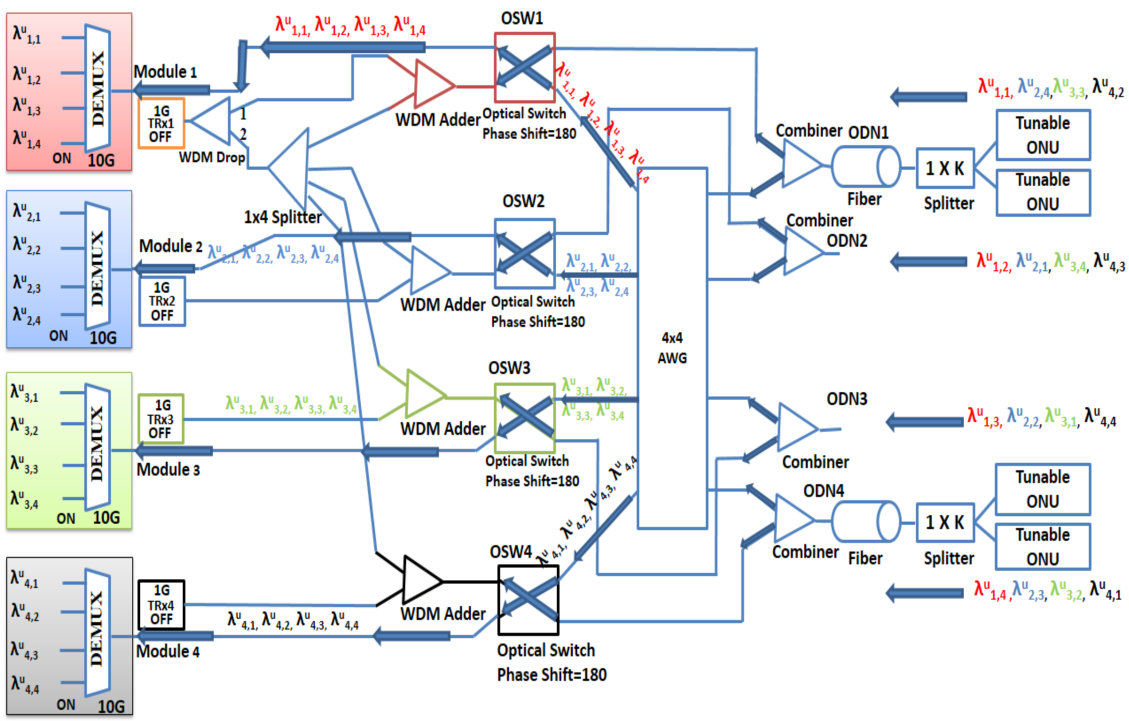

Fig. 5.4 Upstream transmission for symmetrical network

If upstream traffic is increasing, then data on other wavelengths from different ODNs may be transmitted. Transmitted set of wavelength from ODN1, ODN2, ODN3 and

ODN4 are ($\lambda^{u}_{1,1}$, $\lambda^{u}_{2,4}$, $\lambda^{u}_{3,3}$, $\lambda^{u}_{4,2}$), ($\lambda^{u}_{1,2}$, $\lambda^{u}_{2,1}$,$\lambda^{u}_{3,4}$, $\lambda^{u}_{4,3}$), ($\lambda^{u}_{1,3}$, $\lambda^{u}_{2,2}$,$\lambda^{u}_{3,1}$, $\lambda^{u}_{4,4}$) and ($\lambda^{u}_{1,4}$, $\lambda^{u}_{2,3}$,$\lambda^{u}_{3,2}$, $\lambda^{u}_{4,1}$). At OLT, received set of wavelengths at module1, module2, module3 and module4 are ($\lambda^{u}_{1,1}$, $\lambda^{u}_{1,2}$, $\lambda^{u}_{1,3}$, $\lambda^{u}_{1,4}$), ($\lambda^{u}_{2,1}$, $\lambda^{u}_{2,2}$,$\lambda^{u}_{2,3}$, $\lambda^{u}_{2,4}$), ($\lambda^{u}_{3,1}$, $\lambda^{u}_{3,2}$,$\lambda^{u}_{3,3}$, $\lambda^{u}_{3,4}$) and ($\lambda^{u}_{4,1}$, $\lambda^{u}_{4,2}$,$\lambda^{u}_{4,3}$, $\lambda^{u}_{4,4}$) respectively. At OLT, AWG is working as demux which separates out all the upstream wavelengths, and respective TRxs receive these wavelengths.

By keeping the phase shift of optical switch zero degree, all the incoming wavelengths from a particular module are diverted directly towards the combiner; thus insertion losses occurring due to AWG are avoided. This arrangement is preferred when the system is operating at full load, i.e., each ODN is operating at 40 Gbps speed. In such a case, AWG can be completely bypassed, thus reducing its insertion loss. This is demonstrated in Fig. 5.5.

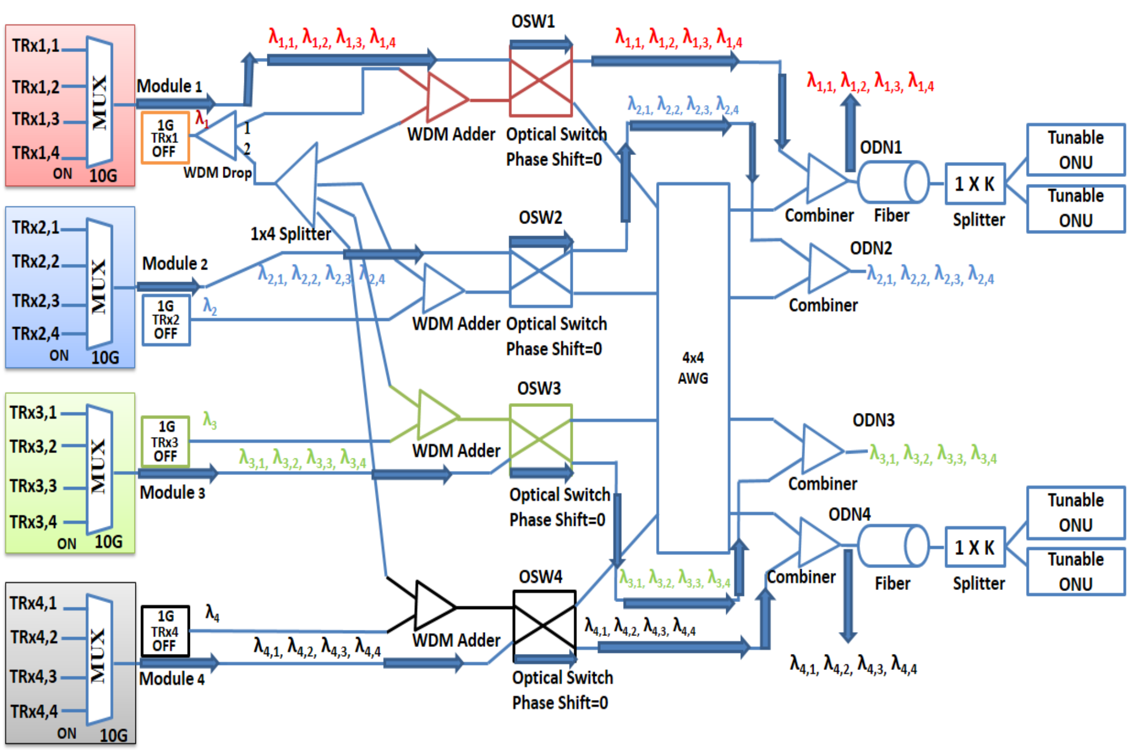

Fig. 5.5 Architecture operating at 10 G with zero-degree phase shift

However, this architecture is not recommended if all the ODNs are having only some active users (i.e. not operating at full load of 40 Gbps) and therefore, demand less bandwidth or are underutilized. Thus, OLT resources are not being utilized efficiently since all four modules are turned ON to serve all the (underutilized) ODNs. In such a case, the scheme presented in Fig. 5.3 (using AWG) is preferred so that the load can be assigned to only a few modules instead of distributed load, and the remaining modules can be turned OFF. The number of turned ON TRxs will depend on the bandwidth to be provided. For upstream transmission, wavelengths coming directly from combiner to the optical switch are received by 10G TRxs of respective modules. Wavelengths coming from AWG is directed towards 1G TRx and discarded as TRx is switched off. Transmitted upstream wavelengths from ODN1, ODN2, ODN3 and ODN4 are ($\lambda^u_{1,1}$, $\lambda^u_{1,2}$, $\lambda^u_{1,3}$, $\lambda^u_{1,4}$), ($\lambda^u_{2,1}$, $\lambda^u_{2,2}$,$\lambda^u_{2,3}$, $\lambda^u_{2,4}$), ($\lambda^u_{3,1}$, $\lambda^u_{3,2}$,$\lambda^u_{3,3}$, $\lambda^u_{3,4}$) and ($\lambda^u_{4,1}$, $\lambda^u_{4,2}$,$\lambda^u_{4,3}$, $\lambda^u_{4,4}$) respectively, same set of transmitted wavelengths are received at module1, module2, module3 and module4 respectively.

The proposed architecture is also able to provide asymmetrical load to various ODNs located at different geographical locations (varying from 10 Gbps upto a maximum of 70 Gbps depending on the requirement of a particular ODN). This is illustrated in Fig. 6. This dynamic wavelength allocation provides the efficient use of resources and enhances the bandwidth scalability to the particular network segment.

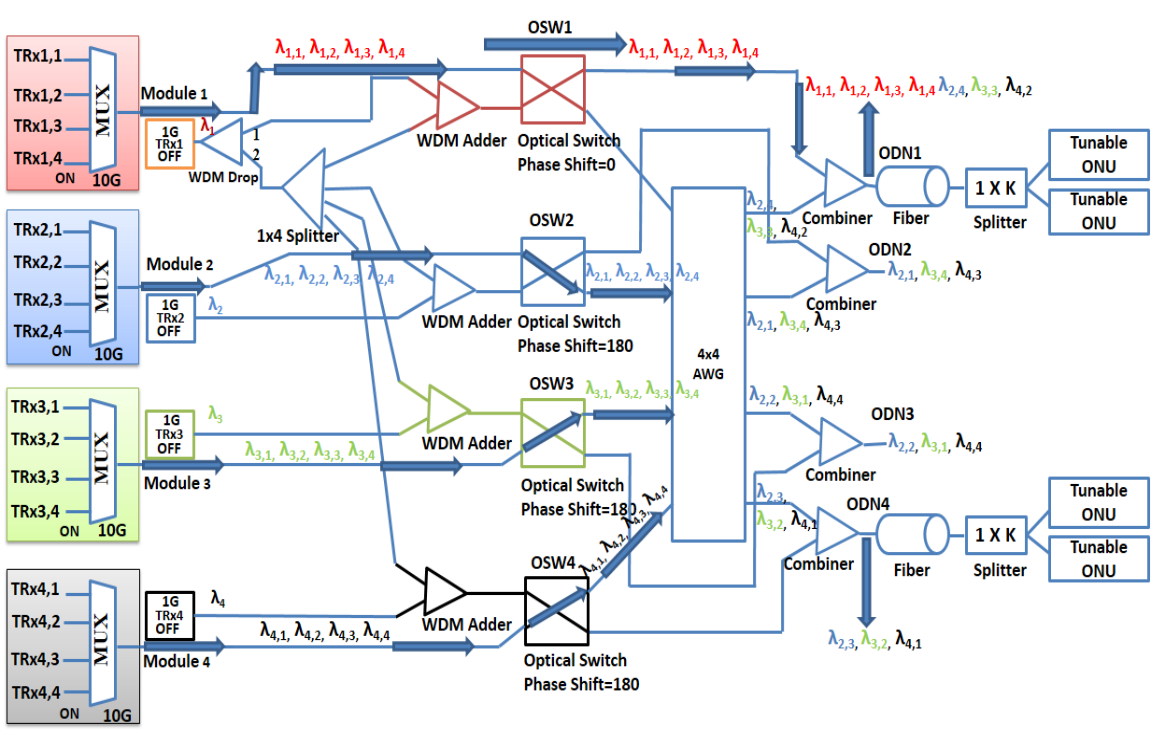

Fig. 5.6 Dynamic bandwidth allocation; asymmetrical network

This also provides the capability to support extended users in the particular network segment. To allocate bandwidth dynamically, the phase shift of some optical switches is kept zero degree while for others it is kept 180 degree as depicted in Fig. 5.6.

As shown in Fig. 5.6, ODN1 is provided with a speed of 70 Gbps, This is achieved by keeping phase shift of first optical switch zero degree thus diverting all the wavelengths of module1 to ODN1 giving 40 Gbps while other three wavelengths coming from other three modules via AWG are providing 10 Gbps each (total 30 Gbps), thus up to maximum 70 Gbps data rate can be provided to the particular part/segment of the network. Upstream transmission is shown in Fig. 5.7, transmitted wavelengths from ODN1, ODN2, ODN3 and ODN4 are ($\lambda^u_{1,1}$, $\lambda^u_{1,2}$, $\lambda^u_{1,3}$, $\lambda^u_{1,4}$, $\lambda^u_{2,4}$, $\lambda^u_{3,3}$, $\lambda^u_{4,2}$), ($\lambda^u_{2,1}$, $\lambda^u_{3,4}$, $\lambda^u_{4,3}$), ($\lambda^u_{2,2}$, $\lambda^u_{3,1}$, $\lambda^u_{4,4}$) and ($\lambda^u_{2,3}$, $\lambda^u_{3,2}$, $\lambda^u_{4,1}$).

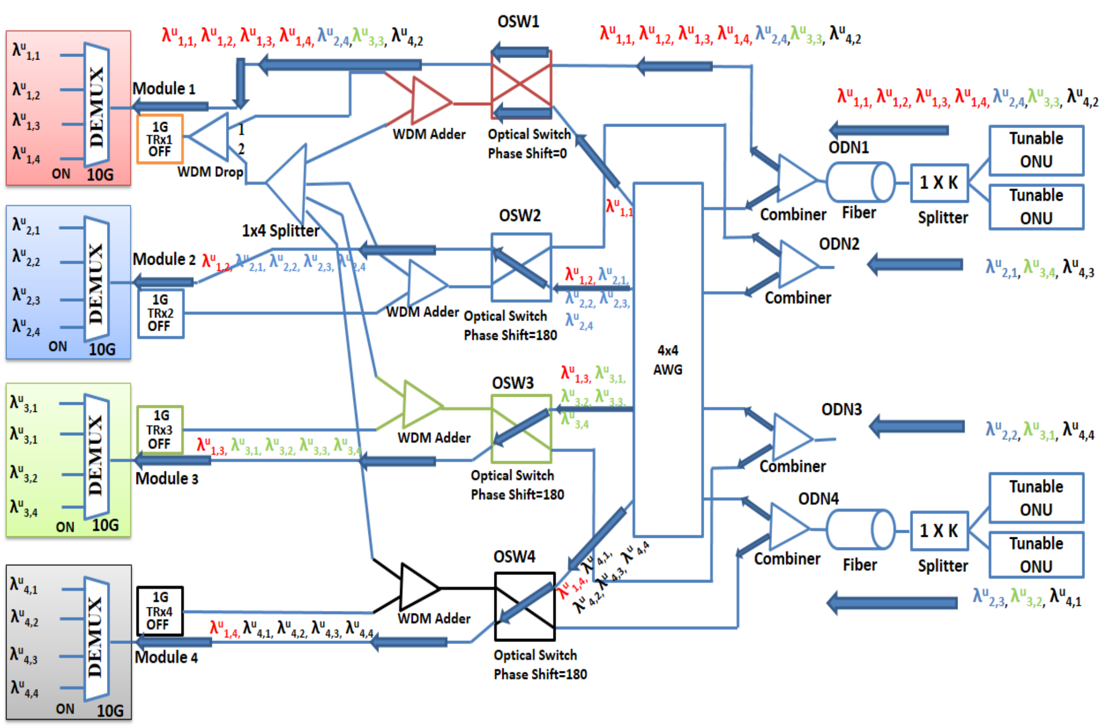

Fig. 5.7 Upstream transmission for asymmetrical network

Out of seven wavelengths of ODN1, four wavelengths ($\lambda^u_{1,1}$, $\lambda^u_{1,2}$, $\lambda^u_{1,3}$, $\lambda^u_{1,4}$) are directly received by respective TRxs at module1 and wavelengths ($\lambda^u_{2,4}$, $\lambda^u_{3,3}$, $\lambda^u_{4,2}$) will not be passed through demux at OLT. AWG also receives the wavelengths coming from different ODNs and distribute to its different ports. Wavelengths ($\lambda^u_{1,1}$), ($\lambda^u_{1,2}$, $\lambda^u_{2,4}$), ($\lambda^u_{1,3}$,

$\lambda^u_{3,3,}$) and ($\lambda^u_{1,4,}$ $\lambda^u_{4,2}$) will be distributed to AWG port1, port2, port3 and port4 respectively. Final set of wavelengths ($\lambda^u_{1,1,}$ $\lambda^u_{1,2,}$ $\lambda^u_{1,3,}$ $\lambda^u_{1,4}$), ($\lambda^u_{2,1,}$ $\lambda^u_{2,2,}$ $\lambda^u_{2,3,}$ $\lambda^u_{2,4}$), ($\lambda^u_{3,1,}$ $\lambda^u_{3,2,}$ $\lambda^u_{3,3,}$ $\lambda^u_{3,4}$) and ($\lambda^u_{4,1,}$ $\lambda^u_{4,2,}$ $\lambda^u_{4,3,}$ $\lambda^u_{4,4}$) are passed by respective AWGs of different OLT modules and received by respective TRxs, whereas the other wavelengths are discarded.

When the traffic load in the network is at the minuscule level, then it is not advised to use 10 G TRxs as these consume more power. To reduce the power consumption of proposed architecture, it is also installed with 1 G TRxs, one for each module. When traffic load in the network is below the certain threshold, all 10 G TRxs are turned OFF while all 1 G TRxs are turned ON. The phase shift of all optical switches is kept 180 degree, thus each transmitted wavelength can reach directly to their respective ODN as shown in Fig. 5.8 i.e. for each ODN; separate 1 G TRx is to be turned ON. These signals do not face the insertion losses occurring due to AWG.

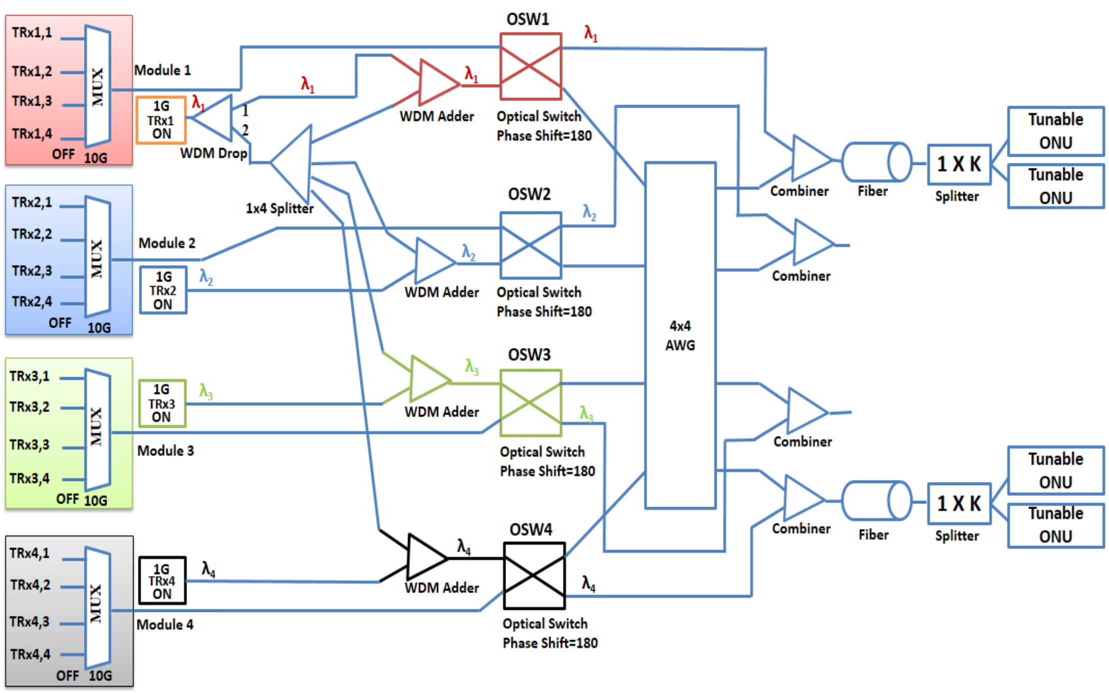

Fig. 5.8 Architecture operating at 1 G

If traffic load of some ODNs is higher and for others lower than the threshold, then for higher load ODNs, respective 10 G TRxs are turned ON while for low load ODNs, respective 1 G TRxs are turned ON and phase shift of optical switches is changed accordingly. To broadcast or transmit the same message signal to all the ONUs of all ODNs, a 1x4 power splitter is cascaded with one port of WDM drop filter. For normal case or point to point communication, the wavelength of WDM drop filter is kept anything other than the transmitted wavelength so that transmitted wavelength can directly reach to optical switch like other wavelengths. While for broadcasting, the wavelength of WDM drop filter is kept exactly the wavelength on which signal is to be broadcasted.

This wavelength is dropped and goes to 1×4 power splitter which connects the transmitted signal to all four WDM adders and optical switches from where all the ODNs are directly connected. The phase shift of optical switches is kept 180 degree. This whole mechanism is depicted in Fig. 5.9.

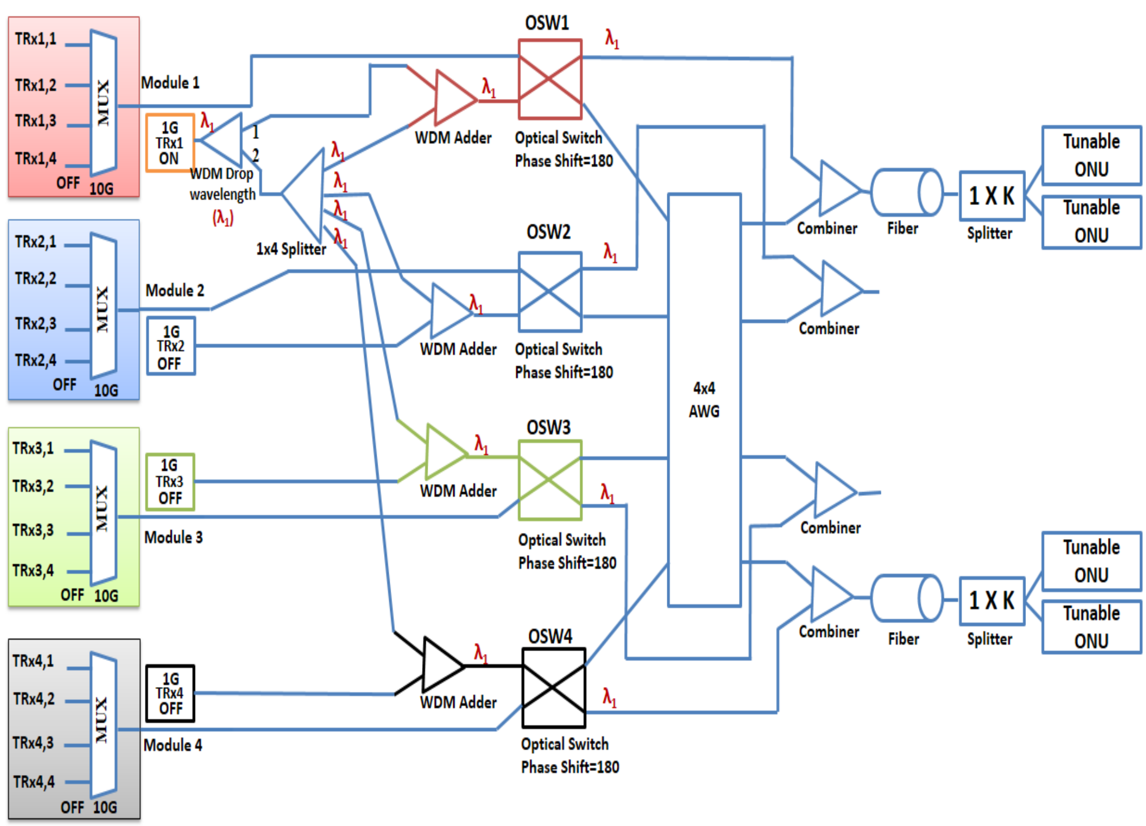

Fig. 5.9 Broadcasting at 1 G

This broadcasting mechanism reduces the need for transmitting the same message from each module and allows switching off other modules and reduces power consumption significantly. Upstream transmission for 1 G architectures can be achieved similarly as in the case of the10 G architectures discussed earlier.

