A

**Dissertation Report**

On

# ONU-Internetworking in Passive Optical Networks

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*in the partial fulfilment of the requirements for the award of the degree*

*of*

**Master of Technology**

**in Electronics & Communication Engineering with Specialization**

**in "Wireless & Optical Communication"**

*by*

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# CERTIFICATE

This is to certify that the thesis entitled, "ONU Internetworking in Passive Optical Networks" submitted by **Ms. Baria Dipikaben Manharbhai** to the **MNIT, Jaipur,** is a record of bonafide thesis work that has been done by her under my supervision and guidance in order to get considered for the award of degree of Master of Technology in the Department of Electronics & Communication Engineering with Specialization in "Wireless & Optical Communication" of the Institute.

**Place: Jaipur**                                        **Dr. Vijay Janyani**

**Date:**                                                    **(Assoc. Prof., ECE Dept.)**

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**Baria Dipikaben Manharbhai**

# ABSTRACT

For the ever increasing bandwidth hungry applications, Passive Optical Network (PON) is assumed to be an effective solution. It is a system which leads optical fiber cables and signals all or most to the end user. It is a technology of telecommunication that implements a point to multipoint architecture and utilizes unpowered components to enable a single fiber to serve multiple end users without the need of having individual fibers between the customer and the hub.

We propose and demonstrate a Remote Node (RN) architecture that enables direct Optical Network Unit (ONU) internetworking within a group and/or with another group by using Fiber Bragg Grating (FBG) array in Time Division Multiplexed PON (TDM-PON). The specific wavelength assignments are used for the traffic intended for various virtual private groups formed in the network and to be received by the specific group of ONUs, for overall broadcasting and to be received by all ONUs in the network. The proposed architecture supports downstream, upstream and direct inter-ONU transmission simultaneously.

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# List of Abbreviations

| | |
|---|---|
| ADSL | Asymmetric Digital Subscriber Line |
| AWG | Arrayed Waveguide Grating |
| BER | Bit Error Rate |
| BMR | Burst Mode Receiver |
| BMT | Burst Mode Transmitter |
| CO | Central Office |
| COF | Comb of Filter |
| CSMA/CD | Carrier Sense Multiple Access/Collision Detection |
| CWDM | Coarse Wavelength Division Multiplexing |
| DB | Duo-Binary |
| DFB | Distributed Feedback |
| DSL | Digital Subscriber Line |
| DWDM | Dense Wavelength Division Multiplexing |
| E-CDMA | Electronic Code Division Multiple Access |
| EDFA | Erbium Doped Fiber Amplifier |
| EPON | Ethernet Passive Optical Network |
| FBG | Fiber Bragg Grating |
| FP-LD | Fabry–Perot laser diode |
| FTTH | Fiber To The Home |
| HDTV | High Definition Television |
| IP | Internet Protocol |
| IPTV | Internet Protocol Television |
| LAN | Local Area Network |
| MAC | Media Access Control |
| MZM | Mach-Zehnder Modulator |
| OC | Optical Combiner |
| OCDMA | Optical Code Division Multiple Access |
| ODN | Optical Distribution Network |

| | |
|---|---|
| OF | Optical Filter |
| OFDM-PON | Orthogonal Frequency Division Multiplexed PON |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OLT | Optical Line Terminal |
| ONT | Optical Network Terminal |
| ONU | Optical Network Unit |
| OSW | Optical Switch |
| OVCD | Optical VPN Circulator Device |
| PC | Power Combiner/Coupler |
| PDH | Plesiochronous Digital Hierarchy |
| PON | Passive Optical Network |
| PS | Power Splitter |
| QoS | Quality of Service |
| RF | Radio Frequency |
| RN | Remote Node |
| RX | Receiver |
| SC | Star Coupler |
| SCM | Sub Carrier Multiplexing |
| SDH | Synchronous Digital Hierarchy |
| SMF | Single Mode Fiber |
| SONET | Synchronous Optical Networking |
| TDM | Time Division Multiplexing |
| TDMA | Time Division Multiple Access |
| TDM-PON | Time Division Multiplexed PON |
| TX | Transmitter |
| VPG | Virtual Private Group |
| VPN | Virtual Private Network |
| WB | Wave Band |
| WDM | Wavelength Division Multiplexing |
| WDM-PON | Wavelength Division Multiplexed PON |

# Chapter 1                                                      Introduction

With the turn of the century, we can witness tremendous innovations in the area of telecommunications which have too much impact on our day to day life. So many factors are responsible and drive these innovations. The very first is the never ending requirement for increasing network capacity. This is fulfilled by various elements. The enormous advancements of the World Wide Web and the Internet in context of the users and the time, and hence bandwidth consumed by each user, is a main factor. The traffic on internet has been increasing speedily for a very long time. Concurrently, the broadband access technologies like Digital Subscriber Line (DSL) and cable modems, that provide bandwidths per subscriber on the order of 1 Mbps, have been set up generally. Fiber to the home (FTTH) solution has shown the greatest penetration in the market. Simultaneously, current businesses depend on the faster networks for their businesses. There is a substantial relation between the bandwidth cost and the increase in demand. The advancements in the technology have led to continuous reduction in cost of the bandwidth. This results in increased use of bandwidth due to launch of new applications and impact on usual pattern. For example, if the call rates get reduced, users talk more on the phone. This leads to requirement of more bandwidth. This cycle shows no chances of decrease in near future. The other point that is challenging in the industry is the isolationism of telephone industry. In addition, the network traffic is majorly data instead of being limited to only voice. Formerly, the situation was reverse and networks were designed to handle voice traffic well rather than data. But today, data transfer services have been dominant and have capabilities of providing QoS to the real-time applications. These factors have major contribution in the development of Optical Networks with tremendous capacity and their noticeably quick commercial deployment into real world from the research laboratories. Currently Optical Networks are being deployed in a wide extend to meet the ever increasing requirements of high date rates of number of users. Today, so many public networks are being employed by the service providers [2].