5.5 Results and Discussions

To verify the performance of flexible hybrid WDM-TDM-PON network, proposed design (Fig 5.2) is simulated and verified with OptiSystem simulation tool. For fully operating network, each module is transmitting four 10 G wavelengths, and each wavelength is 100 GHz spaced apart. Starting wavelengths of module1, module2, module3 and module4 are 193.1 THz, 193.5 THz, 193.9 THz and 194.3 THz respectively. With 180-degree phase shift of each optical switch, all the wavelengths are transmitted through the AWG and are received at different ODNs as depicted in Fig. 5.10. When the network is underutilized, some of the TRxs may be switched off to save power, and thus respective wavelengths will disappear at ODN. In case of 1 G TRxs also, the 10 G TRxs are switched off and module1, module2, module3 and module4 are transmitting at 193.1 THz, 193.5 THz, 193.9 THz and 194.3 THz respectively. During broadcasting, 1 G TRx of module1 only is kept ON while all other TRxs are switched off.

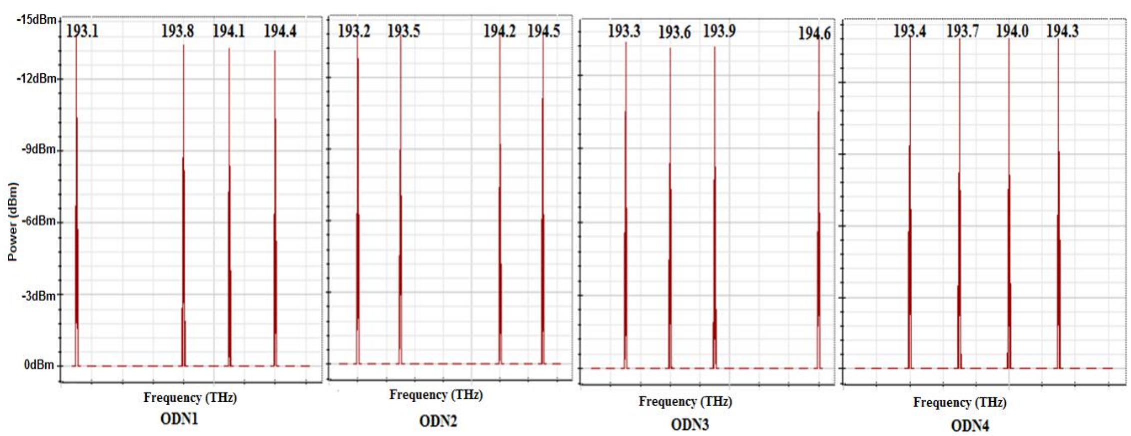

Fig. 5.10 Received wavelengths at different ODNs for symmetrical network

For providing up to 70 Gbps to the specific high load ODN, the phase shift of optical switch which belongs to that particular ODN is kept zero degree, therefore all four wavelengths coming from belonging module will be directed towards that ODN. Three wavelengths one from each of the other three modules are also coming from the AWG.

Thus that particular high load ODN is receiving total up to seven wavelengths each working at 10 Gbps. For example, if the ODN1 requires 70 Gbps data rate, the phase shift of optical switch belonging to the first module is kept zero degree as already discussed and shown in Fig. 5.6. ODN1 receives total seven wavelengths, all four from module1 and one each from other three modules. i.e. ODN1 is serving up to 70 Gbps, and other three ODNs are serving up to 30 Gbps as shown in Fig. 5.11.

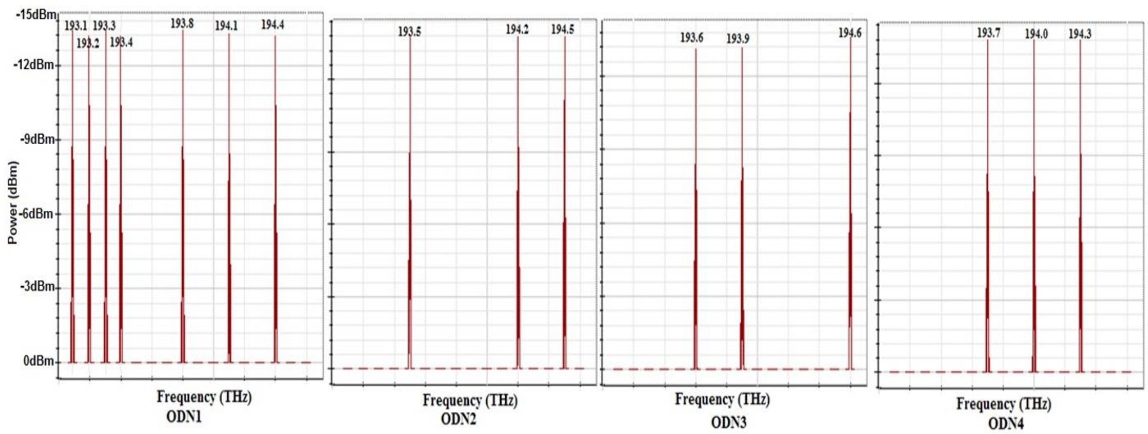

Fig. 5.11 Received wavelengths at different ODNs for asymmetrical network

To analyze the energy saving capability of proposed design (Fig 5.2), a representative traffic pattern of 24 hours for different ODNs is considered and depicted in Fig. 5.12. When each ODN is having traffic load below 10 Gbps, only module1 with all TRxs ON is sufficient to handle the load. Once load of particular ODN increases, a specific TRx of module2, which reaches to that particular ODN is turned ON and so on.

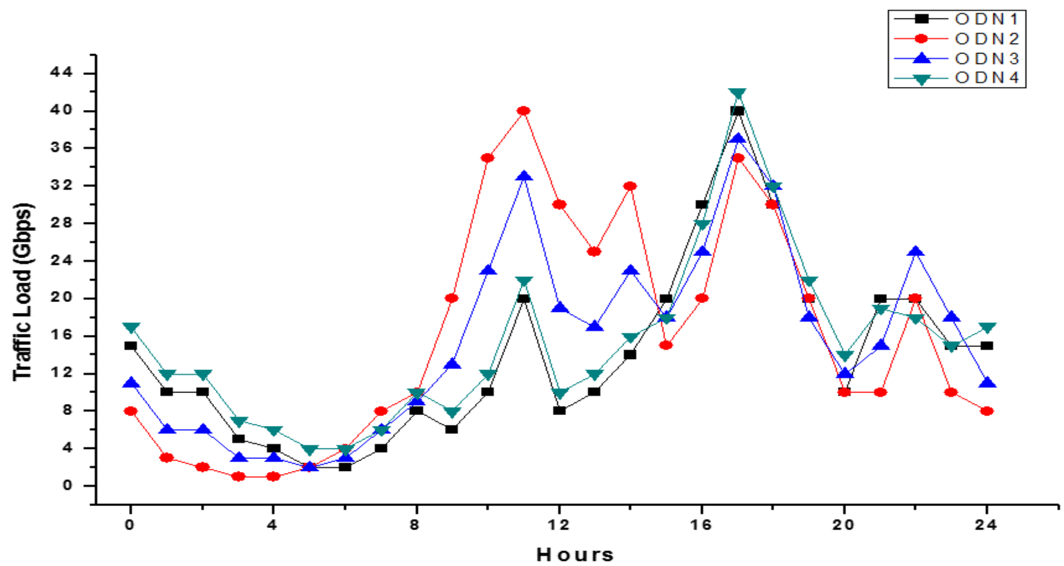

Fig. 5.12 Representative traffic pattern for different ODNs for 24 hours

If traffic load for all available ODNs in the network increases, then complete module with all its TRxs is turned ON. For load up to 10 G, only one module is switched ON and as load increases 10 G then another module is switched ON and so on as shown in Fig. 5.13. This diagram indicates the switching ON the complete Module.

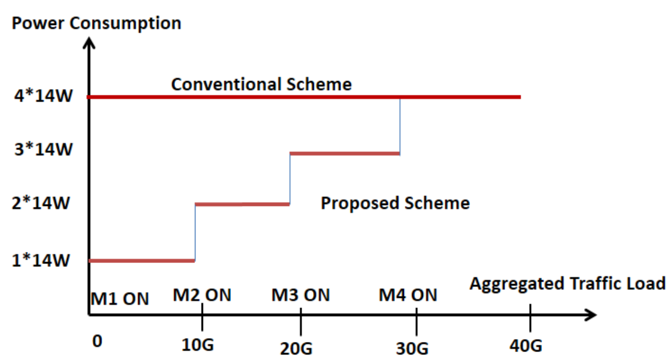

Fig. 5.13 Module switching ON with aggregated traffic load

However, for an unevenly distributed load for the ODNs, a particular TRx of a free module may be turned ON to handle the increased traffic load of a specific ODN. Complete pay-as-you-grow matrix is given in Table.5.1.

Table.5.1: Pay-as-you-grow matrix with increasing traffic load

ODN	*Load*	*Module1*	*Module2*	*Module3*	*Module4*
ODN1	**Load<10G**	ON($\lambda_{1,1}$)	OFF	OFF	OFF
	10<Load<20	ON($\lambda_{1,1}$)	ON($\lambda_{2,4}$)	OFF	OFF
	20<Load<30	ON($\lambda_{1,1}$)	ON($\lambda_{2,4}$)	ON($\lambda_{3,3}$)	OFF
	30<Load<40	ON($\lambda_{1,1}$)	ON($\lambda_{2,4}$)	ON($\lambda_{3,3}$)	ON($\lambda_{4,2}$)
ODN2	**Load<10G**	ON($\lambda_{1,2}$)	OFF	OFF	OFF
	10<Load<20	ON($\lambda_{1,2}$)	ON($\lambda_{2,1}$)	OFF	OFF
	20<Load<30	ON($\lambda_{1,2}$)	ON($\lambda_{2,1}$)	ON($\lambda_{3,4}$)	OFF
	30<Load<40	ON($\lambda_{1,2}$)	ON($\lambda_{2,1}$)	ON($\lambda_{3,4}$)	ON($\lambda_{4,3}$)
ODN3	**Load<10G**	ON($\lambda_{1,3}$)	OFF	OFF	OFF
	10<Load<20	ON($\lambda_{1,3}$)	ON($\lambda_{2,2}$)	OFF	OFF
	20<Load<30	ON($\lambda_{1,3}$)	ON($\lambda_{2,2}$)	ON($\lambda_{3,1}$)	OFF
	30<Load<40	ON($\lambda_{1,3}$)	ON($\lambda_{2,2}$)	ON($\lambda_{3,1}$)	ON($\lambda_{4,4}$)
ODN4	**Load<10G**	ON($\lambda_{1,4}$)	OFF	OFF	OFF
	10<Load<20	ON($\lambda_{1,4}$)	ON($\lambda_{2,3}$)	OFF	OFF
	20<Load<30	ON($\lambda_{1,4}$)	ON($\lambda_{2,3}$)	ON($\lambda_{3,2}$)	OFF
	30<Load<40	ON($\lambda_{1,4}$)	ON($\lambda_{2,3}$)	ON($\lambda_{3,2}$)	ON($\lambda_{4,1}$)

For example, initially, let all four ODNs have individual traffic load up to 10 G and module1 with its all TRxs are handling the load. After some time, the traffic load of ODN4 increases beyond 10 G then this increased traffic can be handled by any of the free modules. This is possible by turning ON third transmitter of mudule2 ($\lambda_{3,2}$) or second transmitter of module3 ($\lambda_{2,3}$) or first transmitter of module4 ($\lambda_{4,1}$). Thus proposed architecture also provides the reliability against any module failure or transmitter failure as another alternative wavelength may continue service. By using this pay-as-you-grow approach, we observe the significant amount of energy saving.

Tab.5.2: Available TRx for particular ODN for different traffic load

ODN	***Load***	***Available TRx on Failure of Module1***		***Available TRx on Failure of Module2***		***Available TRx on Failure of Module3***		***Available TRx on Failure of Module4***		***Reliability***
		Failed	***Available***	***Failed***	***Available***	***Failed***	***Available***	***Failed***	***Available***	
ODN 1	**Load<10G**	$\lambda_{1,1}$	$\lambda_{2,4}$ or $\lambda_{3,3}$ or $\lambda_{4,2}$	$\lambda_{2,4}$	$\lambda_{1,1}$ or $\lambda_{3,3}$ or $\lambda_{4,2}$	$\lambda_{3,3}$	$\lambda_{1,1}$ or $\lambda_{2,4}$ or $\lambda_{4,2}$	$\lambda_{4,2}$	$\lambda_{1,1}$ or $\lambda_{2,4}$ or $\lambda_{3,3}$	300%
	10<Load<20	$\lambda_{1,1}$	$\lambda_{3,3}$ or $\lambda_{4,2}$	$\lambda_{2,4}$	$\lambda_{3,3}$ or $\lambda_{4,2}$	$\lambda_{3,3}$	$\lambda_{2,4}$ or $\lambda_{4,2}$	$\lambda_{4,2}$	$\lambda_{2,4}$ or $\lambda_{3,3}$	200%
	20<Load<30	$\lambda_{1,1}$	$\lambda_{4,2}$	$\lambda_{2,4}$	$\lambda_{4,2}$	$\lambda_{3,3}$	$\lambda_{4,2}$	$\lambda_{4,2}$	$\lambda_{3,3}$	100%
	30<Load<40	$\lambda_{1,1}$	No free TRx	$\lambda_{2,4}$	No free TRx	$\lambda_{3,3}$	No free TRx	$\lambda_{4,2}$	No free TRx	No-Reliability
ODN 2	**Load<10G**	$\lambda_{1,2}$	$\lambda_{2,1}$ or $\lambda_{3,4}$ or $\lambda_{4,3}$	$\lambda_{2,1}$	$\lambda_{1,2}$,or $\lambda_{3,4}$ or $\lambda_{4,3}$	$\lambda_{3,4}$	$\lambda_{1,2}$,or $\lambda_{2,1}$ or $\lambda_{4,3}$	$\lambda_{4,3}$	$\lambda_{1,2}$,or $\lambda_{2,1}$ or $\lambda_{3,4}$	300%
	10<Load<20	$\lambda_{1,2}$	$\lambda_{3,4}$ or $\lambda_{4,3}$	$\lambda_{2,1}$	$\lambda_{3,4}$ or $\lambda_{4,3}$	$\lambda_{3,4}$	$\lambda_{2,1}$ or $\lambda_{4,3}$	$\lambda_{4,3}$	$\lambda_{2,1}$ or $\lambda_{3,4}$	200%
	20<Load<30	$\lambda_{1,2}$	$\lambda_{4,3}$	$\lambda_{2,1}$	$\lambda_{4,3}$	$\lambda_{3,4}$	$\lambda_{4,3}$	$\lambda_{4,3}$	$\lambda_{3,4}$	100%
	30<Load<40	$\lambda_{1,2}$	No free TRx	$\lambda_{2,1}$	No free TRx	$\lambda_{3,4}$	No free TRx	$\lambda_{4,3}$	No free TRx	No-Reliability
ODN 3	**Load<10G**	$\lambda_{1,3}$	$\lambda_{2,2}$ or $\lambda_{3,1}$ or $\lambda_{4,4}$	$\lambda_{2,2}$	$\lambda_{1,3}$ or $\lambda_{3,1}$ or $\lambda_{4,4}$	$\lambda_{3,1}$	$\lambda_{1,3}$ or $\lambda_{2,2}$ or $\lambda_{4,4}$	$\lambda_{4,4}$	$\lambda_{1,3}$ or $\lambda_{2,2}$ or $\lambda_{3,1}$)	300%
	10<Load<20	$\lambda_{1,3}$	$\lambda_{3,1}$ or $\lambda_{4,4}$	$\lambda_{2,2}$	$\lambda_{3,1}$ or $\lambda_{4,4}$	$\lambda_{3,1}$	$\lambda_{2,2}$ or $\lambda_{4,4}$	$\lambda_{4,4}$	$\lambda_{2,2}$ or $\lambda_{3,1}$	200%
	20<Load<30	$\lambda_{1,3}$	$\lambda_{4,4}$	$\lambda_{2,2}$	$\lambda_{4,4}$	$\lambda_{3,1}$	$\lambda_{4,4}$	$\lambda_{4,4}$	$\lambda_{3,1}$	100%
	30<Load<40	$\lambda_{1,3}$	No free TRx	$\lambda_{2,2}$	No free TRx	$\lambda_{3,1}$	No free TRx	$\lambda_{4,4}$	No free TRx	No-Reliability
ODN 4	**Load<10G**	$\lambda_{1,4}$	$\lambda_{2,3}$ or $\lambda_{3,2}$ or $\lambda_{4,1}$	$\lambda_{2,3}$	$\lambda_{1,4}$ or $\lambda_{3,2}$ or $\lambda_{4,1}$	$\lambda_{3,2}$	$\lambda_{1,4}$ or $\lambda_{2,3}$ or $\lambda_{4,1}$	$\lambda_{4,1}$	$\lambda_{1,4}$ or $\lambda_{2,3}$ or $\lambda_{3,2}$	300%
	10<Load<20	$\lambda_{1,4}$	$\lambda_{3,2}$ or $\lambda_{4,1}$	$\lambda_{2,3}$	$\lambda_{3,2}$ or $\lambda_{4,1}$	$\lambda_{3,2}$	$\lambda_{2,3}$ or $\lambda_{4,1}$	$\lambda_{4,1}$	$\lambda_{2,3}$ or $\lambda_{3,2}$	200%
	20<Load<30	$\lambda_{1,4}$	$\lambda_{4,1}$	$\lambda_{2,3}$	$\lambda_{4,1}$	$\lambda_{3,2}$	$\lambda_{4,1}$	$\lambda_{4,1}$	$\lambda_{3,2}$	100%
	30<Load<40	$\lambda_{1,4}$	No free TRx	$\lambda_{2,3}$	No free TRx	$\lambda_{3,2}$	No free TRx	$\lambda_{4,1}$	No free TRx	No-Reliability

As in pay-as-you-grow model, for small traffic only few modules are used and other modules are free. These modules can be used for handling the traffic load in case of any module or transmitter failure. However, the reliability decreases with increasing traffic load because free modules or transmitters decreases with traffic. For example, If the load of ODN1 is less than 10G then services may be continued on wavelengths $\lambda_{2,4}$ or $\lambda_{3,3}$ or $\lambda_{4,2}$. Network has 300%, 200% and 100% reliability for load below 10 G, 20 G and 30 G respectively. For load greater than 30 G, no free transmitter is available, and thus network has limited reliability. The network is also reliable against the failure of module2 or module3 or module4. The complete list of available TRxs for all ODNs for different traffic load with its reliability is given in Table.5.2.

Energy saving by proposed design (Fig. 5.2) for an ODNs as compared to fully operating conventional scheme (Fig. 5.1) based architecture will be given by equation (5.1):

$$1-\frac{\sum_{n=1}^{4} n\times h_n \times P_{10G} + \sum_{S=1}^{4} S\times h_s \times P_{OSW}}{[N\times H\times P_{10G}]} \quad \text{.............................}(5.1)$$

where N and H represent the total number of TRx reaching to an ODN and total traffic duration respectively (considered equal to 4 and 24 hours respectively), n represents a particular number of working TRx at any instant; h_n is duration for which particular n number of TRx are ON. P_{10G} is the power consumed by each 10 G TRx and assumed to be 3.5 W [90]. P_{OSW} is the power consumed by the optical switch and which is 3 mW [121]. S is the number of used switches and h_s is duration for which particular S number of switches are used. Numerator of above expression indicates the energy consumed by the proposed architecture whereas the denominator indicates the energy consumed by a fully operating conventional architecture. Energy saving for different ODNs for assumed representative pattern in Fig. 5.12 is given in Fig. 5.14.

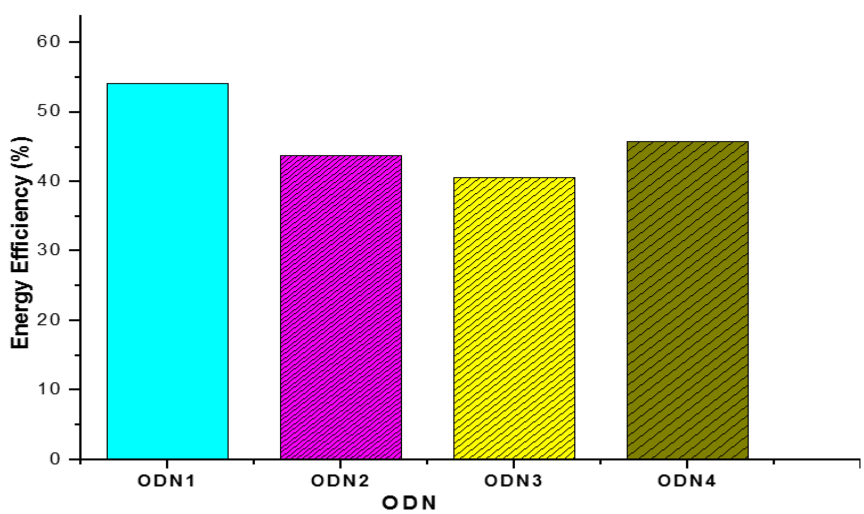

Fig. 5.14 Achieved energy efficiency for different ODNs for assumed pattern

While for overall system, energy saving for considered traffic pattern is given by equation (5.2):

$$1-\frac{\sum_{n=4}^{16} n\times h_{n}\times P_{10G}+\sum_{S=1}^{4} S\times h_{s}\times P_{OSW}}{[N\times H\times P_{10G}]} \quad \text{.............................}(5.2)$$

$$= 46.08\%$$

For the whole system, the total number of TRxs *N* will be 16 and minimum TRxs at any instant will be four and other parameters remain same. Numerator part indicates the energy consumed by the proposed architecture and denominator part indicates the energy consumed by a fully operating conventional architecture. The approximated energy saving for overall system for assumed representative pattern is 46.08%.

When the traffic load is at the minuscule level and supposed to be handled by 1 G TRxs. The representative pattern having minuscule load is given in Fig. 5.15. This traffic also has broadcasting data at different instants. Generally, all the 10 G TRxs are turned OFF, and all 1 G TRxs are turned ON and for broadcasting only 1 G TRx of module1 is kept ON, and other 1 G TRxs are turned OFF, which further reduces power consumption. Given traffic pattern consists of three broadcasting slots and are highlighted in circles.

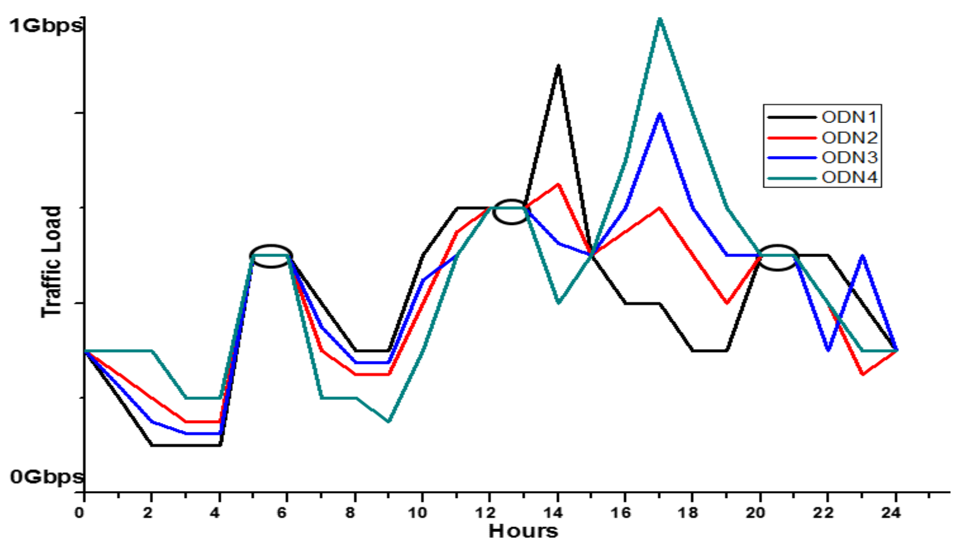

Fig. 5.15 Low traffic load with broadcasting slots

Energy saving by 1 G TRxs with broadcasting (Fig. 5.10) as compared to fully operating 1 G architecture (Fig. 5.1) is given by equation (5.3):

$$1-\frac{[N\times(h-h_b)\times P_{1G}+1\times h_b\times P_{1G}]+\sum_{S=1}^{4}S\times h_s\times P_{OSW}}{[N\times h\times P_{1G}]}\ldots\ldots\ldots\ldots\ldots(5.3)$$

$$=8.775\%$$

Where N is the total no of 1 G TRx (four in our case), h is the total duration of minuscule traffic, h_b is the duration for which data is to be broadcasted, P_{1G} represents power consumed by each 1 G TRx and which is assumed to be 0.5 W [90]. The numerator part indicates the energy consumed by the proposed architecture operating at 1 G with broadcasting and denominator part indicates the energy consumed by the fully operating architecture at 1 G without broadcasting. Due to the use of mixed broadcasting slots, the architecture further reduces the power consumption by 8.775 % for given traffic pattern as compared to normal architecture.

For the above-proposed architectures, OLT capital expenditure (CAPEX) is increased somewhat for installing the additional 1 G TRxs at each module, but the OPEX is reduced proportionately to the energy saving as at low traffic loads, one has to pay less bandwidth cost. The cost of Hilink 10 G TRx is approximate $320.00 while for Hilink 1 G TRx is approximate $86.00 [117]. Thus by installing additional one 1 G TRx in a module containing four 10 G TRx will increase the module CAPEX by 6.7 % approximately. From the service provider’s point of view, they need not worry about it as increased CAPEX and can easily be compensated by the reduced OPEX and may offer dynamic bandwidth to the costumers with high energy efficiency and reliability.

5.6 Summary

In this chapter, we discussed about our proposed flexible hybrid WDM-TDM PON system and demonstrated it for 40 Gbps capacity. It is also capable of supporting up to 70 Gbps asymmetric data rates by diverting the wavelengths to one particular network segment i.e. it supports wavelength allocation within different ONUs and different ODNs dynamically. It also supports pay-as-you-grow deployment to reduce the OPEX as well as power consumption. Efficient power mileage is achieved by installing dual rate TRxs. Reliability of the proposed design is achieved up to 300% by dynamically allocating the wavelength to the failed network segment until its recovery and verified by the simulation tool. The proposed design is capable of reducing power consumption significantly for the underutilized network. The system also supports broadcasting at 1 Gbps with simultaneous P2P transmission at 10 Gbps this further reduces the power consumption of the network. For considered traffic pattern proposed architecture saves up to 46.08% energy with pay-as-you-grow architecture as compared to conventional fully operating 10 G architecture. Mixed broadcasting slots at 1 G further reduce 8.775% energy consumption as compared to fully normal 1 G architecture. Finally, proposed architecture is flexible, reliable, bandwidth scalable and energy efficient to support next-generation optical access networks.

Chapter 6

6. Resilient, Bandwidth Scalable and Energy-Efficient Hybrid PON Architecture

This chapter presents another resilient, bandwidth scalable and energy efficient WDM-TDM PON architecture that provides network access services to the end user at very high data rates and reduces the power consumption of access network significantly in the presence of low traffic / underutilized network. The proposed power saving technique includes the efficient use of proper line cards (LC) and adaptive link rate (ALR) mechanism at OLT located at the central office. In the presence of low traffic, ALR switches the link rate from 10Gbps to 1Gbps depending on the particular threshold value of traffic load. In the presence of narrowband traffic, a significant amount of energy is saved. Proposed architecture also saves capital expenditure (CAPEX) at remote node and reduces significant CAPEX for larger networks. This architecture also provides network resiliency against LC/TRx or module failure and bandwidth scalability to support future generation PON architectures without any service interruption.

6.1 Introduction

The conventional hybrid WDM-TDM-PON system as shown in Fig. 6.1 is not energy efficient especially when network has low loads and its resources are not fully utilized. In the conventional hybrid WDM-TDM-PON system, the number of input ports of CO AWG (M) and output ports of remote node AWG (N) are equal. The routing property of AWG is based on the equation (6.1) [58].

$$j = 1 + \left(i - 1 + \left\lfloor \frac{f-1}{C} \right\rfloor \right) \bmod M \qquad (6.1)$$

$$i, j \in [1, M] \; and$$

$$f \in [1, \infty]$$

where *i*,*j* and *f* represent the input port, output port and wavelength number respectively, *M* is the size of AWG and *C* denotes the coarseness factor which represents the number of contiguous wavelengths passing at a time. In our case, the value of coarseness factor is unity hence equation (6.1) can be reduced to equation (6.2).

$$j = 1 + \left(i - 1 + (f - 1)\right) \bmod M \qquad (6.2)$$

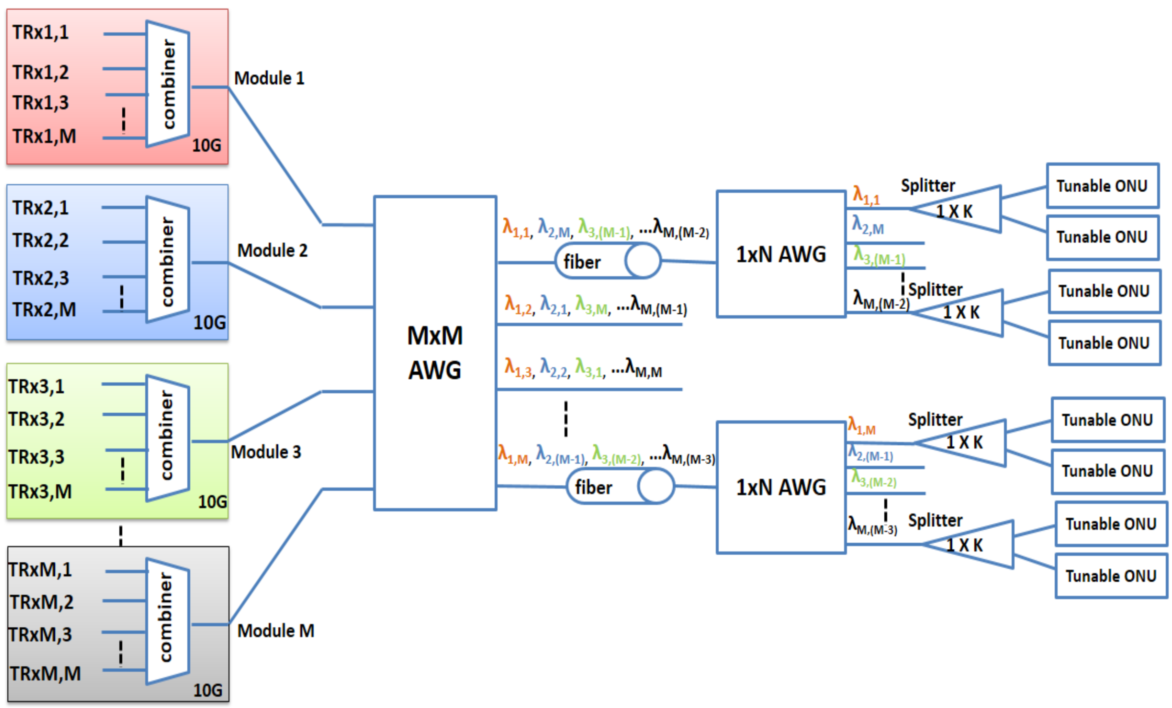

Fig. 6.1 Conventional hybrid WDM-TDM PON architecture

ALR and sleep mode hybrid mechanism have been already proposed to reduce the ONU power consumption in 10 Gbps Ethernet PON system [77]. In sleep mode, ONU switches its mode from active to sleep in the absence of traffic. In ALR mechanism, downlink rate between OLT and ONU switches from 10 Gbps to 1 Gbps when total traffic is below a certain threshold level [77]. For other type of networks also, such as hybrid fiber-coaxial (HFC) access networks, dual rate transmission may be utilized to reduce the energy consumption of the access networks [99-102]. In recent days, elastic optical networks (EON) are also being used to provide bandwidth segmentation, aggregation, traffic grooming and to provide variable data rates according to the network load [103-106] i.e.

spectrum utilization and energy efficiency can be improved by using EON. Energy efficiency of optical access network can also be achieved by using direct ONU interconnection techniques in which message of one is sent directly to another ONU without the intervention of the OLT.

Implementation of sleep mode at OLT is a challenging task, since the OLT sleep may discontinue communication with ONU and there may be a disruption in the service. To resolve the users' service disruption issue, a proper mechanism is needed. In this chapter, to save OLT power, we propose an architecture that utilizes the ALR mechanism for traffic below a certain threshold. For this, we have considered the power consumption of each 10 Gbps and 1 Gbps OLT line card (LC) approximately 3.5 W and 0.5 W respectively [90]. As network traffic is random in nature, instead using 10 Gbps line card all the time, 1 Gbps line cards are used whenever possible in order to reduce the power consumption. ALR may be based on Module switching or LC switching as discussed in the next section.

6.2 Module and Line Card Switching

Module Switching: By considering the power consumption of each 10 G LC and 1 G LC as 3.5 W and 0.5 W respectively, total power consumed by LCs in each module is calculated. Switching mechanism for module having M number of LCs is shown in Fig. 6.2. Total power consumed by each module depends on the M number of LCs inside the module and power consumed by the TRx. Fig. 6.2 shows the power consumed by LCs inside the module.

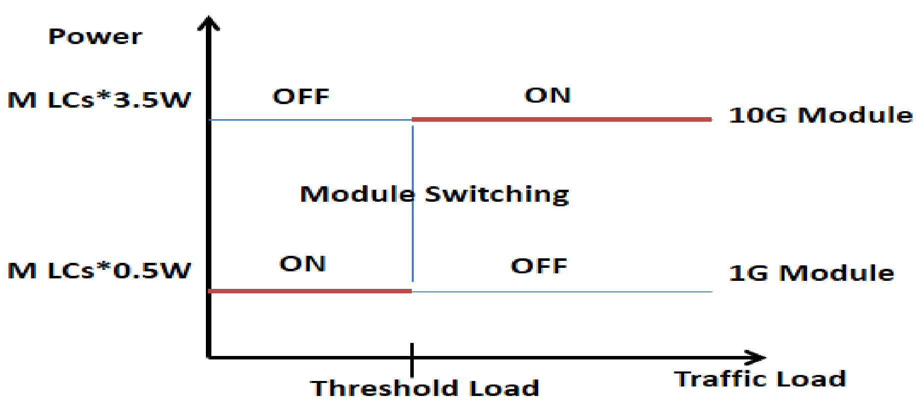

Fig. 6.2 Module switching

LC Switching: For some specific cases such as any LC/TRx failure or bandwidth scalability of any particular ONU, switching of specific LC with its TRx may be preferred instead of complete module switching. Power consumption due to LCs and their switching is given in Fig. 6.3.

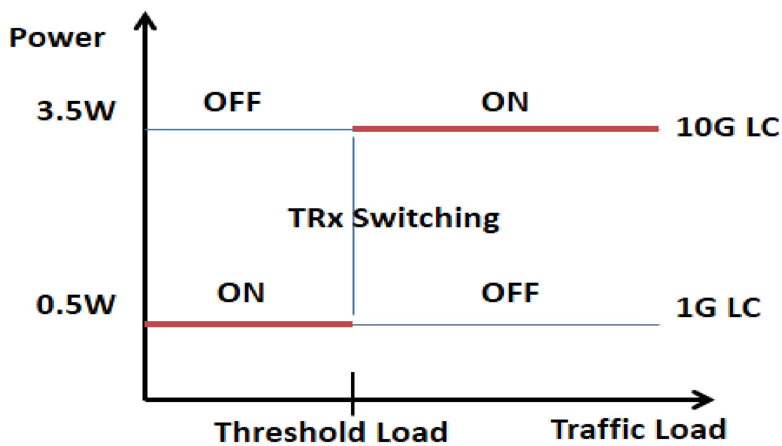

Fig. 6.3 LC switching

6.3 Proposed Hybrid WDM-TDM PON Architecture and Its Working

To make the conventional hybrid WDM-TDM PON system shown in Fig. 6.1 energy efficient, we propose an architecture as depicted in Fig. 6.4. This architecture uses an M×M cyclic AWG at the central office (CO AWG) and 1×N AWGs at remote node (RN AWG). Basic difference between conventional architecture and proposed architecture is the number of output ports of both the AWGs. In conventional architecture, number of output ports of central office AWG and remote node AWGs are equal (M=N), and OLT of this architecture transmits the fixed and dedicated wavelength to each PON branch i.e. in conventional architecture, a particular wavelength is transmitted regardless the traffic load. When network is underutilized, OLT resources are also not utilized efficiently and each transmitter of each module has to keep switched ON for providing the service to end user. Whereas in our proposed architecture in Fig. 6.4, the number of output ports of remote node AWGs are kept half as compared to central office AWG (M=2N). OLT at central office consists of M modules and M^2 line cards and M^2 transceivers. Out of M modules, half (N or M/2) modules are designed to support broadband traffic (10 G-LCs) while remaining half (M-N) for narrowband traffic (1 G-LCs). Due to the cyclic property of AWG, each ONU is receiving M/2 wavelengths out of which half are broadband and half are narrowband.

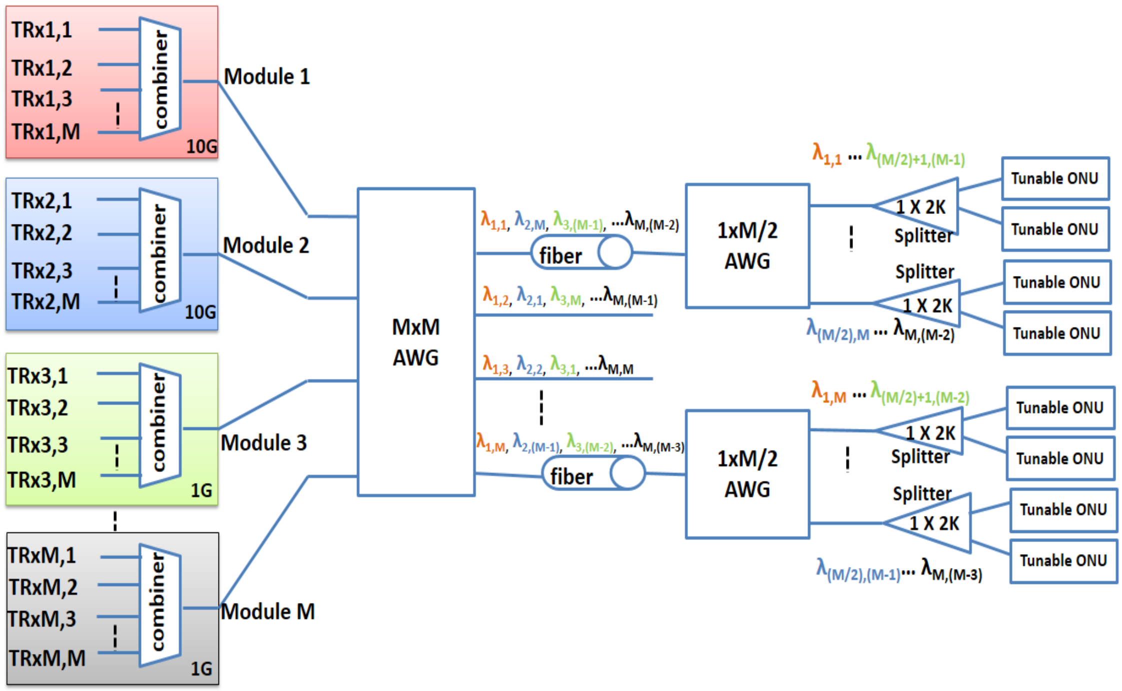

Fig. 6.4 Proposed hybrid WDM-TDM PON architecture (M=2N)

Each ONU is designed with 1 G and 10 G dual rate wavelength tunable transceiver. When OLT has high data rate downstream signal to transmit, each 10G module transmits M wavelengths $\lambda_{M,1}$, $\lambda_{M,2}$, $\lambda_{M,3}$,…$\lambda_{M,M}$ where subscripts M,M indicate the respective module and respective transceiver respectively. For simulation purpose, we have assumed the value of M as four as shown in Fig. 6.5.

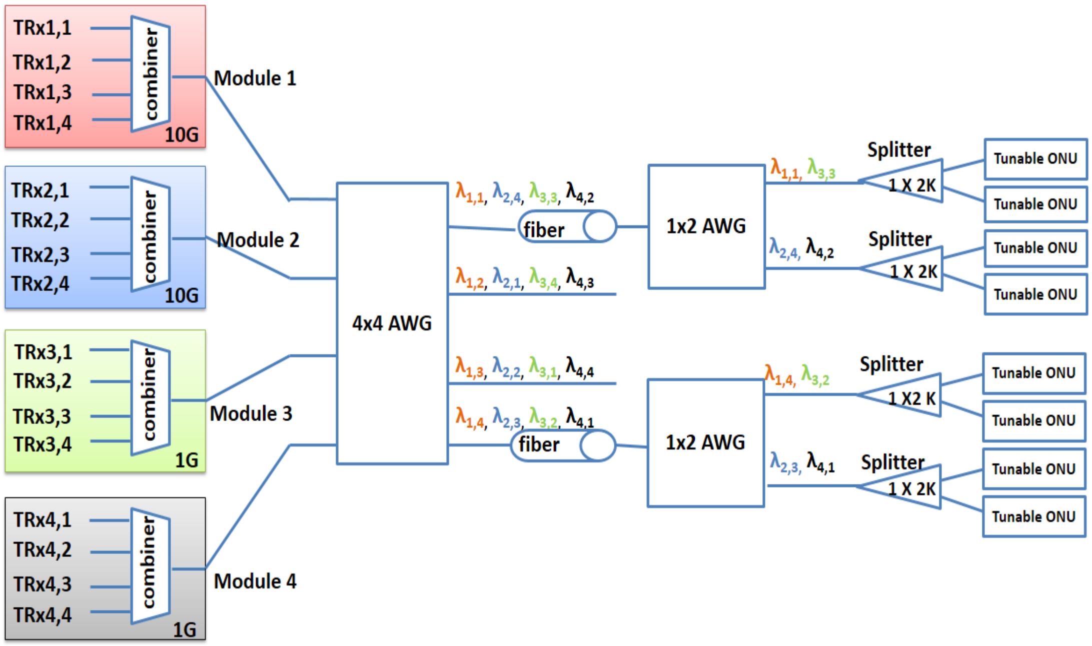

Fig. 6.5 Proposed hybrid WDM-TDM PON architecture (M=4)

Each one of these wavelengths has to serve one PON branch consisting 2K (here, 8) ONUs with the help of 1×2K (here, 1×8) power splitter, where 2K is the number of output ports of power splitter. Now all the ONUs may be served by only 10 G modules and switching off all 1 G modules to save power as shown in Fig. 6.6(a).

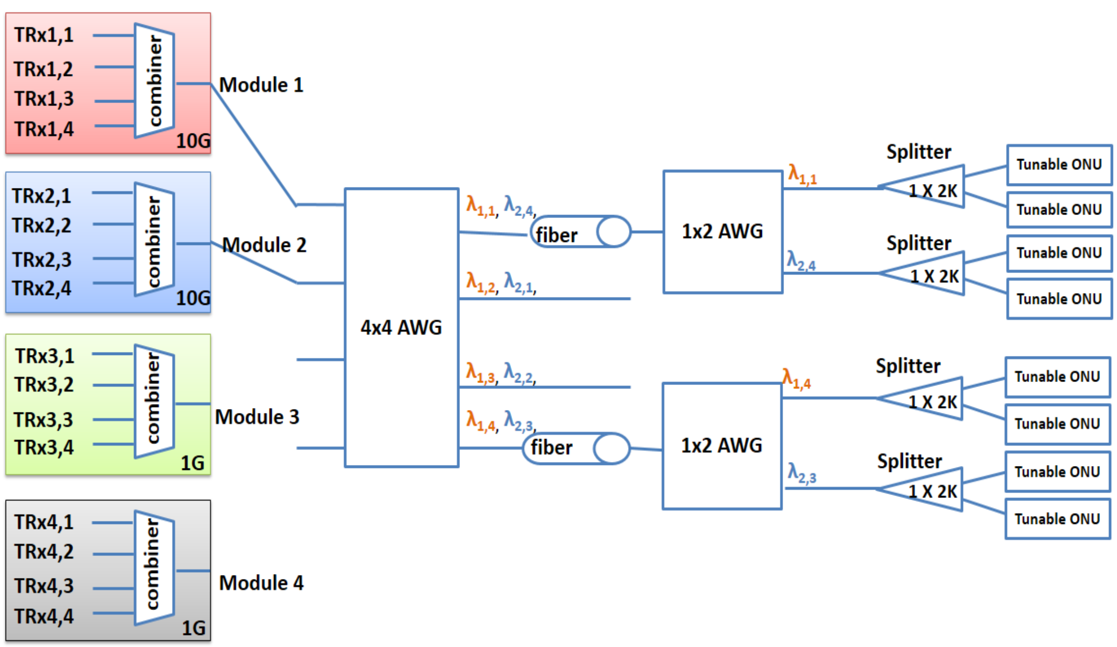

Fig. 6.6(a) Proposed WDM-TDM PON architecture working at 10 Gbps

Supported ONUs may be increased by improving the power budget or by using amplifiers. Tunable ONUs may increase a little bit cost, but as it may receive any wavelength available in the network therefore simultaneously it is providing energy efficiency, resiliency and bandwidth scalability and these factors cannot be ignored. Capital expenditure at the remote node is also reduced significantly and explained in later part of this section.

On the other hand, when OLT has low data rate downstream signal, all 1 G modules transmit another set of four wavelengths, and all 10 G modules are switched off as shown in Fig. 6.6(b). By transmitting low data rates, bandwidth and energy consumption can be saved significantly. The link rate diagram for different modules is shown in Fig. 6.7.

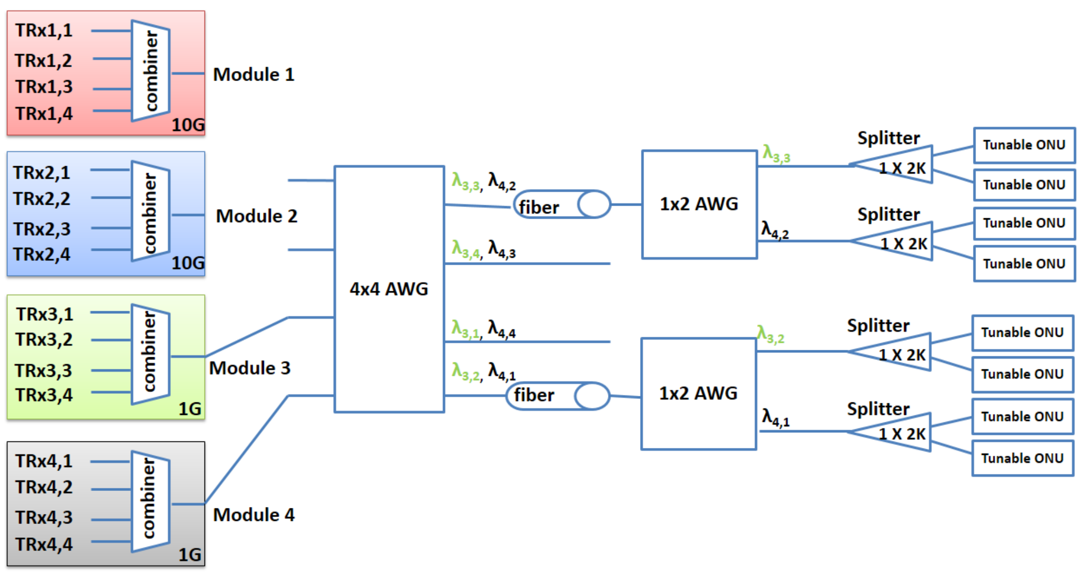

Fig. 6.6(b) Proposed WDM-TDM PON architectures working at 1 Gbps

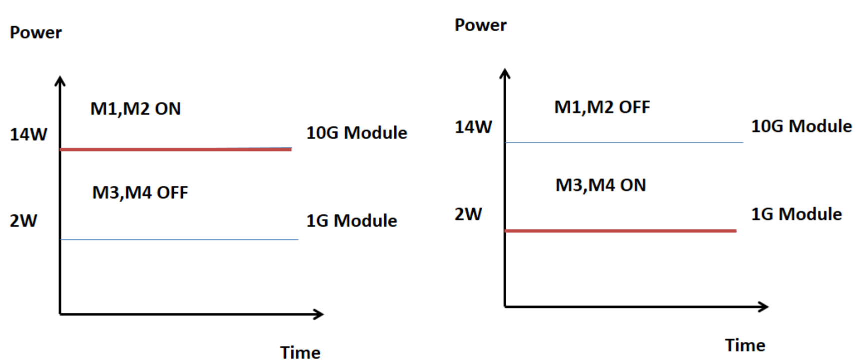

Fig. 6.7 Link rate diagram for different modules working at 10 Gbps and 1 Gbps

In this way, our architecture utilizes the advantages of both switching off idle elements and adaptive link rate control. Switching off idle elements reduces the energy consumption in the absence of traffic while ALR saves power in the presence of low traffic. This unique feature (flexibility to transmit wavelengths according to traffic) of our proposed architecture makes it more energy efficient than conventional architecture. Another important feature of proposed architecture is that it utilizes only half the number of output ports at remote node AWGs as compared to conventional architecture at the cost of marginal power penalty. This is done by doubling the number of output ports of power splitter at distribution network which reduces the significant amount of CAPEX as the associated cost with AWG is given by $500+70*\log_2(X)$ while for power splitter it is approximately $200+50*\log_2(X)$ [47].