## 1.1    Telecommunication Network Types

Typical fiber telecommunication network can be complex and vast and various parts of the network can be operated and owned by different carriers. These networks are broadly divided into three types:

1.    Long Haul Networks
2.    Metropolitan Networks
3.    Access Networks

## 1.1.1  Long Haul Networks

Long-haul networks carry a huge amount of data than any other networks and covering much greater distances that can reach over hundreds and thousands of kilometers connecting the continents and countries distributed geographically worldwide [1] [2]. Typical rates of operation of these networks are 2.5 Gbps and 10 Gbps. However, the efforts are going on to implement 40 Gbps transmission in to provide the extra bandwidth requirements as a result of applications requiring higher bandwidth requirements. As long haul networks cover much greater distances, it is a challenging task to keep the signal clear and the losses minimum possible. Finding the most efficient fiber with least dispersion is a crucial matter for signals to travel longer distance and hence outstanding optical fibers have been designed for this application. Moreover in  long haul networks using Erbium Doped Fiber Amplifiers (EDFAs) [3], regeneration of transmitted signal must be done at every 400 km or so (based on EDFA performance) so as to combat the signal losses due to distortion and attenuation caused by dispersion, fiber non-linear effects and noise generated by EDFA itself. This regeneration equipment is required on a per-channel basis, which is costly. However, a combination of a hybrid distributed Raman amplifier and an EDFA has led to the extended regeneration-site spacing from 500 km to 2000 km. In these networks, Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM) are used to meet the requirements for distance, bit rate, and capacity.

## 1.1.2 Metropolitan Networks

Metropolitan (or Metro) networks are the connecting agent between first-mile network areas (access networks) and long-haul networks. The Metropolitan Network is designed in order to connect networks in a metropolitan area, city, campus, community, etc. with dedicated or high performance hardware. It spans more than Access Network which can only be used in one building, floor or wide room but less than Long haul Network which goes beyond one area or city to another location. Hence the coverage of Metropolitan network in terms of geography is between Access Network and Long Haul Network. They also combine many next-generation technologies including optical transmission over DWDM or coarse WDM (CWDM) rings, traditional circuit-switched transport protocols (SONET/SDH/PDH) and data protocols like Ethernet, IP and Fiber Channel. Over the last few years, Ethernet has come out as a leading solution in Metropolitan networks.

## 1.1.3 Access Networks

Access Network is a network that connects directly the end user or customer to the immediate service provider and through the carrier network, to other networks such as the Internet. It feeds Metropolitan Networks by gathering data. It covers a distance of 0 to 20 km [3].
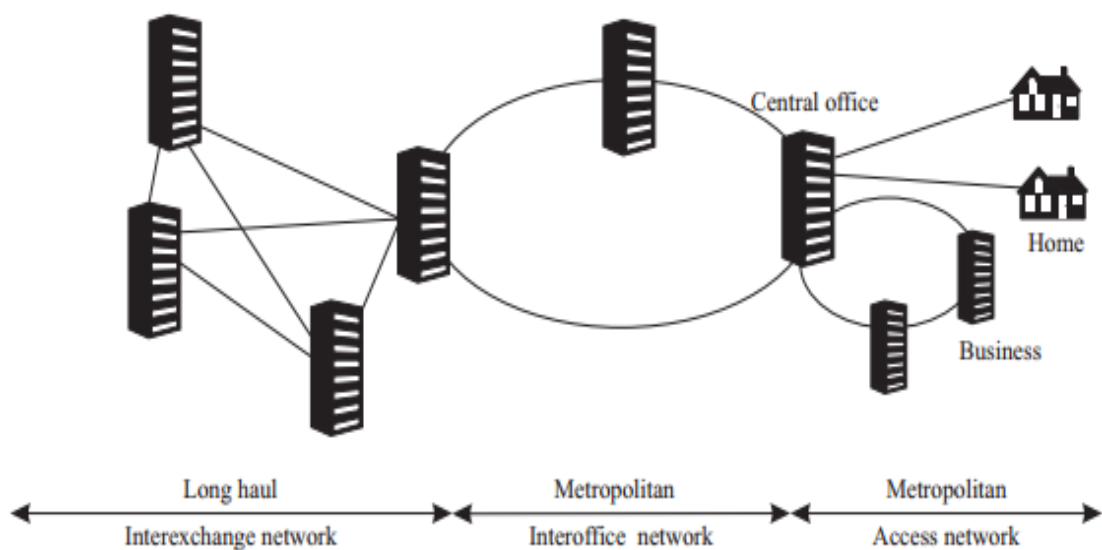


Figure 1.1  Various parts of Telecommunication Network [3]

There are various types of access networks available nowadays. The most commonly installed wired Local Area Network (LAN). It typically uses coaxial cable or twisted pair wires with special grades. By using wireless LANs mobile users can connect via wireless connection. Optical fiber networks such as FTTH use optical fiber from a central hub directly to individual buildings like residents and offices. Asymmetric Digital Subscriber Line (ADSL) is a type of DSL technology, a data communications technology that enable information transmission at a high bandwidth over copper transmission lines to homes and offices. However, copper wire lines are unable to support the ever increasing broadband applications such as High Definition Television (HDTV). Therefore, FTTH will be a promising for such applications. Among all access networks PONs are the most promising solution for the ever increasing bandwidth hungry applications of broadband access networks.