6.4 Results and Discussions

Resiliency and Bandwidth Scalability are the main important features of proposed architecture; it provides resiliency in case of any module or transmitter failure. Each PON branch can receive two wavelengths in the proposed architecture, one at 10 Gbps and another at 1 Gbps. In case of any wavelength failure, service may be continued just by switching the downstream traffic on an alternative wavelength. Wavelength failure may be due to the failure of respective module or LC or TRx. Although the transmission speed may be affected but it can surely avoid service disruption until failed module or failed transmitter is recovered. Fig. 6.8 shows resiliency against module failure.

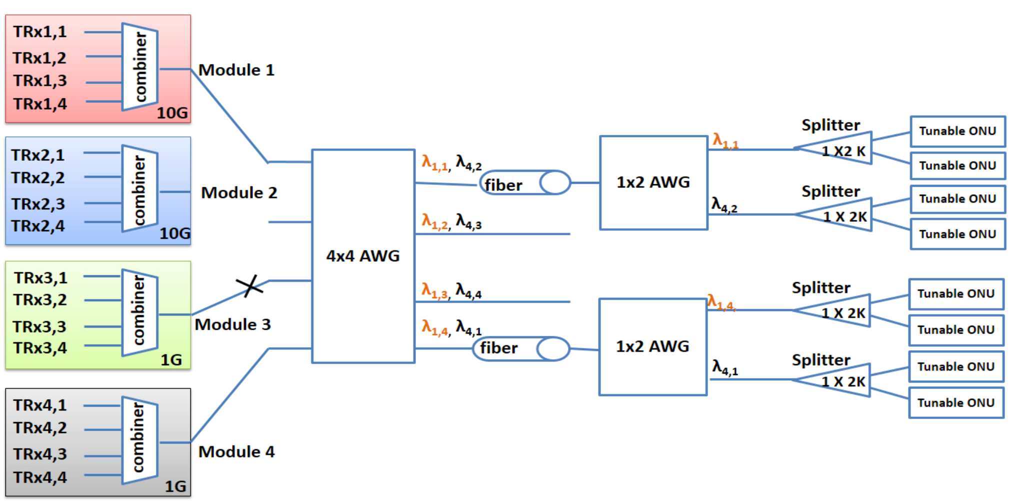

Fig. 6.8 Protection against module failure

Initially, network is working at 1 Gbps with two working modules, module 3 (M3) and module 4 (M4). If at any instant M3 fails, the load of M3 is diverted on M1. Similarly, this can also be used when M1 and M2 are working and at any instant M2 fails then its load is handed over to M4. Switching mechanism is shown in Fig. 6.9.

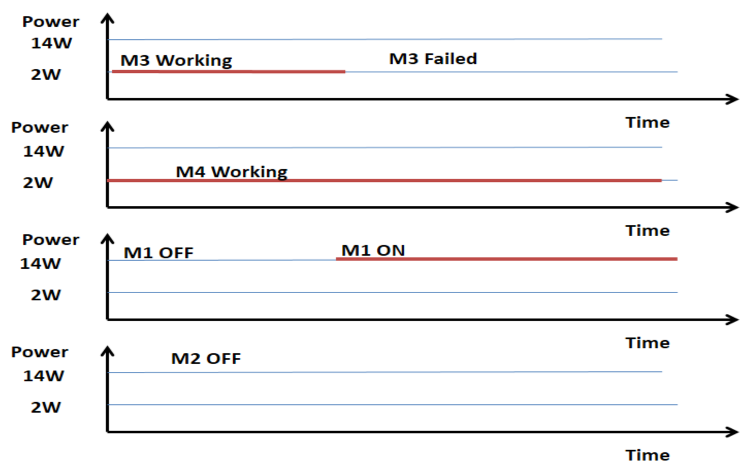

Fig. 6.9 Switching ON of module M1 on failure of module M3

Proposed architecture is also resilient against any transceivers (TRx) failure instead of complete modules as shown in Fig. 6.10.

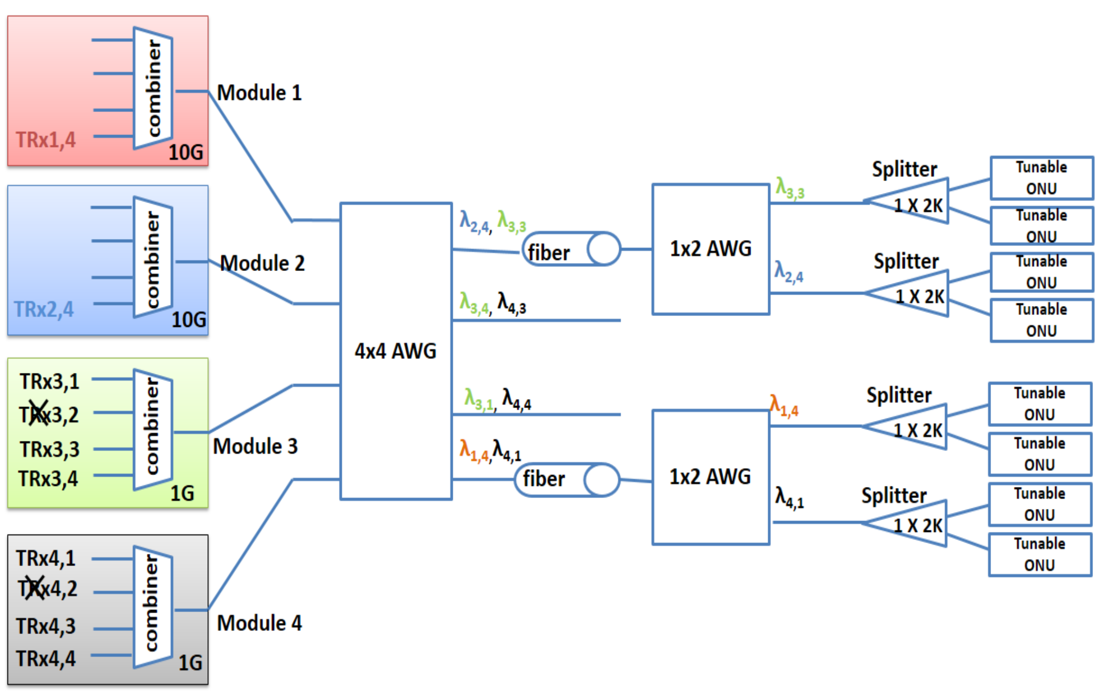

Fig. 6.10 Protection against transceiver failure

Suppose initially M3 and M4 are working, and that at particular instant TRx3,2 of module 3 and TRx4,2 of module 4 fail. In such a case, to avoid service disruption, TRx1,4 of module 1 and TRx2,4 of module 2 are switched ON immediately. By switching idle TRx or module, proposed architecture is also capable of providing bandwidth scalability. Bandwidth scalability means to provide more bandwidth to a particular PON branch whenever bandwidth demand increases on that PON branch. According to the network segment for which bandwidth has to scale, an appropriate TRx is switched ON to provide more bandwidth.

To evaluate the performance of our proposed architecture, it is simulated by using simulation tool OptiSystem 13.0. Insertion losses of AWGs of both stages (central office as well as remote node) are considered approximately 5 dB, while for power splitter we considered standard insertion loss as 3.5 $\log_2(K)$, where K is the number of output ports of power splitter. For single mode fiber (SMF) of length 20 km, 0.2 dB/km standard fiber losses are being considered. BER versus input optical power is depicted in Fig. 6.11.

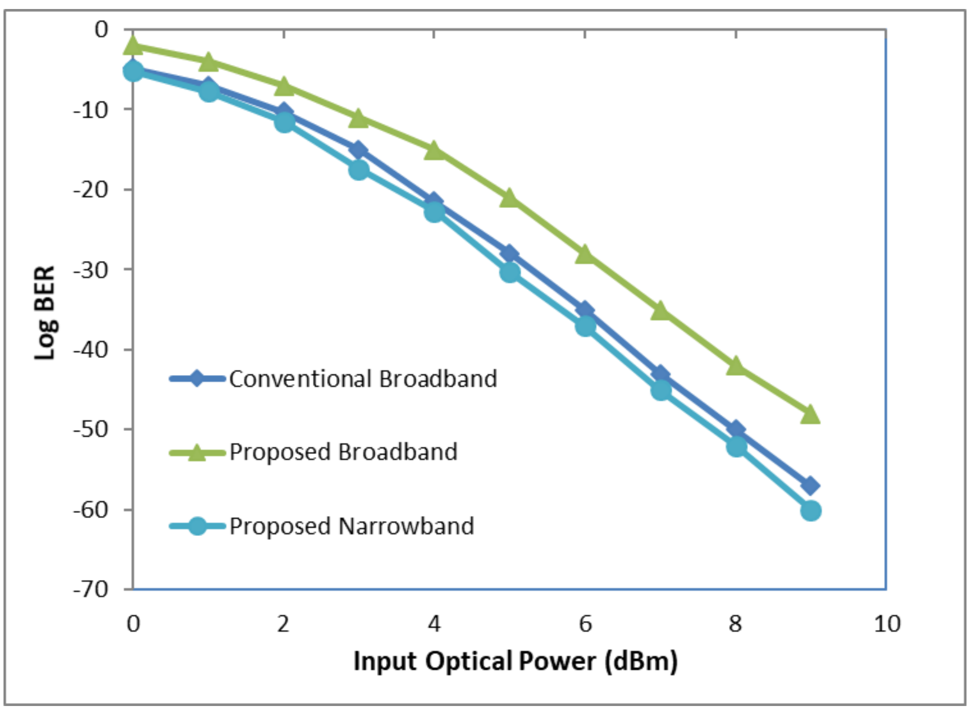

Fig. 6.11 Bit error rates versus input optical power (dBm)

Transmission of broadband signal requires comparatively more input power than narrowband transmission for achieving same BER at receiver. For Log (BER) of -9;

required input power for conventional broadband, proposed broadband and proposed narrowband are 1 dBm (or 1.25 mW), 4 dBm (or 2.5 mW) and 1 dBm (or 1.25 mW) respectively. Proposed broadband require 3dB more power due to the doubling of splitting ratio.

However, total power consumption of the proposed architectures decreases as only the half OLT resources (module/LCs) are used. Total power consumption in the network depends on the used Module/LCs and power required to drive the TRx.

For calculating the efficiency and power saving capability of the proposed architecture, we have considered the representative traffic pattern as shown in Fig. 6.12. This pattern indicates the network traffic load for 48 hours duration which is random in nature.

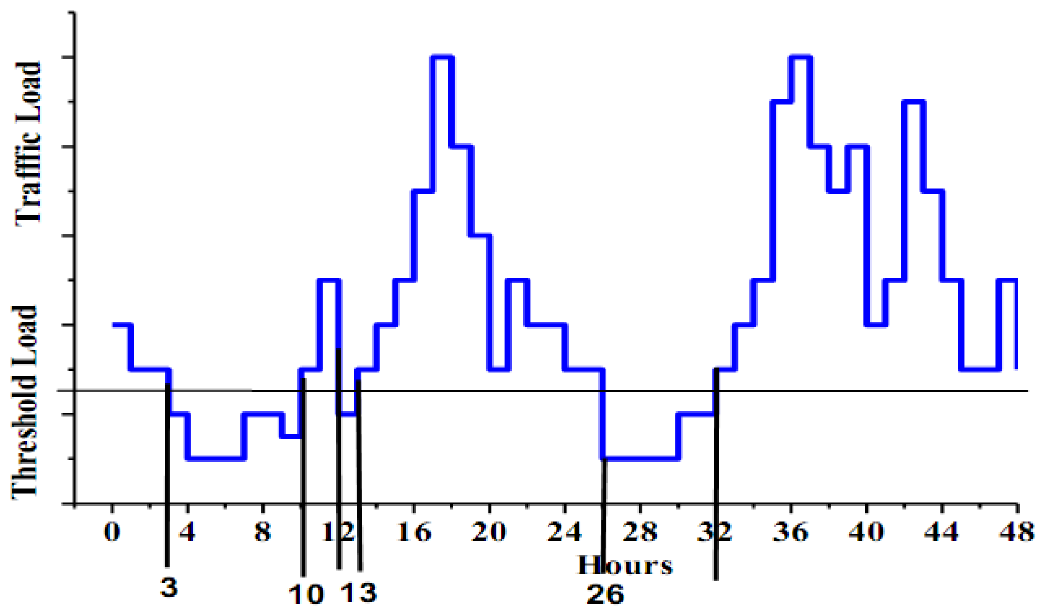

Fig. 6.12 Representative 48 hour traffic pattern

- Period for which traffic load is below threshold level: (10-3) + (13-12) + (32-26) = 14 Hours
- Period for which traffic load is above threshold level: (3-0) + (12-10) + (26-13) + (48-32) = 34 Hours.

Energy consumption ratio (E.C.R.) of proposed architecture (Fig. 6.4) to conventional architecture (Fig. 6.1) will be given by equation (6.3)

$$E.C.R. = \frac{\begin{array}{c}\text{[No. of working 1 G LCs* (power consumed by each 1 G LC+ power consumed by each 1 G TRx) * time duration] +} \\ \text{[No. of working 10 G LCs* (power consumed by each 10 G LC+ power consumed by each 10 G TRx) * time duration]}\end{array}}{\text{[Total no. of working 10 G LCs* (power consumed by each 10 G LC+ power consumed by each 10 G TRx) *total time duration]}} \quad ..(6.3)$$

Percentage energy saving in proposed architecture (Fig 6.4) as compared to conventional architecture (Fig 6.1) will be given by equation (6.4)

Energy saving (%)= [1- E.C.R.] ……………………………………..………..(6.4)

$$1 - \frac{[8*(0.5\,\text{W}+1.25\,\text{mW})*14\,\text{Hours}]+[8*(3.5\,\text{W}+2.5\,\text{mW})*34\,\text{Hours}]}{[16*(3.5\,\text{W}+2.5\,\text{mW})*48\,\text{Hours}]} = 62.5\%$$

Thus the total energy saving of proposed architecture is 62.5%. For low traffic load, a significant amount of energy is saved and this energy saving capability may change according to the assumed different traffic patterns. Cost saving at remote node is given by equation (6.5):

$$1 - \frac{[(\text{No. of RN AWG*Cost of 2 port AWG in \$}) + (\text{No. of 1 X 2K splitter*Cost of each splitter in \$})]}{[(\text{No. of RN AWG*Cost of 4 port AWG in \$}) + (\text{No. of 1 X K splitter*Cost of each splitter in \$})]} \quad ....(6.5)$$

By calculating the cost of AWG and Power splitter from 500+70*$\log_2$(X)$ and 200+50*$\log_2$(X)$ respectively, the cost of 4 port AWG is 640$ and for 2 port AWG is 570$. While for 4 port power splitter cost is 300$ and for 8 ports is 350$. For our proposed architecture the cost saving as compared to the conventional architecture is approximately 20.75%. The cost efficiency may significantly reduce the CAPEX for larger networks.

$$\text{Cost saving at remote node} = 1 - \frac{[(16*570\$)+(8*350\$)]}{[(16*640\$)+(16*300\$)]} = 20.75\%$$

6.5 Summary

In this chapter, we discussed our proposed architecture which allows transmitting of broadband and narrowband signals simultaneously. Broadband sources (10 G) are used only in presence of broadband traffic having traffic load above a certain threshold level otherwise narrowband sources are used to save power. This architecture continues to work even in case of Module/ LC/ TRx failure i.e. proposed architecture provides network resiliency against Module/ LC/ TRx failure. Proposed network is also able to provide bandwidth scalability to support future generation optical networks. At remote node, resource sharing is also improved to reduce CAPEX to help network operators. For the considered representative traffic pattern, proposed architecture reduces the central office power consumption and remote node CAPEX up to 62.5% and 20.75% respectively. Feasibility and performance of the proposed architecture have been verified with the simulation results.

Chapter 7

7. Direct Inter-ONU Communication Schemes in Passive Optical Network

This chapter reviews various direct inter-ONU communication techniques which reduces the transmission latencies among ONUs. After that we discuss our proposed two remote node stage based flexible architecture which is capable of communicating with all ONUs available in the network and/or ONUs located within a subgroup or within an optical distribution network (ODN). As per the need, data from one ONU is transmitted to the other ONUs just by tuning the transmission wavelength. Later part of the chapter discuss our proposed energy–efficient and latency-aware WDM-PON network with ONU interconnection capability. This architecture transmits simultaneous dedicated point to point (P2P) and broadcasted downstream transmission. This also allows simultaneous upstream and inter-ONU signal transmission. It provides the efficient bandwidth utilization, bandwidth scalability, and network extensibility and low latency for inter-ONU communication to support the future optical networks.

7.1 Introduction

In PONs, downstream data is sent from OLT located at the central office CO to ONUs located at the user end, and upstream data is sent from ONUs to OLT [83], [84]. To support the ever increasing bandwidth demand, downstream and upstream bandwidth must be improved. This can be done either by increasing the bandwidth or by utilizing the available bandwidth efficiently. Downstream signal may be transmitted for dedicated point to point (P2P) and broadcasting transmission depending upon the used application or demanded bandwidth. Dedicated P2P transmission provides the high bandwidth up to several Gbps to each user. However, cost of WDM system is high because dedicated transmitter is required for each user regardless of the traffic load [29]. Broadcasting provides the best resource utilization and reduces the requirement of transmitting the same signal from multiple transmitters and thus reduces the OPEX.

In a case where any ONU wants to communicate with another ONU, conventionally it needs to first send the message to OLT with upstream signal and then OLT re-routes, re-modulates and sends back to the target ONU with downstream signal [42], [46]. These inter-ONU signals occupy some fraction of both upstream as well as downstream bandwidth and impose extra fiber latency to the system [122], which may not be desirable for many applications like financial or stock exchange etc. This conventional transmission mechanism also incurs additional cost and consumes additional energy for transmitting inter-ONU signal from ONU to OLT and vice-versa. Such architecture enhances the additional burden on transceivers at both ONU and OLT, and also requires unnecessary complex buffering and scheduling algorithms at OLT. Various applications such as local community networking, networking with neighbors, telemedicine, teleconferencing, shared online games, multimedia stream sharing etc. [123] require frequent communication among them, and conventional transmission scheme is not preferred due to above said problems. ONU direct interconnection mechanism can resolve aforementioned problems by redirecting the ONU's interconnection signal from remote node (RN) towards ONU. Direct ONUs interconnection also provides a higher level of security than the conventional transmission mechanism because direct inter-ONU signal is not received at OLT. Nowadays, many private universities and enterprises have started the installation of local area networks (LANs) to share the message to its peers locally.

Various direct interconnection schemes for WDM-PON have been reported previously. For the interconnection of ONUs, downstream signal is remodulated at ONU and send directly to the other ONU to save the bandwidth. In [122], interconnection of ONUs has been explained for two different cases: broadcasting and virtual private group (VPG). For broadcasting, data of each ONU is transmitted to all other ONUs by using AWG and splitter at the remote node (RN) while in VPG, a virtual group of various ONUs is formed and data is shared among that group only. For accomplishing VPG, a specific code is multiplexed with a RF tone and that same RF tone is used to decode the signal at each receiver. Several such VPGs can be simultaneously supported by WDM-PON [122]. To form ONU-VPGs, one can utilize any one of the following three techniques: electronic code division multiple access (E-CDMA) [124], subcarrier multiplexing

(SCM) [125] and reflected waveband grouping [126] technique. An efficient method of optical star designed ring based PON network using N×N AWG is employed [127]. This architecture is capable of bypassing any ring node either in case of node failure or cut in the cable which connects the two ports of AWG. Reflective semiconductor optical amplifier (RSOA) based upstream transmission and neighboring ONU interconnection is proposed in [128]. In this, wavelength seeding of RSOA is done by two fiber Bragg gratings (FBG) having different Bragg wavelengths and avoids the need of external seeding of sources for switching the wavelength. Reflected wavelength of one FBG is used for upstream transmission and that of another FBG is used for neighboring ONU [128]. By using AWG at the remote node, and launching it with the tunable source from one ONU may also provide the intercommunication with another ONU. Due to the cyclic property of AWG, as launched wavelength changes, output port of AWG also changes which is connected to the particular ONU. By selecting the launched wavelength appropriately, destined AWG port changes thus changing the destined ONU. This architecture works in ring nature and does not provide broadcasting [129].

Remote node FBG based ONU interconnection in time division multiplexed (TDM) PON is proposed in [130]. In this architecture, one FBG is cascaded with the splitter to transmit the signal in the downstream direction and reflect the signal in the upstream direction. The main purpose of FBG is to reflect a particular wavelength (equal to the Bragg wavelength) while transmitting all other wavelengths. Downstream/ upstream wavelengths are transmitted through the FBG, while Bragg wavelength at which ONU interconnection to be done is reflected. This reflected wavelength is broadcasted by the optical splitter and received by all ONUs. For higher ONUs/splitting ratio, system power budget becomes the challenging issue as inter-ONU signal suffers twice the insertion losses i.e. in the backward and forward direction [130]. The approximated insertion loss of power splitter is given by $3.5\text{Log}_2(n)$, where n denotes the splitting ratio. We proposed two stage remote node based ONU interconnection in which provides ONU interconnection within a group of nearby located ONUs or overall ONUs in the system. Each remote node consists an FBG followed by an optical splitter. Bragg wavelengths of first stage FBG and second stage FBG are different. For overall ONU intercommunication, inter-ONU signal is transmitted at first stage Bragg wavelength thus reflected signal from the first stage FBG is broadcasted to all ONUs via second stage remote nodes. For subgroup ONU intercommunication, inter-ONU signal is transmitted at second stage Bragg wavelength, and this signal is reflected from the second stage FBG and broadcasted to only ONUs which are located within the same group. The detailed architecture is being discussed in the next section of the chapter.

7.2 Overall/ Subgroup ONU Intercommunication based on Two Stage Flexible PON Network

In the architecture as shown in Fig. 7.1 which was proposed in [130], an FBG is used to reflect the inter-ONU signal and broadcast the inter-ONU signal to the entire ONUs. All ONUs are installed with tunable receivers to receive any particular wavelength signal. This type of architecture reduces the latency for inter-ONU signal as FBG is reflecting back the inter-ONU signal from the remote node only. However, this architecture transmits the inter-ONU signal to the entire ONUs available in the network and does not provide the inter-ONU communication within the group of nearby located ONUs. While for some applications, due to security, power budget matching, and low power requirements; it is highly desirable to communicate in a small group of ONUs. In this section, we have proposed a flexible, two-remote-node stage based architecture which is capable of communicating with all ONUs available in the network and/or ONUs located within a subgroup or within an optical distribution network (ODN).

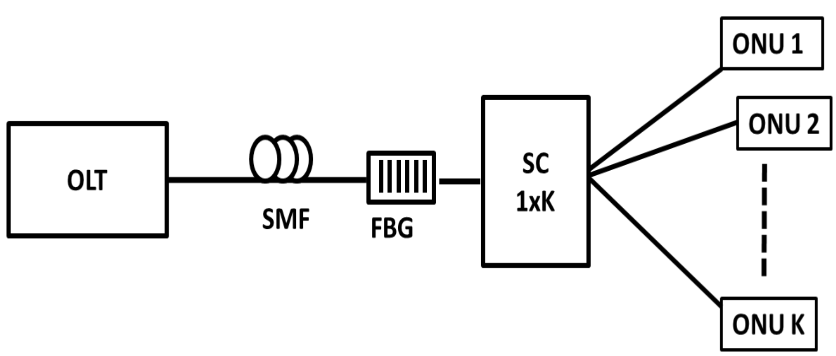

Fig. 7.1 Conventional PON Architecture [130]

Let ONU1 wants to communicate with three other ONUs, it transmits inter ONU signal at 193.5 THz. The Bragg wavelength is also kept 193.5 THz. The transmitted wavelength from ONU1 is passed to star coupler. and reaching at FBG. As transmitted wavelength matches the FBG wavelength, it is reflected back as shown in Fig. 7.2. This reflected signal may be received by other ONUs with the help of star coupler.

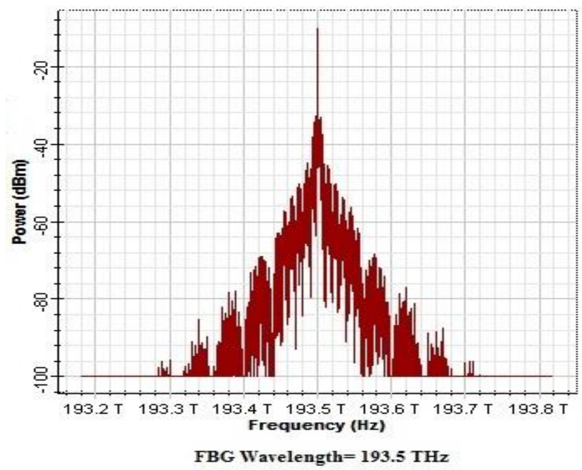

Fig. 7.2 Reflected output of FBG for one stage PON

7.2.1 Flexible Two Stage PON Architecture

The architecture of proposed flexible ONU intercommunication scheme is shown in Fig. 7.3. This architecture is based on two cascaded stages of remote nodes (RN1 and RN2). Splitting ratio of RN1 and RN2 is 1xM and 1xN respectively. Designed architecture have M optical distribution networks (ODN) and each ODN consists of N ONUs. Total number of supported ONUs remain same as the conventional architecture, and product MN= K. Each remote node is placed with a star coupler (SC) thus each ONU can receive the wavelength transmitted from the OLT. An FBG is also cascaded just before each remote node. The purpose of FBG is to transmit the upstream and downstream wavelength signals and reflect back the ONU intercommunication data at a particular wavelength. Downstream and upstream transmissions are just similar to any two stages PON as FBG is not affecting the downstream and upstream wavelengths. All the ONUs are designed with tunable transceivers to transmit and receive any specific wavelengths for ONU interconnection purpose.

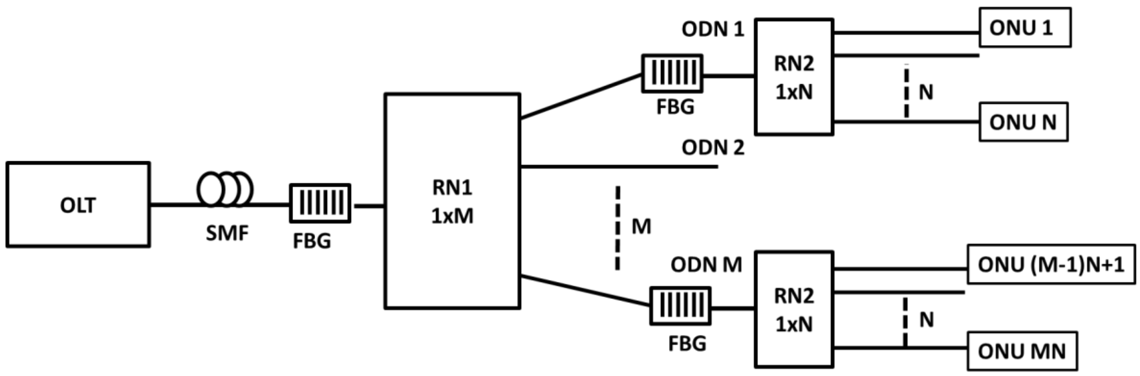

Fig. 7.3 Proposed two stage PON Architecture

7.2.2 Working and Flexibility Analysis

By placing SC at both the remote nodes, designed architecture is fully flexible. Any OLT transmitter is capable of transmitting to any ONU since OLT transmitter is broadcasting the data. For the simplicity and simulation purpose, we considered the value of M and N as 4. Suppose WDM transmitter at OLT is transmitting four wavelengths λ_1, λ_2, λ_3 and λ_4. All these wavelengths travel through a 20 km single mode fiber (SMF) link and reach at RN1. Standard values of 0.2 dB/km attenuation loss and 16.75 nm/ps/km dispersion loss is considered for this fiber. At RN1, 1x4 SC distributes these wavelengths to four ODNs. Since SC does not provide any demultiplexing, all the ODNs receive all the wavelengths. At RN2, another 1x4 SC is used to serve four ONUs located in a building or nearby buildings. The insertion loss for SC is considered as 3.5 $\log_2(X)$ dB [131] where X being the splitting ratio of SC. Calculated insertion loss for a 1x4 SC is 7 dB for upstream/ downstream transmission. For inter-ONU signal, insertion losses are doubled (14 dB) as signal has to travel through SC twice in back and forth direction respectively. At ONU, wavelength signals are received by the tunable optical receiver. Downstream transmission of proposed architecture is shown in Fig. 7.4. All the transmitted wavelengths from OLT are transmitted from the FBGs and broadcasted at both the remote nodes.

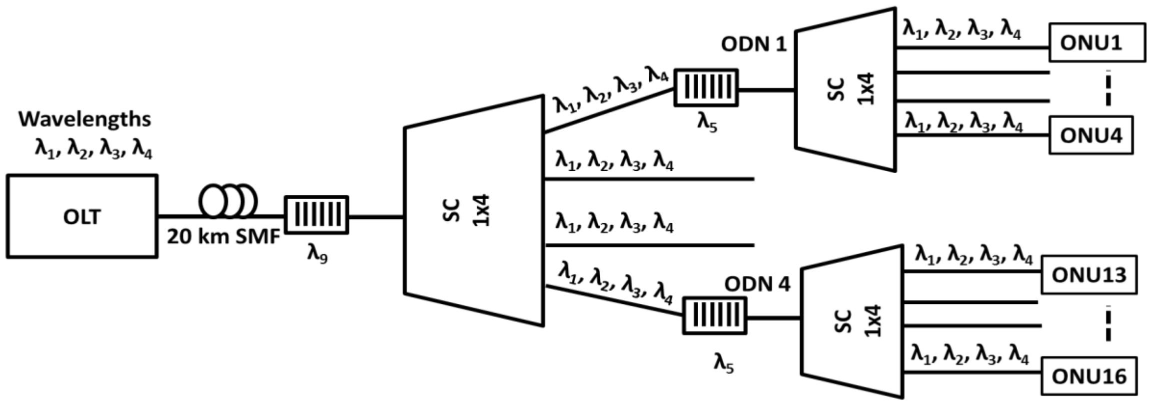

Fig. 7.4 Downstream transmission of proposed architecture

For inter-ONU communication, any ONU can communicate directly with all ONUs available in the network and/or within a subgroup of nearby located ONUs (ONUs located within a particular optical distribution network). We consider two cases as representative examples, as explained in Fig. 7.5. First; ONU1 is communicating with all ONUs available in the network (overall inter-ONU communication), and second; ONU1 is communicating with ONUs located within its subgroup/ ODN (subgroup inter-ONU communication).

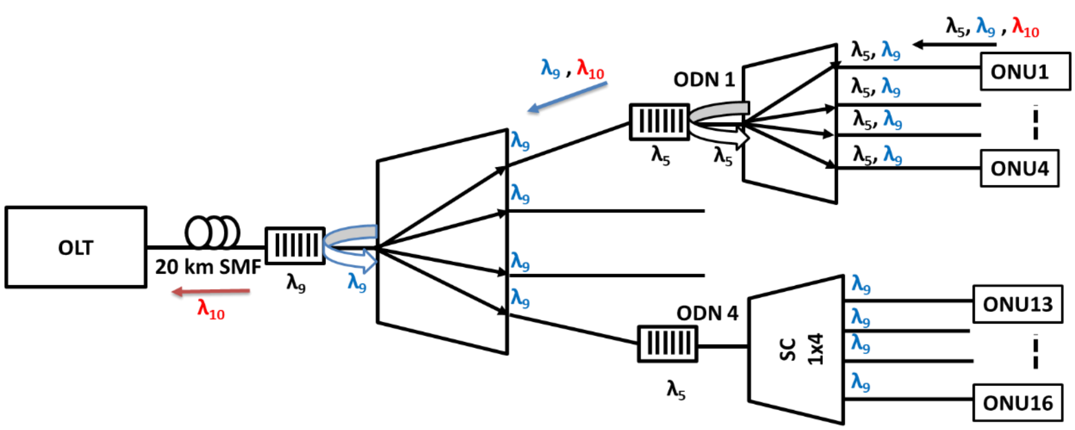

Fig. 7.5 ONU interconnection mechanism within ODN or all ONUs

For first case ONU1 transmits inter-ONU signal at wavelength λ_9. Since the Bragg wavelength of FBG at RN2 is λ_5 and FBG at RN1 is λ_9, therefore FBG at RN2 pass the transmitted wavelength while FBG at RN1 reflect it as shown in Fig. 7.5.

Reflected inter-ONU signal is then distributed by SC and reached to all ODNs at RN2. SCs of RN2 again distribute the received inter-ONU signals and these signals may be received by the tunable receivers of all ONUs. In this case, the total insertion loss for the inter-ONU signal is almost same as conventional architecture as shown in Fig. 7.1. This is because overall splitting ratio of SC remains same i.e. 1×16. For the second case, inter-ONU signal from ONU1 is transmitted at wavelength λ_5 and the same wavelength is kept for RN2 FBG. This wavelength is reflected back from RN2 only and distributed to only those ONUs which belong to the same ODN i.e. now inter-ONU communication is held between a small group of nearby located ONUs. The reflected FBG output for both the FBGs is shown in Fig. 7.6. For this the value of λ_5 and λ_9 is chosen as 193.5 THz and 193.9 THz respectively.

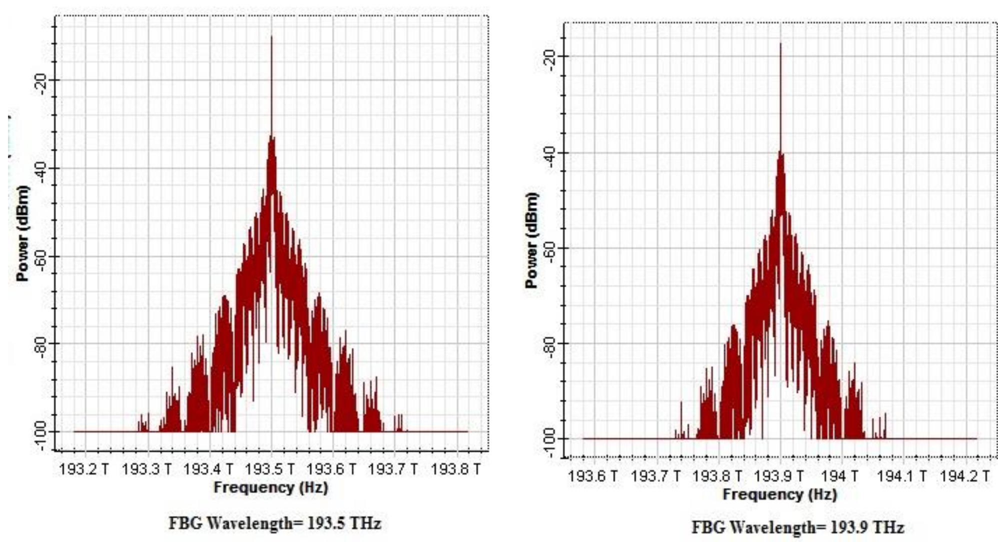

Fig. 7.6 Reflected outputs of FBG for two stage PON

Total insertion losses for subgroup inter-ONU communication is 14 dB less as compared to overall ONU intercommunication as subgroup inter-ONU signal has to travel only RN2 SC, which has the splitting ratio of 1×4. Architecture shown in Fig. 7.3 also supports upstream transmission. The upstream transmitted wavelength is kept other than the wavelength of RN1 FBG and RN2 FBG, so that it will not be reflected by any remote node. For example, signal transmitted at λ_{10} is not reflected by any remote node and reaching at the OLT. At OLT this signal is successfully received by the OLT receiver.

Input power versus measured bit error rate (BER) is plotted for both subgroup inter-ONU communication and overall inter-ONU communication and shown in Fig. 7.7(a) and Fig.

7.7(b) respectively. By observing at $1x10^{-9}$ BER, overall inter-ONU communication requires approximately 14 dB more power as compared to subgroup inter-ONU communication. This 14 dB power can be used for extending the subgroup up to four times or can be used for saving the user power in the network.

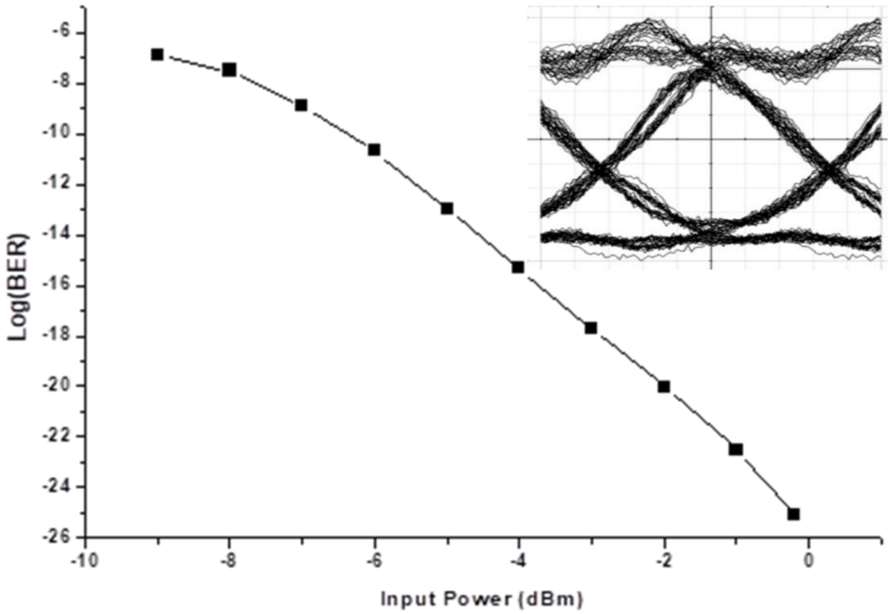

Fig. 7.7(a) Subgroup inter-ONU communication

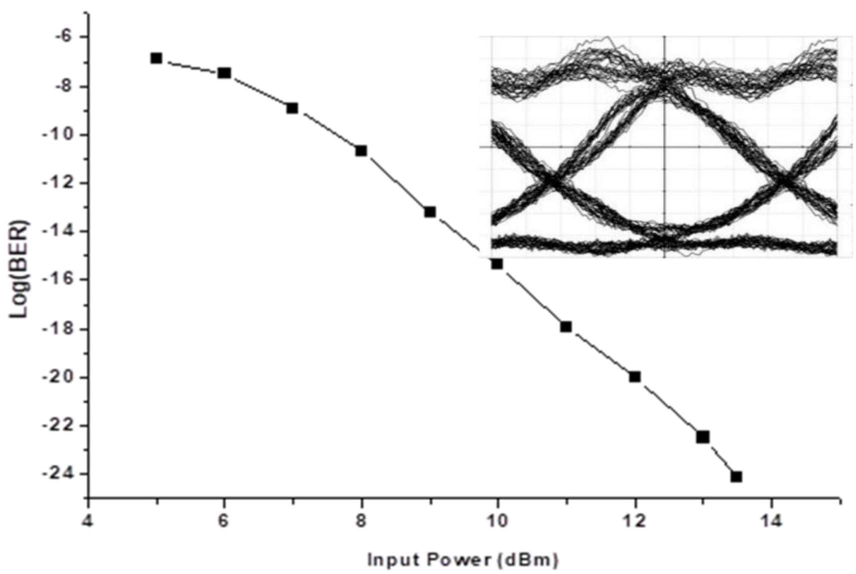

Fig. 7.7(b) Overall inter-ONU communication

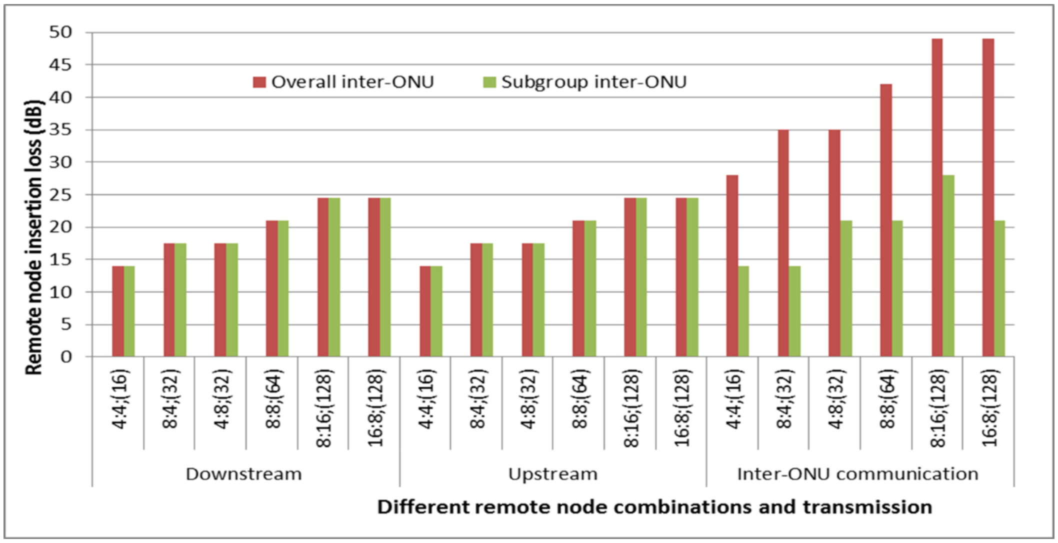

Fig. 7.8 Insertion losses (dB) for different remote node for different transmissions

Fig. 7.8 shows the insertion losses at remote node due to SC for different remote node combinations for upstream, downstream and inter-ONU communication. For the receiver sensitivity of -30 dBm, upto 16 ONUs can easily communicate in a subgroup with any power budget issue.

7.2.3 Summary

This section proposed a two-remote-node based flexible PON architecture which provides the overall inter-ONU communication or subgroup (nearby located ONUs) inter-ONU communication. Based on the requirement/ application, inter-ONU communication mode can be changed just by changing the inter-ONU communication wavelength. For M=N=4 or K=16, subgroup inter-ONU communication required 14 dB less power as compared to overall inter-ONU communication. This 14 dB power can be used to handle up to four times larger subgroups or save user power significantly. Subgroup inter-ONU communication is also suitable for secured communication as data is communicated within its subgroup only. As in inter-ONU communication, ONU transmits data for another ONU directly without involving OLT, upstream and downstream bandwidth is also saved.

7.3 WDM-PON for Dedicated and Broadcasting Downstream Transmission with Energy-Efficient and Latency-Aware ONU Interconnection Capability

In this section, we have proposed energy–efficient and latency-aware WDM-PON network with ONU interconnection capability. Proposed architecture is capable of transmitting simultaneous dedicated point to point (P2P) and broadcasted downstream transmission. This also allows simultaneous upstream and inter-ONU signal transmission. It provides the efficient bandwidth utilization, bandwidth scalability, and network extensibility and low latency for inter-ONU communication to support the future optical networks.

7.3.1 Proposed Architecture

Proposed energy efficient and latency aware WDM-PON architecture is shown in Fig. 7.9, which has N tunable transmitters and N receivers at OLT to transmit and receive downstream and upstream signals respectively. An N×1 MUX/DE-MUX is used at OLT to multiplex and demultiplex the downstream and upstream signals respectively. An additional WDM overlay transceiver (TRx) is also incorporated at OLT which is normally used for broadcasting the data in the existing WDM network. WDM overlay data at particular wavelength is combined at central office by a CWDM. Another CWDM is used just before the RN AWG; it separates the downstream broadcasting signal transmitted by WDM overlay TRx. This WDM overlay signal is diverted towards (N+1)×(N+1) SC and broadcasted to all its output ports from where any ONU can receive. WDM overlay TRx can also be used for transmitting downstream data if any OLT TRx is failed until dedicated TRx is recovered. Therefore, reliability of the network is increased against the OLT TRx failure. At RN, a 1×N AWG is used to separate the incoming downstream signals for different ONUs. The 1×N AWG has a frequency spacing of 100 GHz between its two consecutive output ports. Each ONU has two receivers, one for downstream and another for inter-ONU signal/ WDM overlay signal. It also has two transmitters, one for upstream/inter-ONU and another for WDM overlay signal. Proposed architecture is capable of transmitting simultaneous dedicated point to point (P2P) and broadcasted downstream transmission. This also allows simultaneous upstream and inter-ONU signal transmission.

Upstream signals are transmitted at 100 GHz (even multiple of 50 GHz) separations while for inter-ONU transmission, the same transmitter transmits 50 GHz shifted (odd multiple of 50 GHz) signals w.r.t. upstream signal. N 50 GHz interleavers are used between the RN AWG and ONUs (one for each port) as shown in Fig. 7.9. These N interleavers just separate out the 50 GHz shifted inter-ONU signals from the upstream path and direct them to the (N=1)×(N+1) SC. All 50 GHz even-multiple signals are received at OLT and all 50 GHz odd-multiple signals are directed to the N input ports of the (N+1)×(N+1) SC. Remaining one input port of SC is used for downstream broadcasting signal transmitted from WDM overlay transmitter.

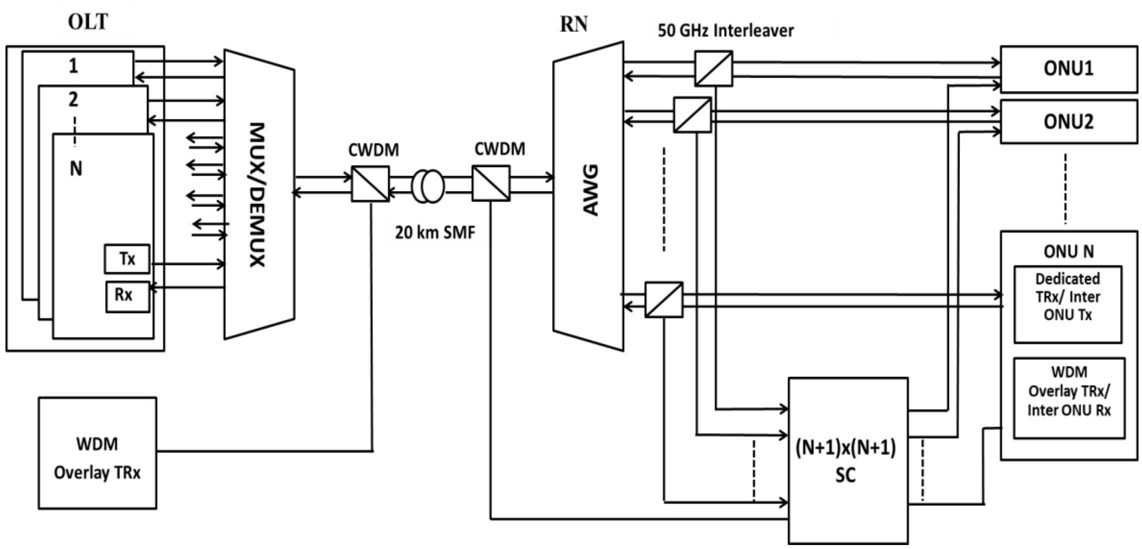

Fig. 7.9 Proposed WDM-PON network with ONU interconnection capability

N output ports of SC are connected with N ONUs respectively to provide broadcasting and inter-ONU communication while one output port remains free and which may be utilized for bandwidth scalability or to extend the network in the near future. This free port may also be used in case of any output port failure to enhance the reliability of the network. Therefore, proposed architecture provides bandwidth scalability, reliability, and increases survivability to utilize it in the future. (N+1)×(N+1) SC distributes all the WDM overlay broadcasting signals / inter-ONU signals to its each output port, and these signals are received by WDM overlay Rx/inter-ONU Rx at the respective ONU.