## 1.2 Passive Optical Networks

Passive Optical Network (PON) [4-6] consist mainly three parts namely an Optical Line Terminal (OLT) or Central Office (CO), Remote Node (RN) or Optical Distribution Network (ODN) at mid-path and a number of Optical Network Unit (ONU) or Optical Network Terminal (ONT) at end user as shown in Figure 1.2 [4]. An OLT acts as the endpoint hardware device in a PON. It includes a gateway router (GWR), central processing unit (CPU), PON cards and a voice gateway (VGW) uplink cards. Equipment at the customer end is called ONU. In PON, only OLT and ONUs use active (powered) components while the RN used passive (unpowered) components like Power Splitters (PSs), Power Combiners (PCs), Arrayed Waveguide Grating (AWG), Fiber Bragg Grating (FBG), etc. and hence it is called passive network. Due to the use of passive components and avoidance of active components like electronic amplifiers and regenerators between OLT and RN, these networks are energy efficient networks with significantly reduced cost. The fiber between OLT and RN is called feeder fiber which ranges from 20 km or more while that between RN and ONUs is called distribution fiber which usually ranges several kilometers.
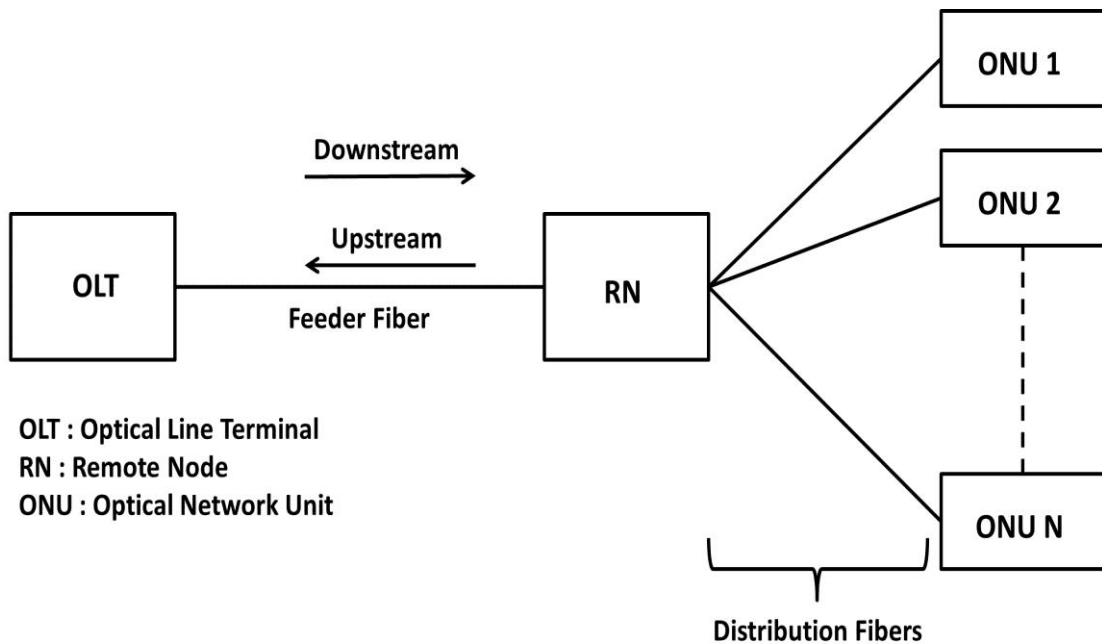
Figure 1.2  Typical PON Architecture [4]

PON is a point to multipoint network which lessens the amount of fiber required and OLT equipment as compared to point to point network. The transmission from ONUs to the OLT is called upstream transmission and that from the OLT to ONUs is called downstream transmission. In the downstream, the traffic is broadcasted while in the upstream it is time division multiplexed.

## 1.3    TDM-PON

In PON, TDM-PON [7] is a concept used for access and long haul networks in order to accommodate more number of users in a network. It is the first PON technology to be standardized and deployed. In the uplink, all ONUs share the same fiber through Time Division Multiple Access (TDMA) by transmitting the signal in specified time duration, and in the downlink direction, the OLT coordinates the ONUs to transmit frames specified for particular ONU in the specific time interval as shown in Figure 1.3. To avoid collisions in the upstream some point to multipoint media access protocols are to be used.  At RN, the downstream signal is split via power splitter and the same signal is received at each ONU in the network. Each ONU detects the signal intended for it according to the specific time slot.
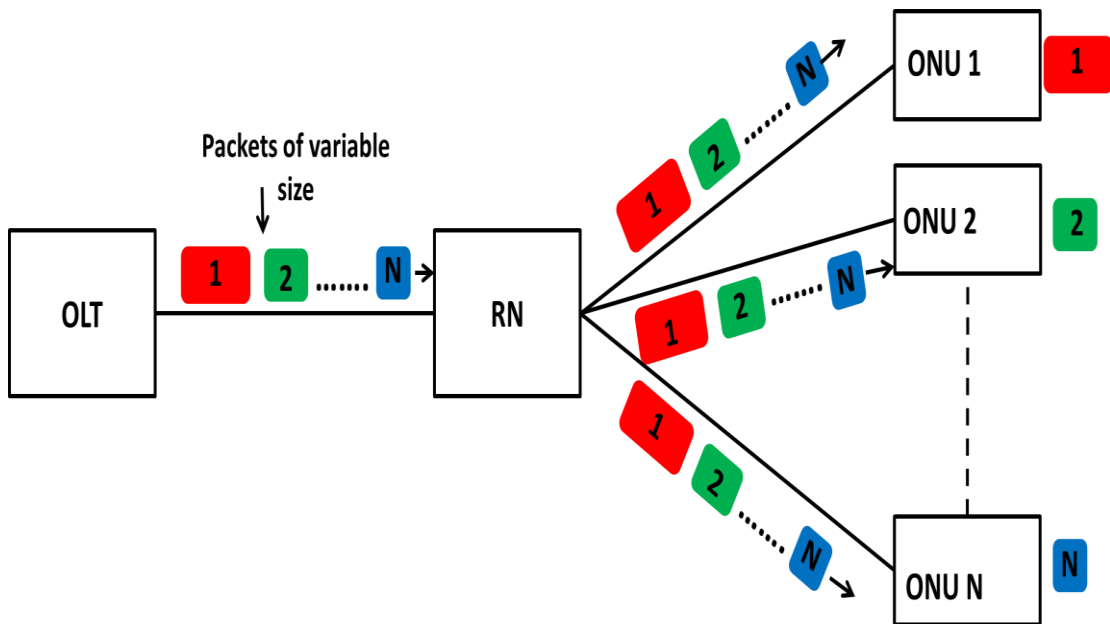
Figure 1.3 TDM-PON Architecture [7]