7.3.2 Working and Operation

Simulation setup of the proposed architecture is shown in Fig. 7.10, in which we have considered eight dedicated transceivers at the OLT. All the transmitters are spaced 100 GHz apart and transmit signals at 193.1 THz, 193.2 THz and so on, up to 193.8 THz. WDM overlay TRx transmits a particular broadcasting wavelength λ^d_b in the downstream direction. After multiplexing these signals using MUX and combining them with the broadcasting wavelength using CWDM, the combined signals are transmitted through the 20 km single mode fiber (SMF). Attenuation and dispersion loss of 0.2 dB/km and 16.75 ps/nm/km respectively have been considered.

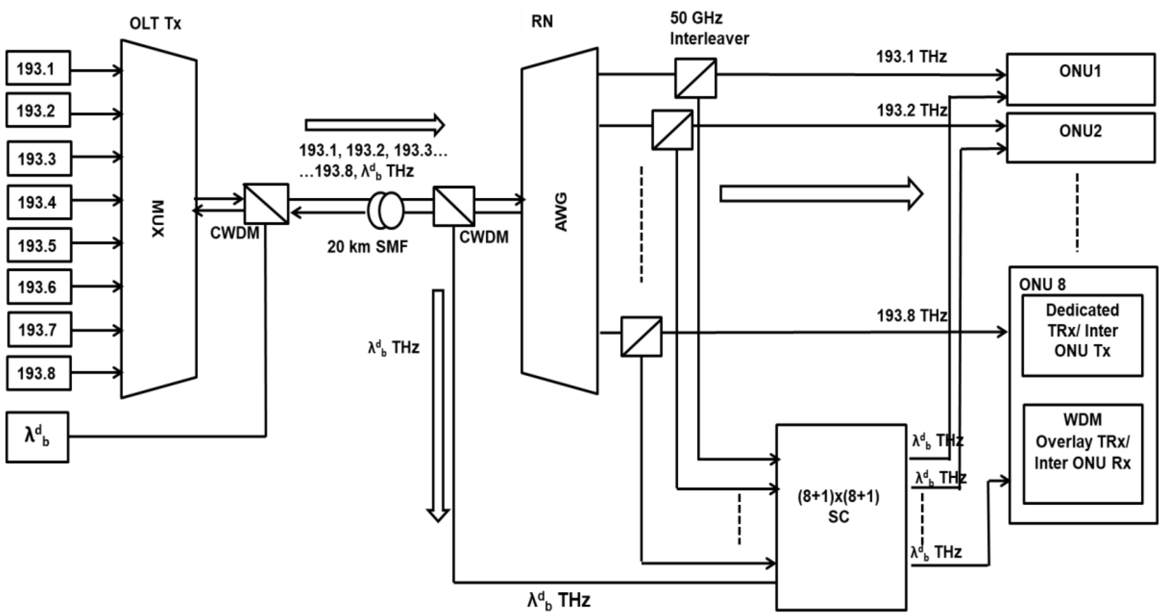

Fig. 7.10 Downstream with broadcasting transmission in proposed architecture

The RN AWG has a center frequency of 193.1 THz. Due to the cyclic property of AWG, its each output port receives one downstream signal i.e. port1, port2…port8 receive 193.1 THz, 193.2 THz…193.8 THz respectively. Each output port of AWG is connected to each ONU via 50 GHz interleaver. The main function of interleaver is to separate out the even and odd multiple of 50 GHz wavelength signals. As all transmitted downstream signals are even multiple of 50 GHz, these signals pass through the interleavers and reach to respective ONU and detected by dedicated receiver. At RN, broadcasting wavelength λ^d_b is separated by the second CWDM and directed to the last port of (8+1)×(8+1) SC.

This SC broadcasts the wavelength λ^d_b to its each output port, and WDM overlay receiver of each ONU receives it.

Upstream signals are transmitted at 100 GHz apart from each ONU, and these wavelengths are 194.7 THz, 194.8 THz…195.4 THz respectively, which are also even multiples of 50 GHz. All these upstream wavelengths pass through the respective 50 GHz interleavers and reach the RN AWG. Due to the cyclic property of AWG, all upstream wavelengths are multiplexed and transmitted at a single port as shown in Fig. 7.11.

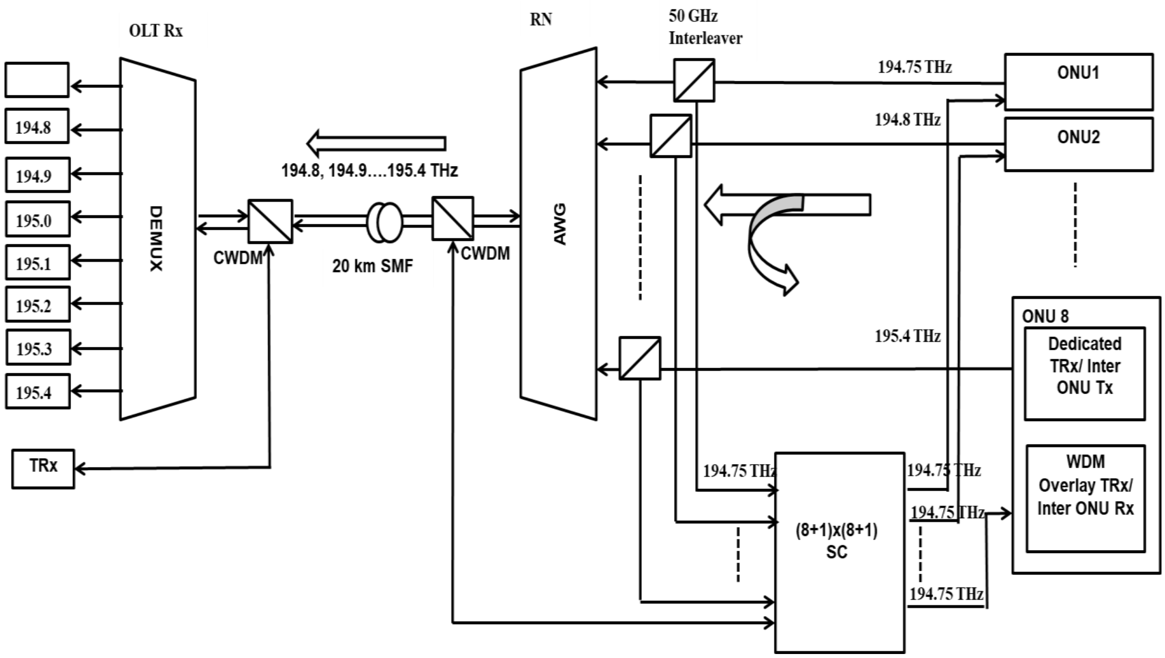

Fig. 7.11 Upstream transmission and ONU interconnection mechanism

These upstream wavelengths pass through the CWDMs and SMF to the OLT. At the OLT, all these wavelengths are demultiplexd and received by their respective receiver. For the direct ONU interconnection, each tunable ONU transmits a signal in such a way that it is 50 GHz shifted from the upstream signal. In our case, each inter-ONU transmitter transmits signal at 194.75 THz, 194.85 THz…195.45 THz wavelengths respectively. As signals are odd multiple of 50 GHz, these are separated out and diverted back by the interleavers towards the (8+1)×(8+1) SC. This SC distributes each received inter-ONU signal to its each output port i.e. each inter-ONU receiver receives all the inter-ONU signals. Since broadcasting/ inter-ONU receiver is tunable, it can receive the signal transmitted from any ONU. For example, as depicted in Fig. 7.11, suppose ONU1 wants to communicate with other ONUs, then it will shift its upstream wavelength by 50 GHz and transmit signal at 194.75 THz. This signal will be diverted by interleaver towards first input port of (8+1)×(8+1) SC. Now, this signal is broadcasted to all the ONUs and can be received successfully by any other ONU. Simultaneous upstream transmission for dedicated and WDM overlay receiver is depicted in Fig. 7.12. Dedicated TRx of all ONUs transmit upstream signals as usual as discussed earlier, while WDM overlay TRx of an ONU transmits an upstream wavelength λ^u_b (ONU8 in this particular example depicted in Fig. 7.12).

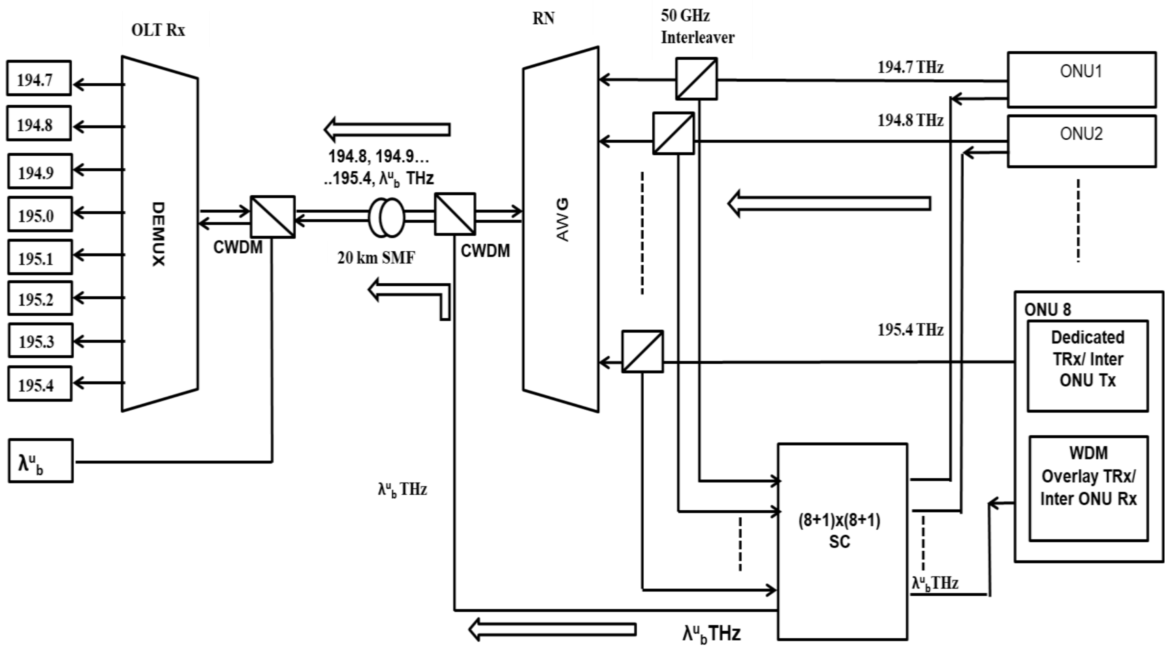

Fig. 7.12 Simultaneous dedicated and WDM overlay upstream transmission

WDM overlay wavelength from the ONU is provided as input to the respective port of (8+1)×(8+1) SC, from where this WDM overlay upstream signal is directed to the RN CWDM, to be combined with dedicated upstream data. At OLT the other CWDM separates the dedicated signals from the WDM overlay signal. All dedicated upstream signals are further separated by AWG demux and received by respective receivers.

7.3.3 Results & Discussions

To determine the energy saving and latency saving capabilities of the proposed architecture, a hypothetical case of a university is considered, in which director office is assumed to be the CO/OLT and various professors are assumed to be the ONUs. Table 7.1 illustrates the various possible frequencies used for communication between different locations.

Table 7.1: A hypothetical case of a university for transmissions

	Director Office *(CO/OLT)*	***Prof. 1 (ONU1)***	***Prof. 2 (ONU2)***	***Prof. 3 (ONU3)***	***Prof. 4 (ONU4)***	***Prof. 5 (ONU5)***	***Prof. 6 (ONU6)***	***Prof. 7 (ONU7)***	***Prof. 8 (ONU8)***
Director Office *(CO/OLT)*		193.1 THz	193.2 THz	193.3 THz	193.4 THz	193.5 THz	193.6 THz	193.7 THz	193.8 THz
Prof. 1 (ONU1)	194.7 THz		194.75 THz	194.75 THz	194.75 THz	194.75 THz	194.75 THz	194.75 THz	194.75 THz
Prof. 2 (ONU2)	194.8 THz	194.85 THz		194.85 THz	194.85 THz	194.85 THz	194.85 THz	194.85 THz	194.85 THz
Prof. 3 (ONU3)	194.9 THz	194.95 THz	194.95 THz		194.95 THz	194.95 THz	194.95 THz	194.95 THz	194.95 THz
Prof. 4 (ONU4)	195.0 THz	195.05 THz	195.05 THz	195.05 THz		195.05 THz	195.05 THz	195.05 THz	195.05 THz
Prof. 5 (ONU5)	195.1 THz	195.15 THz	195.15 THz	195.15 THz	195.15 THz		195.15 THz	195.15 THz	195.15 THz
Prof. 6 (ONU6)	195.2 THz	195.25 THz	195.25 THz	195.25 THz	195.25 THz	195.25 THz		195.25 THz	195.25 THz
Prof. 7 (ONU7)	195.3 THz	195.35 THz	195.35 THz	195.35 THz	195.35 THz	195.35 THz	195.35 THz		195.35 THz
Prof. 8 (ONU8)	195.4 THz	195.45 THz	195.45 THz	195.45 THz	195.45 THz	195.45 THz	195.45 THz	195.45 THz	

For example, 193.1 THz is used for downstream transmission from OLT (director office) to ONU1 (Prof1). 194.7 THz is used for upstream transmission from ONU1 to OLT. Direct inter-ONU communication from Prof. 1 to Prof. 5 is done at 194.75 THz. Representative fiber distances between RN and different ONU locations are also considered as given in Table 7.2.

Table 7.2: Distance between RN to different ONU locations

	Prof. 1 (ONU1)	***Prof. 2 (ONU2)***	***Prof. 3 (ONU3)***	***Prof. 4 (ONU4)***	***Prof. 5 (ONU5)***	***Prof. 6 (ONU6)***	***Prof. 7 (ONU7)***	***Prof. 8 (ONU8)***
RN	100 m	200 m	100 m	300 m	500 m	200 m	400 m	300 m

To analyze the latency efficiency of the proposed architecture, first we calculate the effective velocity in the fiber as given by equation (7.1). Latency occurring between different locations may be easily determined by adding the total fiber latency to the latencies occurring due to different system components. Maximum latency in the system is due to the optical fiber only which depends on its length (*l*) and refractive index (*n*). The effective velocity *v* is given by $v = c / n$. At 1550 nm, the value of *n* is 1.4682 [132]. Effective velocity is-

$$v = \frac{c}{n} = \frac{299792.45 km / s}{1.4682} = 204190.477 km / s \quad (7.1)$$

One side latency to travel 20 km fiber is: $t_{fiber} = \frac{l}{v} = \frac{20km}{204190.477 km / s} = 97.94 \mu s$.

Latency can be calculated similarly for other fiber lengths between RN and different ONUs. For other components, latency is depicted in Table 7.3 [133], [134]. A major cause of latency in the optical network is due to the fiber itself. Therefore by reducing the fiber latency, significant latency can be saved.

Table 7.3. Latency for different components used in the link

Components	**Latency**
20 SMF	97.94 µs
AWG	5 ns
Interleaver	1 ns
Power splitter	1 ns
CWDM	5 ns

Latency for transmitting the data from OLT to ONUx is the sum of latencies occurring due to different components placed in the path and is given by-

$$t_{OLT-ONUx} = t_{AWG(CO)} + t_{CWDM(CO)} + t_{Fiber(20km)} + t_{CWDM(RN)} + t_{AWG(RN)} + t_{Interleaver(RN)} + t_{Fiber(RN-ONUx)} \quad (7.2)$$

or if AWG and CWDM located at CO and RN have same latency, then latency will be-

$$t_{OLT-ONUx} = 2t_{AWG} + 2t_{CWDM} + t_{Fiber(20km)} + t_{Interleaver(RN)} + t_{Fiber(RN-ONUx)} \quad (7.3)$$

Latency for transmitting the direct inter-ONU signal from one ONU to another ONU is given by-

$$t_{ONUx-ONUy} = t_{Fiber(RN-ONUx)} + t_{Interleaver(RN)} + t_{SC} + t_{Fiber(RN-ONUy)} \quad (7.4)$$

In the above expressions, $t_{OLT-ONUx}$ is the latency of downstream signal from OLT to ONUx. Upstream transmissions will also suffer the same amount of latency. $t_{RN-ONUx}$ is the latency of fiber between RN and ONUx. $t_{ONUx\text{-}ONUy}$ is the latency experienced by a signal for direct communication of ONUx and ONUy. t_{AWG}, t_{CWDM}, t_{Fiber} and $t_{Interleaver}$ are the latencies occurring due to AWG, CWDM, fiber and interleaver respectively. Other latencies are the component latencies and have their usual meaning. Based on the equations (7.3) and equation (7.4), total latency occurring between OLT to different ONU and from one ONU to another ONU is given in Table 7.4.

Table 7.4: Latency calculations between different locations

	Director Office ***(CO/OLT)***	***Prof. 1 (ONU1)***	***Prof. 2 (ONU2)***	***Prof. 3 (ONU3)***	***Prof. 4 (ONU4)***	***Prof. 5 (ONU5)***	***Prof. 6 (ONU6)***	***Prof. 7 (ONU7)***	***Prof. 8 (ONU8)***
Director Office (CO/OLT)		98.45 µs	98.94 µs	98.45 µs	99.43 µs	100.41 µs	98.94 µs	99.92 µs	99.43 µs
Prof. 1 (ONU1)	98.45 µs		1.471 µs	0.981 µs	1.96 µs	2.94 µs	1.471 µs	2.45 µs	1.96 µs
Prof. 2 (ONU2)	98.94 µs	1.471 µs		1.471 µs	2.45µs	3.43 µs	1.96 µs	2.94 µs	2.45 µs
Prof. 3 (ONU3)	98.45 µs	0.981 µs	1.471 µs		1.96 µs	2.94 µs	1.471 µs	2.45 µs	1.96 µs
Prof. 4 (ONU4)	99.43 µs	1.96 µs	2.45 µs	1.96 µs		3.92 µs	2.45 µs	3.43 µs	2.94 µs
Prof. 5 (ONU5)	100.41 µs	2.94 µs	3.43 µs	2.94 µs	3.92 µs		3.43 µs	4.41 µs	3.92 µs
Prof. 6 (ONU6)	98.94 µs	1.471 µs	1.96 µs	1.471 µs	2.45 µs	3.43 µs		2.94 µs	2.45 µs
Prof. 7 (ONU7)	99.92 µs	2.45 µs	2.94 µs	2.45 µs	3.43 µs	4.41 µs	2.94 µs		3.43 µs
Prof. 8 (ONU8)	99.43 µs	1.96 µs	2.45 µs	1.96 µs	2.94 µs	3.92 µs	2.45 µs	3.43 µs	

Table 7.5 shows the contact duration of one ONU with another ONUs and OLT for 24hours period. For example, out of 24 hours, ONU1 communicates with ONU2, ONU3, ….., ONU8 for 2, 5,….4 hours respectively. For example, communication duration between ONU1 and OLT is 1 hour and that is for ONU1 and ONU2 is 2 hours.

Table 7.5: Contact duration (hours) between one ONU with another ONUs and OLT

	OLT	***ONU1***	***ONU2***	***ONU3***	***ONU4***	***ONU5***	***ONU6***	***ONU7***	***ONU8***
ONU1	1		2	5	2	3	5	2	4
ONU2	5	2		2	3	5	2	4	1
ONU3	3	5	2		5	2	4	1	2
ONU4	2	2	3	5		4	1	2	5
ONU5	1	3	5	2	4		2	5	2
ONU6	5	5	2	4	1	2		2	3
ONU7	3	2	4	1	2	5	2		5
ONU8	2	4	1	2	5	2	3	5	

Conventional transmission based communication of one ONU with another ONU is shown in Fig. 7.14, in which ONU first sends its data to OLT and then OLT sends it to the different ONUs.

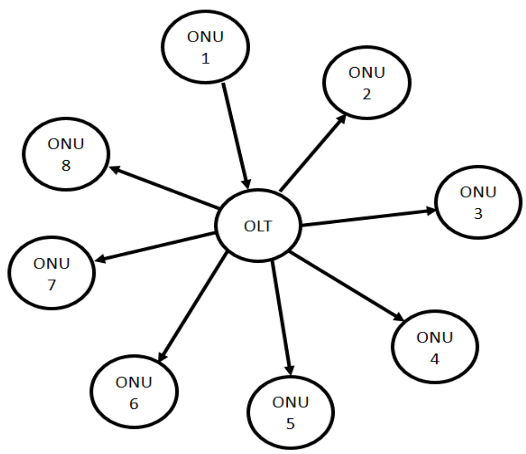

Fig. 7.14. ONU1 is communicating with other ONUs via OLT

For the proposed architecture, direct inter-ONU communication is achieved as shown in Fig. 7.15. A number on each branch indicates the contact duration between two connected nodes which is taken from Table 7.5.

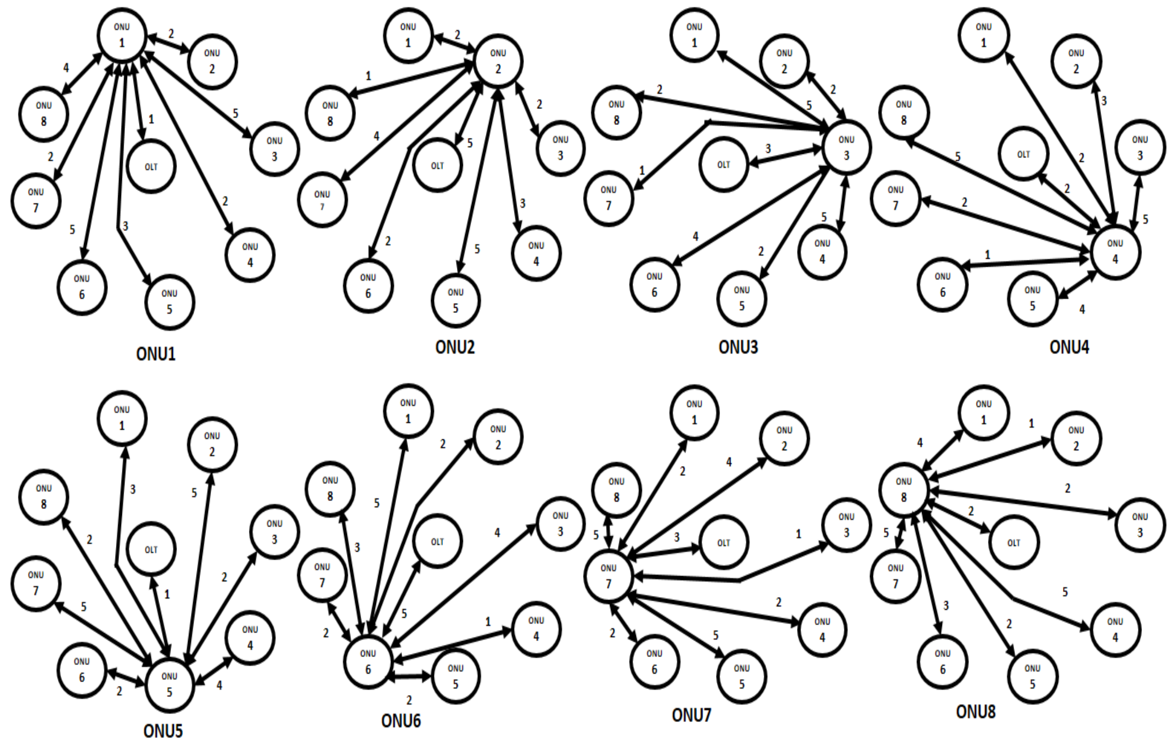

Fig. 7.15 Direct communication of one ONU among different ONUs

Latency saving for a particular ONUx is the difference of latencies occurring in conventional and proposed method and which can be given by-

$$t_{Saving}(ONUx) = \sum_{y=1}^{8}(t_{ONUx-OLT-ONUy} - t_{ONUx-ONUy}) \quad \text{...(7.5)}$$

where x indicates the specific ONU number for which latency saving is calculated. y indicates the destined ONU for which data is transmitted from ONUx. $t_{ONUx\text{-}OLT\text{-}ONUy}$ is the total latency for inter-ONU communication through OLT. $t_{ONUx\text{-}ONUy}$ is the latency for direct inter-ONU communication. Based on the equation 7.5 and transmission latencies given in Table 7.4, latency saving for different ONUs is given in Fig 7.16.

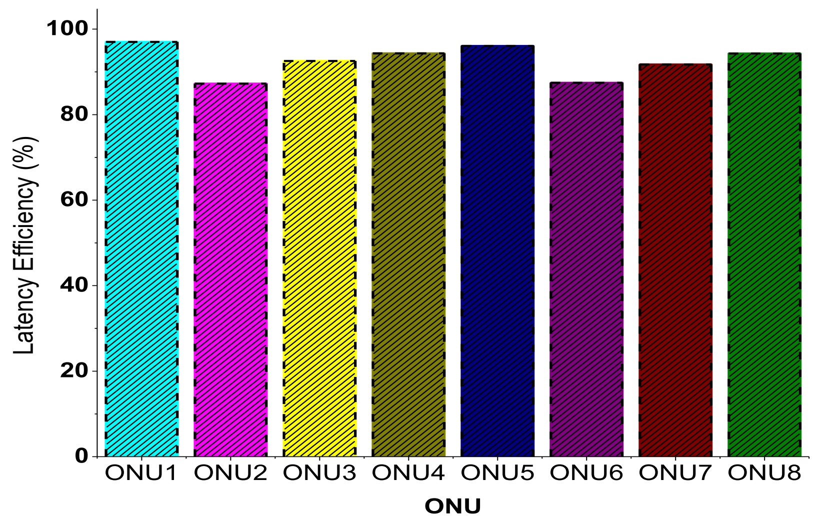

Fig. 7.16 Latency efficiency (%) for different ONUs

By directly transmitting the data from one ONU to the other ONUs, retransmission of the inter-ONU data from ONU to OLT and then OLT to ONU is avoided. Energy saving for a particular ONUx may be given by-

$$E_{Saving}(ONUx) = \sum_{y=1}^{8}(E_{ONUx-OLT-ONUy} - E_{ONUx-ONUy}) \quad \text{.......(7.6)}$$

$$E_{Saving}(ONUx) = 8 \cdot E_{ONUx-OLT} + \sum_{y=1}^{8}(E_{OLT-ONUy} - E_{ONUx-ONUy}) \quad \text{.......(7.7)}$$

$$E_{Saving}(ONUx) = 8 \cdot P_{ONUx-OLT} \cdot h_{ONUx-OLT} + \sum_{y=1}^{8}(P_{OLT-ONUy} \cdot h_{OLT-ONUy} - P_{ONUx-ONUy} \cdot h_{ONUx-ONUy}) \text{..(7.8)}$$

$E_{ONUx\text{-}OLT\text{-}ONUy}$ is the total energy consumed for communication between ONUx and ONUy through OLT. $E_{ONUx\text{-}ONUy}$ is energy consumed for direct communication between ONUx and ONUy. $P_{ONUx\text{-}OLT}$ is the power consumed during communication of ONUx and OLT. $h_{ONUx\text{-}OLT}$ is the duration for which ONUx and OLT communicates. $P_{OLT\text{-}ONUy}$ is the power consumed during communication of OLT and ONUy. $h_{OLT\text{-}ONUy}$ is the duration for which OLT and ONUy communicates. $P_{ONUx\text{-}ONUy}$ is the power consumed during the direct communication of ONUx and ONUy. $h_{ONUx\text{-}ONUy}$ is the duration for which ONUx and ONUy communicate directly.

During the retransmission of inter-ONU signal from ONUx to OLT and back to the ONUy, OLT line cards are switched off which require 3.5 W of power. For doing the energy consumption analysis, we again considered that a particular ONU is engaged with other ONUs and OLT as given in Table 7.5. For the proposed architecture, total losses occurring for downstream or upstream transmission are about 25 dB. For direct Inter-ONU losses are about 11.6 dB. The losses for various components are considered as given in Table 7.6.

Table 7.6: Insertion loss for different system components

Components	Insertion loss (dB)
SMF	0.2 dB/km
AWG	5 dB
Interleaver	1 dB
Power splitter	10.5 dB
CWDM	5 dB

By including safety margin of 3 dB and 2.4 dB for downstream/upstream and direct inter-ONU communication; 0 dBm (1 mW), -6.5 dBm (0.223 mW) and -20.5 dBm (0.01 mW) power is required for 10 Gbps downstream, 2.5 upstream and 2.5 inter-ONU communication respectively to satisfy the receiver sensitivities at 1×10^{-9} BER.

By using proposed direct inter-ONU communication, for the duration of 24 hours, energy saving obtained for each ONU is given in Fig. 7.17. Proposed architecture achieves the energy saving of up to 80 Wh for the duration of 24 hours for the considered ONUs engagement duration.

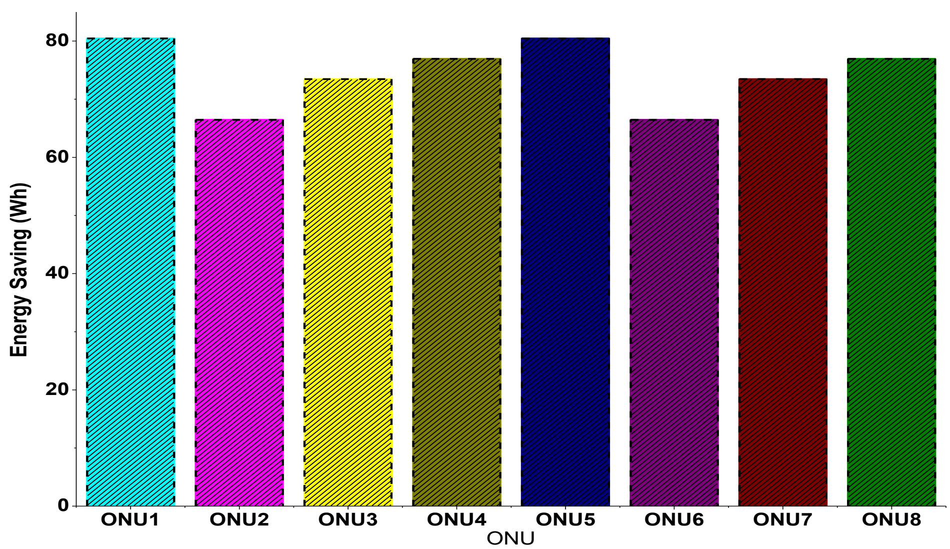

Fig. 7.17 Energy saving (Wh) for different ONUs

7.3.4 Summary

A flexible WDM-PON architecture has been proposed which provides dedicated P2P, broadcasting downstream transmission and energy efficient and latency aware direct inter-ONU communication. A particular wavelength is diverted from the downstream path and directed to (N+1)×(N+1) star coupler (SC) to achieve the broadcasting. This separation is done by RN CWDM. For direct inter-ONU communication, a 50 GHz tuned wavelength is transmitted and separated from the upstream path with RN interleaver. Direct inter-ONU communication reduces the transmission latency significantly by avoiding the main 20 km fiber. Proposed architecture also reduces the energy consumption of the network significantly by transmitting minimum power from ONU and switching off OLT line cards and transmitters. Complex routing mechanism of the inter-ONU signal at OLT is avoided, and therefore reliability is increased. By using proposed architecture, inter-ONU signal does not impose any extra burden downstream bandwidth thus provide efficient bandwidth utilization.

Chapter 8

8. Conclusion and Future Works

8.1 Conclusion

In this thesis, we attempted to develop some flexible hybrid WDM-TDM PON architectures to utilize the advantages of both TDM-PON and WDM-PON. Designed hybrid PON architectures reduce energy consumption and operational expenditure (OPEX) significantly for variable traffic loads. Moreover, the proposed schemes also provide additional desirable features simultaneously such as bandwidth scalability, reliability, resiliency and broadcasting etc.

We also propose some architectures for direct inter-ONU communication to reduce significant transmission latency among locally communicating users and give the opportunity to utilize various resources such as upstream and downstream bandwidth, central office transceivers and optical networking unit transceivers efficiently. This further reduces OPEX and energy consumption of the network.

To understand the background of the telecom networks, a hierarchy including core network, metro network and access network have been studied in chapter 2. Energy saving approaches in core network including switching off idle network elements, efficient network designing and green routing have also been studied. After that, optical access network technologies including fiber to the home (FTTH) network, GPON networks have been studied. Then different multiplexing techniques and various PON standards such as BPON, GPON and EPON have been discussed. At the end of the chapter, existing energy saving approaches at OLT and ONU have been discussed.

The flexibility of passive optical networks has been analyzed in chapter 3. Cost and energy efficient multiplexing techniques are identified for different network scenarios such as different fiber length, different users, and different data rates. Identified multiplexing combination requires the minimum number wavelengths for a given set of parameters for minimum cost and acceptable BER performance. In this chapter, power budget improvement by using Duobinary coding over NRZ coding has also been discussed. Improved power budget can be used to transmit data for longer reach or more users without increasing the input power. Alternately, for the fixed reach and number of users, lower input powers can be provided.

An adaptive bandwidth mechanism using dual rate OLT for energy efficient WDM-TDM PON architecture has been proposed and discussed in chapter 4. Various significant advantages of proposed architecture such as bandwidth scalability, resiliency to OLT TRx/ Line Card failure, network extensibility and broadcasting capability have been discussed. Proposed architecture reduces the energy consumption and OPEX significantly. These features are very important for any optical communication system to survive in the long run and handle the future applications easily.

Flexible hybrid WDM-TDM passive optical network with pay as you grow deployment capability has been proposed and discussed in chapter 5. In this chapter, we first discussed how the proposed architecture is providing up to 40 Gbps, equal data rates to all optical distribution networks (ODNs) and up to 70 Gbps asymmetrical data rate to the specific ODN. Pay-as-you-grow-deployment capability of the proposed architecture allows service providers to spend as they grow. This reduces network energy consumption and OPEX significantly. This architecture also provides bandwidth scalability, broadcasting and reliability to support next generation optical access networks. Another resilient, bandwidth scalable and energy efficient hybrid PON architecture is discussed in chapter 6. By utilizing proper OLT line cards and adaptive link rate mechanism, proposed architecture reduced significant access network power consumption in the presence of low traffic / underutilized network. In the presence of low traffic, ALR switches the link rate from 10 Gbps to 1 Gbps depending on the particular threshold value of traffic load. Proposed architecture also saves the CAPEX at remote node which becomes significant for larger networks. Network resiliency against LC/TRx or module failure and bandwidth scalability is also supported by the proposed architecture.

In a nutshell, the comparison of generalized proposed architectures described in chapter 4, chapter 5 and chapter 6 is presented in the tabular form below with their features and limitations.

Chapter	*Chapter 4*	*Chapter 5*	*Chapter 6*
Max Energy Efficiency	61.2%	46.08%	62.5%
Bandwidth scalability at particular node	Yes	Yes	Yes
Resiliency to TRx/ LC failure	Yes	Yes	Yes
Pay-as-you-grow deployment	No	Yes	No
Limitations	Broadcasting only at 10 G and/or 1 G, Maximum capacity limited upto 44 Gbps	Broadcasting only at 1 G, Maximum capacity to each ODN limited upto 70 Gbps	No broadcasting, Maximum capacity to each ODN limited upto 11 Gbps

Direct Inter-ONU communication schemes have been discussed in chapter 7 which reduces the latency between any communicating ONUs. First, we discussed various available direct inter-ONU communication techniques. Then, proposed overall/ subgroup ONU intercommunication based on two-stage flexible PON network architecture with its working and flexibility analysis is discussed. Proposed architecture reduces power, upstream and downstream bandwidth consumption. After that another proposed WDM-PON architecture for dedicated and broadcasting downstream transmission is discussed which is energy-efficient, latency-aware and has the direct ONU interconnection capabilities. Proposed architecture reduced the requirement of complex routing mechanism of the inter-ONU signal and therefore the reliability of the system is increased. By using proposed architecture, inter-ONU signal does not impose any extra burden on downstream bandwidth thus provide efficient bandwidth utilization.

8.2 Future Work and Concluding Remarks

Till now, this thesis addressed energy efficient, OPEX efficient, bandwidth scalable, resilient & latency aware flexible optical access networks. For the dual rate operations, proposed schemes require separate 1Gbps and 10Gbps transceivers. In future, we will try to implement single bandwidth variable transceiver (BVT) in place of separate data rate multiple transceivers. This will provide bandwidth scalability at any data rate and reduce further OPEX and CAPEX. Architectures proposed in the thesis are resilient to OLT line cards or TRx or module failure only. In future, we will try to design and implement further architectures which are resilient to global failures such as including OLT, ONU and channel. We would also like to consider elastic optical networks for our future research directions and hope for some more concrete architectures with added advantages and flexibility.

Bibliography

[1] G. J. Holzmann and B. Pehrson, “The Early History of Data Networks,“ Los Alamitos, CA: IEEE Computer Society Press, 1995.

[2] H. Kogelnik, “High-capacity optical communications: personal recollections," Selected Topics in Quantum Electronics, IEEE Journal of, vol. 6, no. 6, pp. 1279 -1286, Dec. 2000.

[3] G. P. Agrawal, Fiber-Optic Communication Systems. New York: John Wiley & Sons, 2002

[4] https://en.wikipedia.org/wiki/Smoke_signal

[5] E. Snitzer, "Cylindrical dielectric waveguide modes*," J. Opt. Soc. Am. 51, 491-498 (1961)

[6] K. C. Kao and G. A. Hockham, "Dielectric-fibre surface waveguides for optical frequencies," in Electrical Engineers, Proceedings of the Institution of, vol. 113, no. 7, pp. 1151-1158, July 1966. doi: 10.1049/piee.1966.0189.

[7] R. D. Maurer, and P. C. Schultz. “Fused Silica Optical Waveguide”. Corning Glass Works, Corning, N.Y., assignee. Patent 3,659,915. 2 May 1972.

[8] S. Ten, "Ultra low-loss optical fiber technology," 2016 Optical Fiber Communications Conference and Exhibition (OFC), Anaheim, CA, 2016, pp. 1-3.

[9] M. Hirano, T. Haruna, Y. Tamura, T. Kawano, S. Ohnuki, Y. Yamamoto, Y. Koyano, and T. Sasaki "Record low loss, record high FOM optical fiber with manufacturable process," 2013 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), Anaheim, CA, 2013, pp. 1-3.

[10] C. A. Brackett, "Dense wavelength division multiplexing networks: principles and applications," in IEEE Journal on Selected Areas in Communications, vol. 8, no. 6, pp. 948-964, Aug 1990. doi: 10.1109/49.57798

[11] T. E. Darcie, "Subcarrier multiplexing for lightwave networks and video distribution systems," in IEEE Journal on Selected Areas in Communications, vol. 8, no. 7, pp. 1240-1248, Sep 1990. doi: 10.1109/49.59123

[12] N. Massa, “Fiber Optic Telecommunication,” in Fundamentals of Photonics, Springfield, 2000, pp.293-347.

[13] Gerd Keiser. Optical Fiber Communications, 2nd ed. Highstown, NJ: McGraw-Hill, 1991. ISBN: 9780070336179

[14] https://www.cablewholesale.com/support/technical_articles/fiber_optics.php

[15] https://en.wikipedia.org/wiki/Optical_fiber

[16] M. D. Feit and J. A. Fleck, "Light propagation in graded-index optical fibers," Appl. Opt. 17, 3990-3998 (1978).

[17] Q. Wang, G. Farrell, and W. Yan, "Investigation on Single-Mode–Multimode–Single-Mode Fiber Structure," Journal of Lightwave Technology. 26, 512-519 (2008).

[18] R. P. Khare, Fiber Optics and Optoelectronics. New York: Oxford University Press, 2004.

[19] Y. Yamamoto, Y. Kawaguchi and M. Hirano, "Low-loss and low-nonlinearity pure-silica-core fiber for C- and L-band broadband transmission," in Journal of Lightwave Technology, vol. 34, no. 2, pp. 321-326, Jan.15, 15 2016. doi: 10.1109/JLT.2015.2476837.

[20] I. Chlamtac, A. Ganz and G. Karmi, "Lightpath communications: an approach to high bandwidth optical WAN's," in IEEE Transactions on Communications, vol. 40, no. 7, pp. 1171-1182, Jul 1992. doi: 10.1109/26.153361.

[21] Y. Koike, T. Ishigure and E. Nihei, "High-bandwidth graded-index polymer optical fiber," Journal of Lightwave Technology, vol. 13, no. 7, pp. 1475-1489, Jul 1995. doi: 10.1109/50.400716.

[22] Y. Zhang, P. Chowdhury, M. Tornatore and B. Mukherjee, "Energy efficiency in telecom optical networks," in IEEE Communications Surveys & Tutorials, vol. 12, no. 4, pp. 441-458, Fourth Quarter 2010. doi: 10.1109/SURV.2011.062410.00034.

[23] L. G. Kazovsky, W. T. Shaw, D. Gutierrez, N. Cheng and S. W. Wong, "Next-generation optical access networks," in Journal of Lightwave Technology, vol. 25, no. 11, pp. 3428-3442, Nov. 2007. doi: 10.1109/JLT.2007.907748.

[24] http://www.tfi.com/pubs/g02007_bellec-fig.html

[25] E. Ghazisaeedi, S. Member, C. Huang, and S. Member, "Off-peak energy optimization for links in virtualized network environment (accepted)," J. IEEE Trans. Cloud Comput., vol. 7161, pp. 1–13, 2015.

[26] T. M. Nam, N. H. Thanh, and S. Covaci, "Energy-aware routing based on power profile of devices in data center networks using SDN," in ECTICON 2015, 2015, pp. 1–6.

[27] P. Monti, A. Morea, A. Nirmalathas, and V. Vokkarane, "Special issue on energy-efficient optical networks," Photonic Network Communications", Volume 30, Issue 1, pp 1–3, 2015.

[28] G. Koutitas, A review of energy efficiency in telecommunication networks, Telfor Journal, Vol. 2, No. 1, pp.2-7, 2010.

[29] N. Cheng, "Flexible TWDM PON with WDM overlay for converged services," Optical Fiber Technology, Volume 26, Part A, pp. 21-30, 2015.

[30] C. Lange, and A. Gladisch, "Energy consumption of telecommunication networks - a network operator's view," in OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions, 2009.

[31] J. Manchester, J. Anderson, B. Doshi, and S. Dravida, "IP over SONET," IEEE Commun. Mag., vol. 36, no. 5, pp. 136–142, May1998.

[32] N. Ghani, S. Dixit, and T. S. Wang, “On IP-over-WDM integration,”IEEE Commun. Mag., vol. 38, no. 3, pp. 72–84, Mar. 2000.

[33] B. Nordman, “ICT, networks, and energy: The energy perspective,”OFC/NFOEC’09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions, San Diego, CA, Mar. 2009.

[34] R. Bolla, R. Bruschi, F. Davoli and F. Cucchietti, "Energy Efficiency in the Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures," in IEEE Communications Surveys & Tutorials, vol. 13, no. 2, pp. 223-244, Second Quarter 2011.

[35] “Ciena white paper Optical Transport System Core Stream Agility,” http://www.ciena.com/files/Optical Transport System PB.pdf.

[36] L. Ceuppens, “Planning for energy efficiency: Networking in numbers,”OFC/NFOEC’09, Workshop on Energy Footprint of ICT: Forecast andNetwork Solutions, San Diego, CA, Mar. 2009.

[37] P. Chowdhury, M. Tornatore, and B. Mukherjee, “On the energy efficiency of mixed-line-rate networks,” OFC/NFOEC’10,SanDiego, CA, Mar. 2010.

[38] B. St. Arnaud, “CANARIE: Research networks to help reduce global warming,” OFC/NFOEC’09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions, San Diego, CA, Mar. 2009.

[39] P. P. Iannone, K. C. Reichmann, M. Birk, N. J. Frigo, R. M. Derosier,D. Barbier, C. Cassagnettes, T. Garret, A. Verlucco, S. Perrier, and J.Philipsen, “A 160-km transparent metro WDM ring network featur-ing cascaded erbium-doped waveguide amplifiers,” OFC/NFOEC’01,2001.

[40] RQ Shaddad, A.B. Mohammad, S.A. Al-Gailani, A.M. Al-hetar, and M.A. Elmagzoub ,"A survey on access technologies for broadband optical and wireless networks," Journal ofNetwork and Computer Applications (2014).

[41] C. Lange and A. Gladisch, “Energy consumption of telecommunication networks - a network operator’s view,” OFC/NFOEC’09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions,SanDiego,CA, March 2009.

[42] G. Kramer and G. Pesavento, “Ethernet Passive Optical Network (EPON): Building a Next-Generation Optical Access Network,” IEEE Commun. Mag., vol. 40, no. 2, pp. 66–73, 2002.

[43] M.P. McGarry, M. Reisslein, and M. Maier, "Ethernet passive optical network architectures and dynamic bandwidth allocation algorithms," IEEE Communications Surveys & Tutorials, vol.10, no.3, pp.46-60, Third Quarter 2008

[44] M. C. Yuang et al., “An Energy and Cost Efficient WDM / OFDMA PON system: design and demonstration,” Journal of Lightwave Technology, vol. 31, no. 16, pp. 2809–2816, 2013.

[45] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, “Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited],” Journal of Optical Networking, vol. 4, no. 11. pp. 737–758, 2005.

[46] S. J. Park, C. H. Lee, K. T. Jeong, H. Park, J. Ahn and K. Song, "Fiber-to-the-home services based on wavelength-division-multiplexing passive optical network," Journal of Lightwave Technology, vol.22, no.11, pp.2582-2591, Nov. 2004

[47] M. De Andrade, A. Buttaboni, M. Tornatore, P. Boffi, P. Martelli, A. Pattavina and G. Gavioli, "Design of long-reach TDM/WDM passive optical access networks," telecommunications network strategy and planning symposium (NETWORKS), 2012 XVth International , pp.1-6, 15-18 Oct. 2012

[48] M. De Andrade, A. Buttaboni, M. Tornatore, P. Boffi, P. Martelli, and A. Pattavina, “Optimization of long-reach TDM/WDM passive optical networks,” Opt. Switch. Netw., vol. 16, pp. 36–45, 2015.

[49] P. Mogensen, N. Wei, I. Z. Kovács, F. Frederiksen, A. Pokhariyal, K. I. Pedersen, T. E. Kolding, K. Hugl, M. Kuusela, "LTE Capacity Compared to the Shannon Bound," 2007 IEEE 65th Vehicular Technology Conference - VTC2007-Spring, Dublin, 2007, pp. 1234-1238. doi: 10.1109/VETECS.2007.260

[50] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," in IEEE Transactions on Information Theory, vol. 43, no. 6, pp. 1986-1992, Nov 1997. doi: 10.1109/18.641562

[51] L. Lovasz, "On the Shannon capacity of a graph," in IEEE Transactions on Information Theory, vol. 25, no. 1, pp. 1-7, Jan 1979. doi: 10.1109/TIT.1979.1055985

[52] Y. Barbarin, X. J. M. Leijtens, E. A. J. M. Bente, C. M. Louzao, J. R. Kooiman, and M. K. Smit, "Extremely small AWG demultiplexer fabricated on InP by using a double-etch process," in Optical Amplifiers and Their Applications/Integrated Photonics Research, Technical Digest (CD) (Optical Society of America, 2004), paper IThG4.

[53] S. Zhang, W. Ji, X. Li, K. Huang and Z. Yan, "Efficient and reliable protection mechanism in long-reach PON," in IEEE/OSA Journal of Optical Communications and Networking, vol. 8, no. 1, pp. 23-32, January 1 2016.

[54] A. Dixit, B. Lannoo, G. Das, D. Colle, M. Pickavet, and P. Demeester, "Flexible TDMA/WDMA passive optical network: Energy efficient next-generation optical access solution," Opt. Switch. Netw., vol. 10, no. 4, pp. 491–506, 2013.