In this PON, all ONU have identical transceivers and TDMA is implemented in electronic domain, this method has been practical and effective solution for the access networks over the globe. But this strategy has some problems problem regarding the difference in distance between different ONUs and RN, therefore, different delays are occurred in the upstream direction, capacity issues due to time sharing, security issues as power split signal is received by all ONUs, requirement of burst mode receiver, etc. The problem of different delays is solved by implementing a procedure called ranging [8] in which the distance of the ONUs from OLT is determined by special control frames and this is used to calculate the exact time of transmission [8]. Predominantly, due to the time sharing and power splitting mechanism, TDM-PON foists some limitations on flexibility and privacy of the network. These issues can be relieved by introducing new technology named Wavelength Division Multiplexing in PON (WDM-PON).

## 1.4    WDM-PON

In PON, WDM-PON [9] [10] [11] is an innovative concept for access and long haul networks. It provides a logical point-to-point architecture by using multiple different wavelengths in the fiber infrastructure that contains no active component in order to increase capacity.
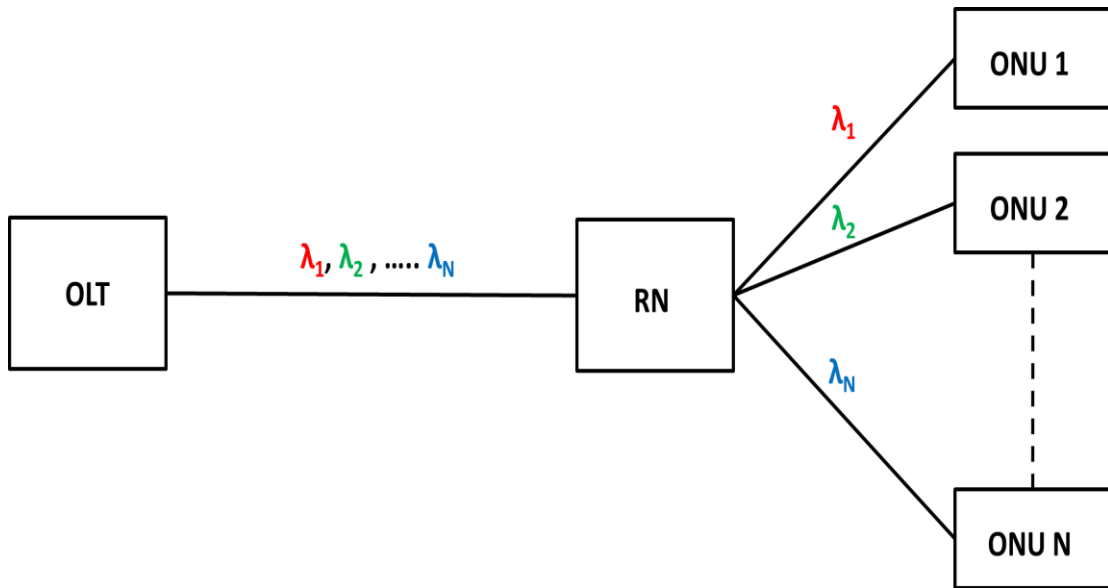
Figure 1.4 WDM-PON Architecture [9]

In WDM-PON upstream is transmitted on different set of wavelengths and downstream traffic is also transmitted on different set of wavelengths as shown in Figure 1.4. For this purpose, a number of transceivers operating at different wavelengths are employed at the OLT and at ONUs, a set of transmitter and receiver with specific wavelength is employed. At RN, a WDM multiplexer and de-multiplexer are required to route specific wavelength to specific ONU. AWG [12] or thin film filter is generally used as multiplexer. For the downstream transmission, the signal at different wavelengths are generated at the OLT, multiplexed and travels through the feeder fiber, on reaching at RN, gets power split and received by all ONUs via filtering and detection process. For the upstream transmission, signals at different wavelengths from different ONUs are multiplexed at RN and gets transmitted to OLT traveling distribution fiber, RN and feeder fiber. This method has a certain guaranteed QoS for broadband services. Moreover, there is no problem of ranging, security and power. It simplifies the control and electronics in the network. However, the cost for dedicated transceivers is still high as compared to TDM-PON, the subscribers can be benefited from extra high available bandwidth. In future, with the research in innovative WDM architectures with colorless ONUs and advancements in the technology, we can expect that the problem of cost will also get partially alleviated.

## 1.5    Objective

▪    In the regular transmission in PONs, the inter-ONU traffic travels with the upstream, scheduled at CO and is directed back towards the destination ONU like downstream transmission. This leads to the increased latency, bandwidth occupancy on upstream as well as downstream, load at CO, power consumption, etc. To reduce these parameters, direct inter-ONU communication has been introduced.

▪    The main objective of the work is to propose an ONU-internetworking scheme that enables overall broadcasting of inter-ONU traffic. In addition to that, achieve Virtual Private Group (VPG) communication also.

## 1.6    Organization of Thesis

In this chapter we have gone through the telecommunication networks, PON and its types. The rest of the thesis is organized as follows:

**Chapter 2** presents background literature in the area of research in ONU-internetworking. It is focused on fundamental concepts on ONU-internetworking. It also explains the role of ONU-internetworking and benefits. In this chapter, different previous internetworking architectures that have been proposed are discussed.

**Chapter 3** describes the proposed Flexible Remote Node Architecture for Energy Efficient Direct ONU Internetworking in TDM-PON in detail.

**Chapter 4** is focused on the simulation results obtained by using OptiSystem 13.0. These results are discussed also in this chapter.

**Chapter 5** gives the conclusion and future scope for work.

# Chapter 2 Overview of Internetworking Architectures

Nowadays, end users are more diverging towards having their own private network in addition to the public network for transferring the information quickly. People living in same apartment, relatives and office employees are the mainly supposed to have their own private network. For such private networks, communication is required to have low latency and high throughput with least power consumption. In Optical Networks, to be specific, in PONs, such private networks are usually termed as VPGs and the traffic intended for these VPGs is called inter-ONU traffic. The communication among ONUs of any VPG is called ONU-internetworking. Hence, ONU-internetworking is a technique in which one ONU in a network can communicate with the other ONUs in the same VPG and/or ONUs residing in another VPGs without the intervention of an OLT. In conventional TDM-PON, the ONUs could not directly communicate with each other.

Providing direct communication benefits the network operators as well as network customers. In view of network operators as the inter-ONU traffic can be directly transmitted and received among the ONUs without using the centralized complex routing protocol at the OLT, it seems that the direct physical connections for ONUs are provided in the networks. Hence, the bandwidths of both, upstream and downstream can be fully utilized for the high value-added broadband applications, such as IPTV, HDTV and so on, with guaranteed certain QoS. Moreover, the direct physical connections among ONUs can provide the secure transmission for the local private data. The security issue has been an increasing concern for business networking applications. Therefore, the direct ONU-internetworking is highly desirable in PONs in future. To fulfill this agenda, the inter-ONU traffic is first transmitted to OLT, it is electronically processed, scheduled and routed there and retransmitted to the ONUs. This result in increased latency, inefficient bandwidth utilization, increased processing and scheduling load at OLT and decreased throughput. To overcome these problems, ONU-internetworking is emerging as an excellent solution.

## 2.1    ONU Internetworking Methods

ONU-internetworking can be done in many different ways. But it can be broadly categorized into two methods:

1.    Inter-ONU Broadcast
2.    Formation of VPGs of ONUs

### 2.1.1  Inter-ONU Broadcast

In case of inter-ONU broadcast, the ONU can communicate with other OUNs, directly in the network without the need of being co-ordinated by the OLT. Thus, the traffic which is intended for inter-ONU communication is redirected back from the RN, broadcast to all the ONUs available in the network. Hence, the traffic is received by all the ONUs.

### 2.1.2  Formation of VPGs of ONUs

In case of some practical scenarios, inter-ONU communication is required to be done in few ONUs forming a group. Thus, by formation of VPGs/VPNs of ONUs, virtual groups of like users are formed and traffic is broadcast to the particular group only. In this, the traffic is received by a specific group of ONUs only. In this case, ONUs in other groups will not be able to receive the inter-ONU traffic. Due to this, the privacy is maintained.

The majority of researches on this topic are focused on development of practical and feasible internetworking architectures for the access networks. So many architectures have already been proposed. Besides, there are also some research interests that try to minimize the number of transmitters and receivers required, minimize the losses, maximize the power budget, improves security and to reduce cost of ONU.

In this chapter, we will review most of the previously proposed internetworking architectures by classifying them in architectures capable of inter-ONU overall broadcast and architectures capable of inter-ONU VPG broadcast communication.

Based on ONU-internetworking, so many schemes including virtual ring network [22], reflection mechanism using FBG [14], [30] loop-back mechanism [17], [20], use

of RF carrier [19], reflective waveband grouping [23], Electronic-code division multiple access (E-CDMA) [24], Sub Carrier Multiplexing (SCM) technique [25], Dynamic waveband reflection, two stage PONs [27] and many more have already been employed. Let us review all of these methods one by one. First of all, the broadcast methods have been discussed and then VPG communication methods have been discussed.