[55] N. Cheng, J. H. Gao, C. Z. Xu, B. Gao, D. K. Liu, L. Wang, X. M. Wu, X. P. Zhou, H. F. Lin, and F. Effenberger, "Flexible TWDM PON system with pluggable optical transceiver modules," Opt. Express, vol. 22, no. 2, pp. 2079–2091, 2014.

[56] H. Feng, C.-J. Chae, A. V. Tran, and A. Nirmalathas, "Cost-effective introduction and energy-efficient operation of long-reach WDM/TDM PON systems," J Journal of Lightwave Technology, vol. 29, no. 21, pp. 3135–3143, Nov. 2011.

[57] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time- and wavelength-division multiplexed passive optical network (TWDM-PON) for next-

generation PON stage 2 (NG-PON2),” Journal of Lightwave Technology, vol. 31, no. 4, pp. 587–593, 2013.

[58] G. Maier, M. Martinelli, A. Pattavina, and E. Salvadori, "Design and cost performance of the multistage WDM-PON access networks," Journal of Lightwave Technology. 18, 125- (2000).

[59] A. Dixit, B. Lannoo, G. Das, D. Colle, M. Pickavet and P. Demeester, "Flexibility evaluation of hybrid WDM/TDM PONs," 2011 Fifth IEEE International Conference on Advanced Telecommunication Systems and Networks (ANTS), Bangalore, 2011, pp. 1-6. doi: 10.1109/ANTS.2011.6163650.

[60] F. J. Effenberger, H. Ichibangase and H. Yamashita, "Advances in broadband passive optical networking technologies," in IEEE Communications Magazine, vol. 39, no. 12, pp. 118-124, Dec 2001. doi: 10.1109/35.968822.

[61] ITU-T. 1998. Recommendation G.983.1 Broadband optical access systems based on Passive Optical Networks (PON) October 1998.

[62] ITU-T. 2005. Recommendation G.983.1 Broadband optical access systems based on Passive Optical Networks (PON). January 2005.

[63] ITU-T. 2003. Recommendation G.984.2 Gigabit-capable Passive Optical Networks GPON): Physical Media Dependent (PMD) layer specification. March 2003.

[64] https://en.wikipedia.org/wiki/Passive_optical_network

[65] http://www.ieee802.org/3/av/public/2008_04/3av_0804_remein_2.pdf

[66] IEEE Standard for Information technology--Telecommunications and information exchange between systems--Local and metropolitan area networks--Specific requirements Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications," in IEEE Std 802.3-2008 (Revision of IEEE Std 802.3-2005) , vol., no., pp.1-2977, Dec. 26 2008

[67] C.F. Lam, “Passive optical networks: principles and practice”. USA: Academic Press, an imprint of Elsevier. 324 p. ISBN: 978-0-12-373853-0, 2007.

[68] IEEE P802.3av 10G-EPON Task Force. 2009.

[69] G.987: 10-Gigabit-capable passive optical network (XG-PON) – ITU, https://www.itu.int/rec/T-REC-G.987/en

[70] D. Nesset, "NG-PON2 Technology and Standards," in Journal of Lightwave Technology, vol. 33, no. 5, pp. 1136-1143, March1, 1 2015. doi: 10.1109/JLT.2015.2389115.

[71] D. C. St. John ,Telcos Saving Serious Money by Upgrading to FTTH, Survey Finds, Apr 02, 2013

[72] IDATE News Release Sep. 06, 2011

[73] A. Otaka, “Power saving ad-hoc report,” presented at the IEEE 802.3Interim Meet, Seoul, Korea, Sep. 2008.

[74] J. Kani," Power saving techniques and mechanisms for optical access networks systems, “Journal of Lightwave Technology, vol. 31, no. 4, pp. 563-570, february 15, 2013

[75] A. R. Dhaini, P. H. Ho, and G. Shen, “Toward green next-generation passive optical networks,” IEEE Commun. Mag., vol. 49, no. 11, pp.94–101, Nov. 2011.

[76] Y. Yan, S.W.Wong, L. Valcarenghi, S. H. Yen, D. R. Campelo, S. Ya-mashita, L. Kazovsky, and L. Dittmann, “Energy management mech-anism for Ethernet passive optical networks (EPONs),” in Proc. 2010IEEE Int. Conf. Commun., Cape Town, South Africa, May 2010, pp.1–5.

[77] R. Kubo, J. Kani, H. Ujikawa, T. Sakamoto, Y. Fujimoto, N. Yoshimoto, and H. Hadama, “Study and Demonstration of Sleep and Adaptive Link Rate Control Mechanisms for Energy Efficient 10G-EPON,” IEEE/OSA J. Opt. Commun. Net., vol.2, no. 9, 2010, pp. 716–729

[78] P. Vetter, “GreenTouchwire lineaccess WG roadmap,” presented at theGreenTouch Forum, Seattle, WA, Nov. 2011

[79] K. Christensen, P. Reviriego, B. Nordman, M. Bennett, M. Mostowfi,and J. A. Maestro, “IEEE 802.3az: The road to energy efficient Ethernet,” IEEE Commun. Mag., vol. 48, no. 11, pp. 50–56, Nov. 2010.

[80] H. Imaizumi, T. Nagata, G. Kunito, K. Yamazaki, and H. Morikawa,“Power saving mechanism based on simple moving average for802.3ad link aggregation,” in Proc. 2nd IEEE Global Commun. Conf.Workshop, Honolulu, HI, Nov.–Dec. 2009, pp. 1–6.

[81] S. Shimazu, J. Kani, N. Yoshimoto, and H. Hadama, “Novel sleep control for EPON optical line terminal employing layer-2 switch functions,” in Proc. IEEE Global Commun. Conf., Miami, FL, Dec. 2010,pp. 1–5.

[82] J. Kani, S. Shimazu, N. Yoshimoto, and H. Hadama, “Energy efficient optical access networks—Issues and technologies,” IEEE Commun.Mag., Feb 2013.

[83] J. Kani, F. Bourgart, A. Cui, A. Rafel, M. Campbell, R. Davey, and S. Rodrigues, "Next-generation PON-part I: Technology roadmap and general requirements," IEEE Communications Magazine, vol.47, no.11, pp.43-49, November 2009

[84] M.D. Vaughn, D. Kozischek, D. Meis, A. Boskovic and R.E. Wagner, "Value of reach-and-split ratio increase in FTTH access networks," Journal of Lightwave Technology, vol.22, no.11, pp.2617-2622, Nov. 2004

[85] D. Lavery and S.J Savory, "Digital coherent technology for long-reach optical access," Optical Fiber Communications Conference and Exhibition (OFC), 2014 , vol., no., pp.1-3, March 2014

[86] G. Kramer and G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," IEEE Communications Magazine, vol.40, no.2, pp.66-73, Feb 2002

[87] M.P. McGarry, M. Reisslein, and M. Maier, "Ethernet passive optical network architectures and dynamic bandwidth allocation algorithms," IEEE Communications Surveys & Tutorials, vol.10, no.3, pp.46-60, Third Quarter 2008

[88] M. C. Yuang, P. Tien, J. Chen, H. Chen, “An energy and cost efficient WDM / OFDMA PON system : Design and Demonstration,” Journal of Lightwave Technology, vol. 31, no. 16, pp. 2809–2816, 2013.

[89] 249025-ICT OASE Project, Requirements for European Next-Generation Optical Access Networks, D2.1.

[90] M. Tadokoro, R. Kubo, S. Nishihara, T. Yamada, and H. Nakamura, “Adaptive Bandwidth Aggregation Mechanisms Using a Shared Wavelength for Energy-Efficient WDM / TDM-PON,” The 10th International Conference on Optical Internet, pp. 87–88, 2012.

[91] C. Lee, W. V Sorin, and B. Y. Kim, “Fiber to the Home Using a PON Infrastructure,” J. Light. Technol., vol. 24, no. 12, pp. 4568–4583, 2006.

[92] M. De Andrade, A. Buttaboni, M. Tornatore, P. Boffi, P. Martelli, and A. Pattavina, “Optimization of long-reach TDM/WDM passive optical networks,” Opt. Switch. Netw., vol. 16, pp. 36–45, 2015.

[93] A. Dixit, B. Lannoo, G. Das, D. Colle, M. Pickavet, and P. Demeester, “Flexibility Evaluation of Hybrid WDM / TDM PONs,” in EEE 5th International Conference on Advanced Networks and Telecommunication Systems (ANTS), pp. 1–6, 2011.

[94] A. B. Ruffin, J. D. Downie, and J. Hurley, “Purely passive long reach 10 GE-PON architecture based on duobinary signals and ultra-low loss optical fiber,” in OFC/NFOEC 2008 - 2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference, 2008, pp. 17–19.

[95] T. Franck, T. N. Nielsen, A. Stentz, B. Laboratories, and L. Technologies, “Experimental verification of SBS suppression by duobinary modulation,” in ECOC, 1997, no. 448, pp. 22–25.

[96] J. Song, C. Yang, Q. Zhang, and X. Huang, “Energy efficiency evaluation of tree-topology 10 gigabit ethernet passive optical network and ring-topology time- and wavelength-division-multiplexed passive optical network”, Opt. Eng. 54(9), 090502.

[97] H. Feng, C. J. Chae, A. V. Tran and A. Nirmalathas, "Cost-Effective Introduction and Energy-Efficient Operation of Long-Reach WDM/TDM PON Systems," Journal of Lightwave Technology, vol. 29, no. 21, pp. 3135-3143, Nov.1, 2011.

[98] J. i. Kani, S. Shimazu, N. Yoshimoto and H. Hadama, "Energy efficient optical access network technologies," 2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference, Los Angeles, CA, 2011, pp. 1-3.

[99] Y. Yuan, P. Lu, J. J. P. C. Rodrigues and Z. Zhu, "Improving energy-efficiency of HFC networks with a master-slave linecard configuration," 2013 IEEE International Conference on Communications (ICC), Budapest, 2013, pp. 4159-4163.

[100] Z. Zhu, "Design of energy-saving algorithms for hybrid fiber coaxial networks based on the DOCSIS 3.0 standard," in IEEE/OSA Journal of Optical Communications and Networking, vol. 4, no. 6, pp. 449-456, June 2012.

[101] Z. Zhu, P. Lu, J. J. P. C. Rodrigues and Y. Wen, "Energy-efficient wideband cable access networks in future smart cities," in IEEE Communications Magazine, vol. 51, no. 6, pp. 94-100, June 2013.

[102] P. Lu, Y. Yuan, Z. Yang and Z. Zhu, "On the performance analysis of energy-efficient upstream scheduling for hybrid fiber-coaxial networks with channel bonding," in IEEE Communications Letters, vol. 17, no. 5, pp. 1020-1023, May 2013.

[103] B. C. Chatterjee, N. Sarma and E. Oki, "Routing and spectrum allocation in elastic optical networks: A Tutorial," in IEEE Communications Surveys & Tutorials, vol. 17, no. 3, pp. 1776-1800, thirdquarter 2015.

[104] B. C. Chatterjee and E. Oki, "Performance evaluation of spectrum allocation policies for elastic optical networks," 2015 17th International Conference on Transparent Optical Networks (ICTON), Budapest, 2015, pp. 1-4.

[105] G. Zhang, M. De Leenheer, A. Morea and B. Mukherjee, "A survey on OFDM-Based elastic core optical networking," in IEEE Communications Surveys & Tutorials, vol. 15, no. 1, pp. 65-87, First Quarter 2013.

[106] G. Zhang, M. De Leenheer and B. Mukherjee, "Optical traffic grooming in OFDM-based elastic optical networks [Invited]," in IEEE/OSA Journal of Optical Communications and Networking, vol. 4, no. 11, pp. B17-B25, Nov. 2012.

[107] C. Bock, J. Prat and S. D. Walker, "Hybrid WDM/TDM PON using the AWG FSR and featuring centralized light generation and dynamic bandwidth allocation," in Journal of Lightwave Technology, vol. 23, no. 12, pp. 3981-3988, Dec. 2005. doi: 10.1109/JLT.2005.853138.

[108] J. Zhang and N. Ansari, "Minimizing the Arrayed Waveguide Grating Cost and the Optical Cable Cost in Deploying WDM Passive Optical Networks," in IEEE/OSA Journal of Optical Communications and Networking, vol. 1, no. 5, pp. 352-365, Oct. 2009. doi: 10.1364/JOCN.1.000352.

[109] G. Maier, M. Martinelli, A. Pattavina and E. Salvadori, "Design and cost performance of the multistage WDM-PON access networks," in Journal of Lightwave Technology, vol. 18, no. 2, pp. 125-143, Feb. 2000. doi: 10.1109/50.822785.

[110] J. Dai, F. Zhou, M. Zhang, and D. Liu, "Electro-optical tunable arrayed waveguide grating based on liquid crystal clad waveguide," in International Photonics and Opto Electronics Meetings, OSA Technical Digest (online) (Optical Society of America, 2014), paper OTh4C.8.

[111] W. Horn, S. Kroesen, J. Herrmann, J. Imbrock, and C. Denz, "Electro-optical tunable waveguide Bragg gratings in lithium niobate induced by femtosecond laser writing," Opt. Express 20, 26922-26928 (2012)

[112] S. Toyoda, N. Ooba, T. Kitoh, T. Kurihara and T. Maruno, "Wide tuning range and low operating power AWG-based thermo-optic wavelength tunable filter using polymer waveguides," in Electronics Letters, vol. 37, no. 18, pp. 1130-1132, 30 Aug 2001.

[113] Y. Yang, X. Hu, J. Song, Q. Fang, M. Yu, X. Tu, "Thermo-Optically Tunable Silicon AWG with above 600 GHz channel tunability," in IEEE Photonics Technology Letters, vol. 27, no. 22, pp. 2351-2354, Nov.15, 15 2015.

[114] H. Zhang, C. Ma, Z. Qin, X. Zhang, and D. Zhang, “Thermo-optic tunable polymer arrayed waveguide grating”. Opt. Eng. Vol. 46 no. 5:054601-054601-4, 21 May 2007.

[115] S. Haxha, B. Rahman, R. Langley, M. Sciences and N. Square, “Broadband and low-driving-power LiNbO3 electrooptic modulators,” Opt. Quantum Electron., vol. 36, no. 14, pp. 1205–1220 2005.

[116] S. Zhang, W. Ji, X. Li, K. Huang and Z. Yan, "Efficient and reliable protection mechanism in long-reach PON," in IEEE/OSA Journal of Optical Communications and Networking, vol. 8, no. 1, pp. 23-32, January 1 2016. doi: 10.1364/JOCN.8.000023.

[117] https://www.aliexpress.com

[118] https://fiber.usinternet.com/plans-and-prices/

[119] G. Talli and P. D. Townsend, “Hybrid DWDM - TDM long-reach PON for next-generation optical access,” J. Light. Technol., vol. 24, no. 7, pp. 2827–2834, 2006.

[120] M. Bitting, "New optical switches enable automated testing with true flexibility," AUTOTESTCON 2004. Proceedings, 2004, pp. 361-366.doi: 10.1109/AUTEST.2004.1436883

[121] J. V. Campenhout, W. M. J. Green, S. Assefa, and Y. A. Vlasov, "Low-power, 2×2 silicon electro-optic switch with 110-nm bandwidth for broadband reconfigurable optical networks," Opt. Express, vol. 17, no. 26, 2009.

[122] Q. Zhao and C. K. Chan, "A wavelength-division-multiplexed passive optical network with flexible optical network unit internetworking capability," in Journal of Lightwave Technology, vol. 25, no. 8, pp. 1970-1977, Aug. 2007.

[123] H. T. Lin, Z. Ho, H. C. Cheng and W. R. Chang, "SPON: A slotted long-reach PON architecture for supporting internetworking capability," Military Communications Conference, 2009. MILCOM 2009. IEEE, Boston, MA, 2009, pp. 1-8.

[124] N. Nadarajah, E. Wong and A. Nirmalathas, "Implementation of multiple secure virtual private networks over passive optical networks using electronic CDMA," in IEEE Photonics Technology Letters, vol. 18, no. 3, pp. 484-486, Feb. 1, 2006.

[125] N. Nadarajah, E. Wong and A. Nirmalathas, "Multiple virtual private networks over passive optical networks using RF subcarrier multiplexing and Fabry–pÉrot laser diodes," in IEEE Photonics Technology Letters, vol. 18, no. 19, pp. 2044-2046, Oct.1, 2006.

[126] Y. Su, P. Hu, J. Zhang, L. Leng, H. He, X. Tian, Y. Jin, "A packet-switched waveband-selective PON enabling optical Internetworking among ONUs," Optical Communication, 2005. ECOC 2005. 31st European Conference on, Glasgow, 2005, pp. 691-692 vol.3.

[127] C. J. Chae and R. S. Tucker, "A protected optical star-shaped ring network using an N x N arrayed waveguide grating and incoherent light sources," in IEEE Photonics Technology Letters, vol. 13, no. 8, pp. 878-880, Aug. 2001.

[128] N. Nadarajah, A. Nirmalathas and K. L. Lee, "Wavelength switchable base station architecture supporting upstream access and local internetworking with a single self-seeded reflective semiconductor optical amplifier," Microwave photonics, 2008. jointly held with the 2008 asia-pacific microwave photonics conference. mwp/apmp 2008. International topical meeting on, Gold Coast, Qld, 2008, pp. 221-224.

[129] C. J. Chae and R. S. Tucker, "Passive virtual optical networking technique using a cyclic N×N arrayed waveguide grating for multiple multihop ring networks," in IEEE Photonics Technology Letters, vol. 16, no. 3, pp. 948-950, March 2004.

[130] C. J. Chae, S. T. Lee, G. Y. Kim and H. Park, "A PON system suitable for internetworking optical network units using a fiber Bragg grating on the feeder fiber," in IEEE Photonics Technology Letters, vol. 11, no. 12, pp. 1686-1688, Dec. 1999.

[131] M. De Andrade, M. Tornatore and A.Pattavina,"Optimization scheme for WDM-based transmission technology selection in future passive optical networks,"IEEE/OSA Journal of Optical Communications and Networking, Volume:5 , Issue: 9,pp 1010-1020, Sept 2013.

[132] Corning Inc., “Corning SMF-28TM optical fiber product information”, Product information sheet, April 2002.

[133] R. Proietti, Z. Cao, C. J. Nitta, Y. Li and S. J. B. Yoo, "A scalable, low-latency, high-throughput, optical interconnect architecture based on arrayed waveguide grating routers," in Journal of Lightwave Technology, vol. 33, no. 4, pp. 911-920, Feb.15, 15 2015. doi: 10.1109/JLT.2015.2395352

[134] https://www.optelian.com/wp-content/uploads/2016/10/Optelian-Low-Latency-Strategy-for-OTN-WP.pdf

Publications

Journals

1. **A.K. Garg**, A.A. Madavi and V. Janyani, "Energy efficient flexible hybrid wavelength division multiplexing-time division multiplexing passive optical network with pay as you grow deployment," **Optical Engineering, SPIE, Vol.56 No.2, 026119 (2017)** http://dx.doi.org/10.1117/1.OE.56.2.026119.
2. **A.K. Garg** and V. Janyani, "Adaptive Bandwidth Mechanism Using Dual Rate OLT for Energy Efficient WDM-TDM Passive Optical Network," **Telecommunication Systems, Springer, DOI: 10.1007/s11235-017-0316-1**.
3. **A.K. Garg**, V. Janyani, "Resilient, Bandwidth Scalable and Energy Efficient Hybrid PON Architecture", **Telecommunication Systems, Springer** https://doi.org/10.1007/s11235-017-0369-1.
4. **A.K. Garg**, V. Janyani, "Analysis of OOK Upstream Signal Remodulation for Different Data Rates in WDM-PON Network", **International Journal of Signal Processing Systems,** Vol. 3, No. 2, pp. 134-138, December 2015. **doi: 10.12720/ijsps.3.2.134-138**.
5. **A.K. Garg**, V. Janyani, G. Singh, T. Ismail & H. Selmy "WDM-PON for Dedicated and Broadcasting Downstream Transmission with Energy-Efficient and Latency-Aware ONU Interconnection Capability," **Telecommunication Systems, Springer,** (***under review***).

Conferences

1. **A.K. Garg**, V. Janyani, "Direct ONU Interconnection Schemes Towards Latency-Aware Passive Optical Networks", IEEE International Conference on Computer, Communications and Electronics, pp. 505-510, 01-02, July. 2017, doi: 10.1109/COMPTELIX.2017.8004022.
2. M.B. Dipikaben, **A.K. Garg**, V. Janyani, "A Flexible Remote-Node Architecture for Energy-Efficient Direct ONU Internetworking in TDM-PON", IEEE International

Conference on Computer, Communications and Electronics, pp. 453-45701-02, July. 2017, doi: 10.1109/COMPTELIX.2017.8004012

3. **A.K. Garg**, V. Janyani, “Overall/ Subgroup ONU Intercommunication based on Two Stage Flexible PON Network”, The International Conference on Fiber Optics and Photonics (**PHOTONICS 2016**), 4-8 December 2016, **Indian Institute of Technology, Kanpur, India**. Paper W3A.1. https://doi.org/10.1364/PHOTONICS.2016.W3A.1.
4. **A.K. Garg**, V. Janyani, “WDM-PON Network for Simultaneous Upstream Transmission with ONU Interconnection Capability”, The International Conference on Fiber Optics and Photonics **(PHOTONICS 2016)**, 4-8 December 2016, **Indian Institute of Technology, Kanpur, India**. Paper Tu4A.13. https://doi.org/10.1364/PHOTONICS.2016.Tu4A.13.
5. **A.K. Garg**, V. Janyani, “Power Budget Improvement in Energy Efficient Long Reach Hybrid Passive Optical Network”, IEEE International Conference on Microwave and Photonics (ICMAP-2015), **Indian Institute of Technology, Dhanbad (ISM Dhanbad),** 11-13, Dec. 2015. https://doi.org/10.1109/ICMAP.2015.7408789.
6. **A.K. Garg**, V. Janyani, “Identification of Cost and Energy Efficient Multiplexing Techniques for LR-PON for Different Network Scenario”, IEEE Workshop on Recent Advances in Photonics, **Indian Institute of Science (IISC) Bangalore**, 16-17, Dec. 2015. https://doi.org/10.1109/WRAP.2015.7805998.
7. A.A.Madavi, **A.K. Garg**, V. Janyani, “A Novel TWDM Architecture With Efficient Power Saving”, IEEE International Conference On Computational Techniques in Information and Communication Technologies (ICCTICT-2016), Indraprastha University Delhi, 11-13, March. 2016, https://doi.org/10.1109/ICCTICT.2016.7514552.
8. **A.K. Garg**, V. Janyani, “Analysis of Energy Efficient Optical Access Network for Different Coding and Data Rates” OSA IONS Asia 6, 2014, **Indian Institute of Technology, Kharagpur, India**.
9. **A.K. Garg**, M.K. Gupta, G. Singh, V. Janyani, “Flexible Hybrid WDM-TDM-PON Architecture” IETE Zonal Seminar-North, A National Conference on **ICT in**

Healthcare, MNIT Jaipur, March 5th, 2016.

Book Chapter

1. A. Sharma, **A.K. Garg,** V. Janyani, "Performance Analysis of Different PON Standards Up-To 10Gbps for Bidirectional Transmission Employing Square Root Module", **Progress in Advanced Computing and Intelligent Engineering, Advances in Intelligent Systems and Computing**, pp 529-537, vol. 563, Springer, Singapore, 2018.

Brief CV

Amit Kumar Garg is the research scholar in the Department of Electronics and Communication Engineering at Malaviya National Institute of Technology (MNIT), Jaipur, India. He received B.E. and M.Tech in ECE from the University of Rajasthan and MNIT Jaipur in 2009 and 2013 respectively. His current research interest includes Fiber Optics & Communication; High-Speed Gigabit Passive Optical Networks (GPON); Flexible, Cost & Energy efficient, Latency-Aware, Bandwidth Scalable and Resilient Optical Access Networks. He is the active student member of SPIE and OSA. He is also the reviewer of various reputed journals including Optical Engineering (SPIE) and Optik (Elsevier). He is the recipient of SPIE Officer Travel Grant to attend "Student Chapter Leadership Workshop (SCLW) 2017", during SPIE Optical Metrology, 24 -29 June 2017, Munich, Germany.