## 2.2 Inter-ONU broadcast Methods

### 2.2.1 Reflection mechanism using FBG

In this method, an FBG is placed near the star coupler (SC) as shown in the Figure 2.1, which reflects the inter-ONU traffic and hence it is broadcast in the whole network. In this, two wavelengths are used, $\lambda_0$ for regular upstream traffic and $\lambda_1$ for inter-ONU traffic. Downstream transmissions follow TDM and upstream transmissions follow TDMA [13]. The Bragg wavelength of FBG is $\lambda_1$ and due to this, it reflects that wavelength while passing the regular upstream traffic freely, experiencing a small amount of insertion loss of 0.62 dB.
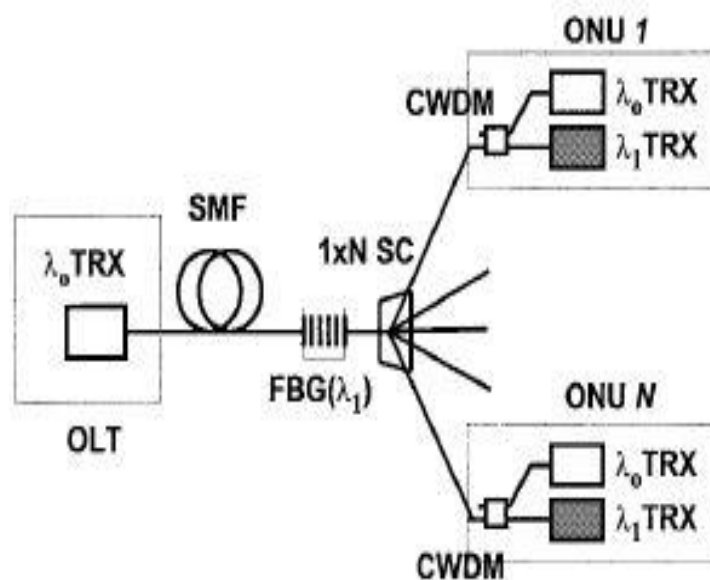


Figure 2.1 Reflection mechanism using FBG [14]

When any one of the ONUs sends its traffic using the $\lambda_1$ transceiver, that wavelength is reflected by the FBG after traveling the CWDM and the SC. No signal with this wavelength is transmitted to OLT. By the SC, this signal power gets split into two parts and gets conveyed to each ONU to detect the data. For this purpose, different MAC protocols can be used [2], [15], [16]. Although it provides a simple inter-ONU communication, a wavelength specific extra transceiver is required at each ONU and it also imposes limitation on power due to high splitting loss [14].

## 2.2.2 ONU-Internetworking Capability Among Users using CSMA/CD
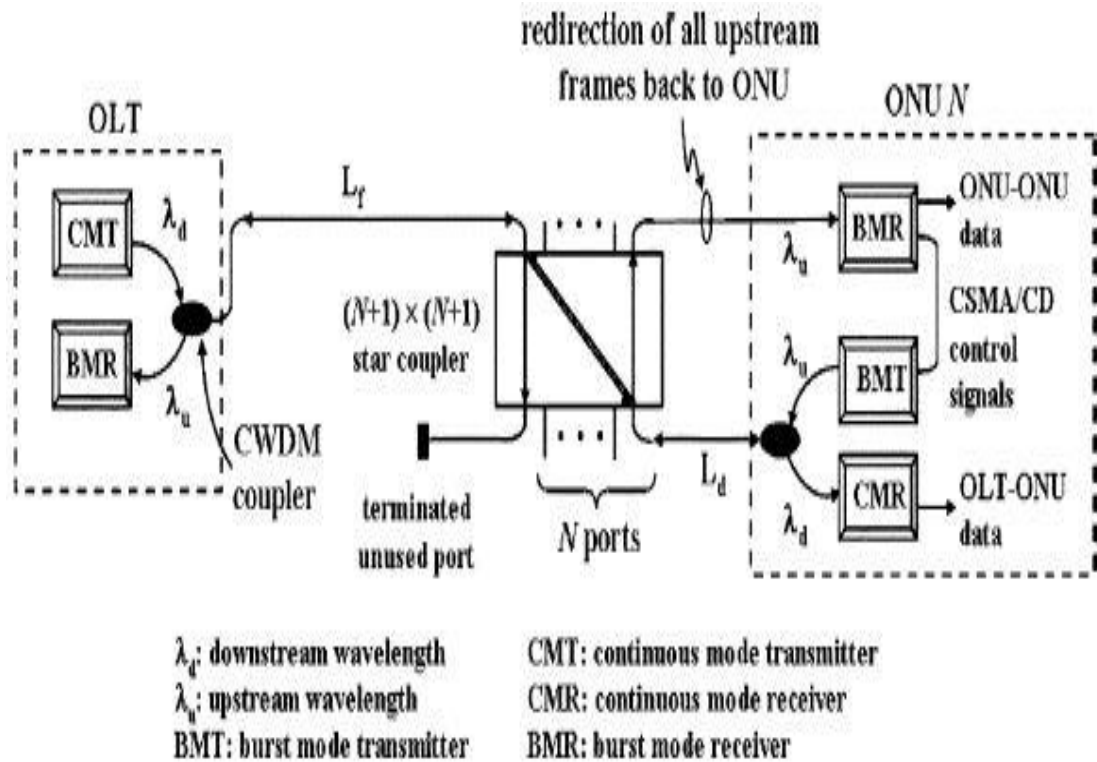


Figure 2.2 ONU-Internetworking using CSMA/CD [17]

A mechanism of loop-back was proposed in order to get the ONU-broadcast capability for TDM-PONs in [17], [18]. The (N+1) x (N+1) SC was used at the RN to transmit the inter-ONU traffic signal to all ONUs present in the network as shown in Figure 2.2. If we compare with the previous mechanism in which reflection is based on a FBG, the inter-ONU traffic will not experience high insertion loss by the round-

trip transmission through star coupler. Hence, it can majorly alleviate the problem of limited power in this scheme so as to support high speed data transmission. Though, the scheme is suitable only for the TDM-PON [17].

## 2.2.3  LAN Emulation Technique using RF carrier

In this technique, inter-ONU i.e. LAN emulation is obtained by using an FBG before SC and RF modulation of inter-ONU data. The only difference with inter-ONU data is that first of all it is amplitude modulated on an radio frequency (RF) carrier which is chosen to be out of band from upstream data using low voltage controlled oscillator. The up converted RF inter-ONU data and upstream data are electrically combined and modulated onto the same wavelength $\lambda_u$ and transmitted. The narrow band FBG placed near SC has Bragg wavelength such that it reflects one of the optically modulated sidebands and it is broadcast to all ONUs as shown in Figure 2.3.
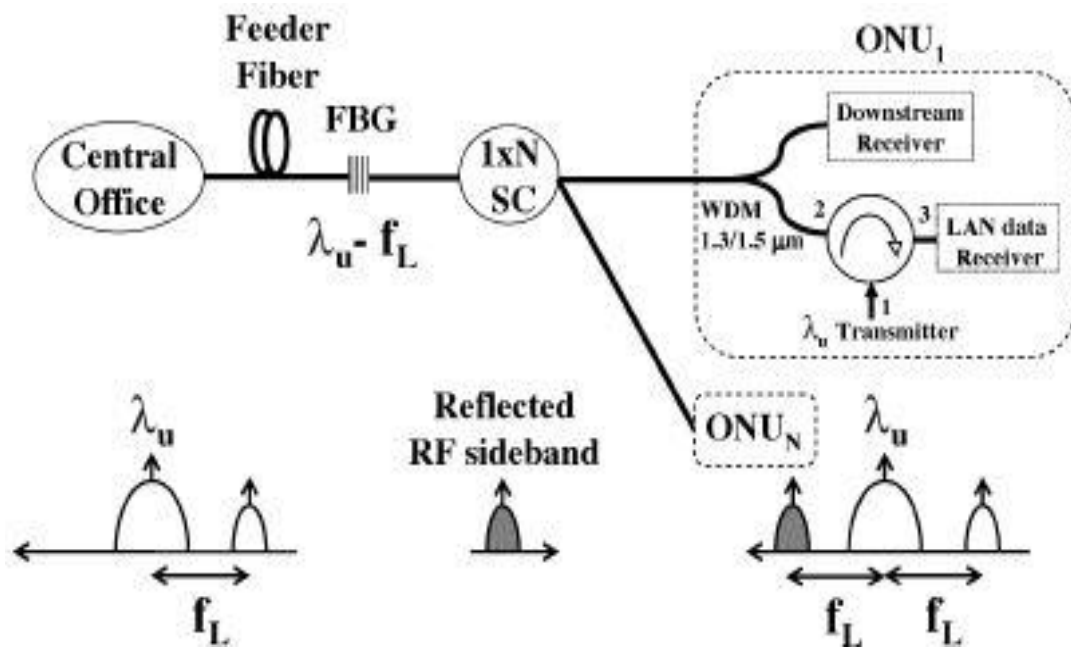


Figure 2.3  LAN Emulation Technique using RF carrier [19]

As the number of ONUs increases in this, required splits at Star Coupler (SC) also increases resulting in increased splitting loss and reduced power margin for each signal [19].

## 2.2.4 WDM-PON Network for Simultaneous Upstream Transmission with ONU Interconnection Capability

In this architecture, at remote node, 1xN AWG is used to de-multiplex the downstream signals. This AWG has the center frequency of 193.1 THz with wavelength spacing of 100 GHz between the two consecutive ports. Cascading of a 50 GHz inter-leaver has been done at each output port of 1 x N AWG as shown in Figure 2.4. These are used to separate out the even and odd multiple of 50 GHz signals into two paths. All even wavelengths are directed towards ONUs and all odd (shifted by 50 GHz) wavelengths are directed towards N x N splitter. The splitter is connected in parallel between the RN inter-leavers and ONUs.
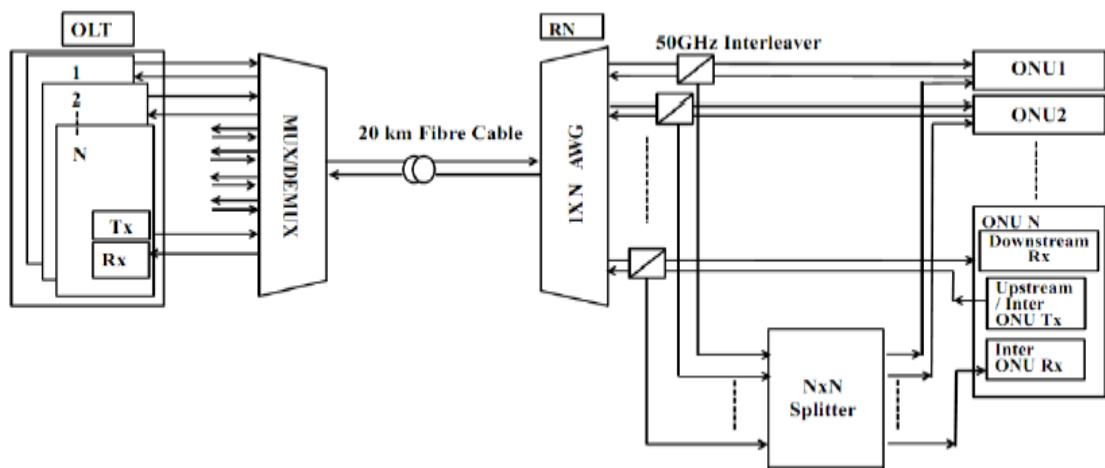


Figure 2.4  WDM-PON Network for Simultaneous Upstream Transmission with ONU Interconnection Capability [20]

The purpose of this splitter is to provide the direct intercommunication of all ONUs without the need of OLT. The downstream and upstream transmissions are done at even wavelengths, and inter-ONU communications are done at 50 GHz shifted odd wavelengths [20].

## 2.3    Formation of VPGs of ONUs

## 2.3.1  Bandwidth-Efficient PON System for Broad-Band Access and Local Customer Internetworking

As shown in the above Figure 2.5, if Optical Switch 1 (OSW1) is in bar state and OSW2 is in cross state, the PON system is in the internetworking mode. In this mode, the signal from burst mode transmitter (BMT) is passed to SC and gets split into parts. Each signal is routed to OSW1 in each ONU through CWDM and then received by burst mode receiver (BMR) via OSW2. The downstream signals reaching on OSW2 gets routed to the antireflection treated port. This enables ONUs to send internetworking data securely [18].
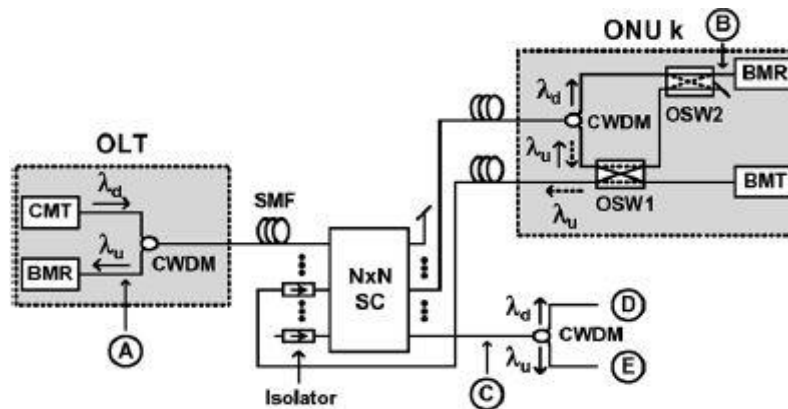


Figure 2.5  Bandwidth-Efficient PON System for Broad-Band Access and Local Customer
Internetworking [18]

## 2.3.2  Internetworking among ONUs in EPON Using OCDMA Technique

Optical CDMA (OCDMA) technique enables multiple users to access the transmission media by assigning different optical code words to different users. Also, OCDMA leads to higher spectral efficiency and higher system capacity. A specific code is assigned to each user to encode its data bits. The encoded data is transmitted and received by a designated receiver. By using this technique multiple private networks can be established on EPON. By using an FBG before SC as shown in

Figure 2.6, a specific wavelength which is taken for VPG communication can be reflected towards ONUs. This technique allows installing multiple private networks on EPON by using a particular code for particular network [21].
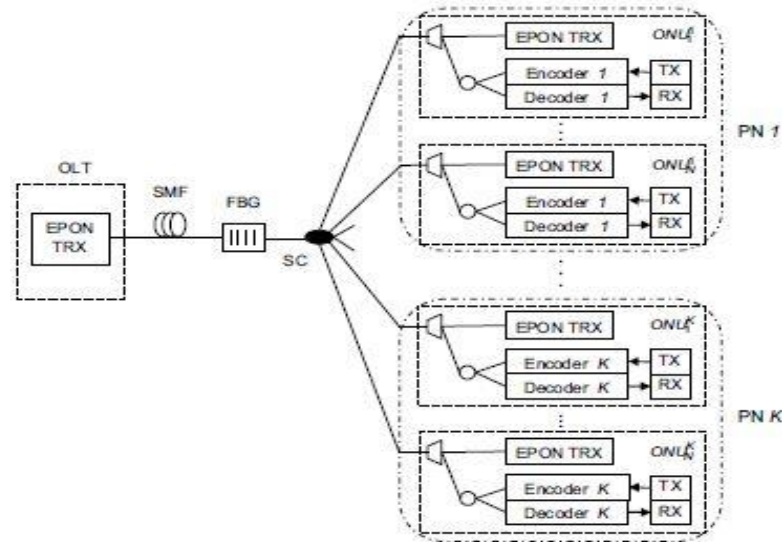


Figure 2.6  Internetworking in EPON Using OCDMA Technique [21]

## 2.3.3 Passive Virtual Optical Networking Technique Using a Cyclic N*N Arrayed Waveguide Grating for Multiple Multi-hop Ring Network

With the use of cyclic property of AWG, a more flexible solution to the multilayer internetworking has been found. The virtual ring network requires only a single fiber between two nodes is required, provides protection in case of fiber cut and it is flexible to be adjusted with changing network size. In accordance with access networks customers can choose their own protocols for control and also can manage their VPN. While the demand is increasing, a single ring network won't be able to serve the purpose of high speed networking. Hence it may be necessary to introduce a multilayer networking to meet the demands. This will lead to more than one VPN for the same group of users. The group size and number of users may vary in a VPN. The use of AWG results in flexible VPN on star configured optical network with legacy and advanced ring network protocols. This method is useful for interconnection of gigabit routers in the metropolitan area and high speed device in large buildings [22].

## 2.3.4 A Packet-Switched Waveband-selective PON Enabling Optical Internetworking among ONUs

In this, a waveband selective PON has been proposed that enables ONU-internetworking within the same waveband (WB). One pair of transmitter/receiver is required at each ONU. ONUs are grouped and form VPNs based on WBs assigned to them. The VPNs are implemented by adjusting a WB reflector, dynamically at the OLT to achieve flexible configuration. As shown in Figure 2.7, the transmitter at ONU is having a specific wavelength and adjacent wavelengths are grouped to form a WB. The receiver at ONU consists of WB filter that covers VPN wavelengths. Hence, the signal from an ONU can be transmitted to other ONUs in same VPN if WB reflector is employed at OLT. The WB can be reconfigured dynamically to handle rapid traffic [23].
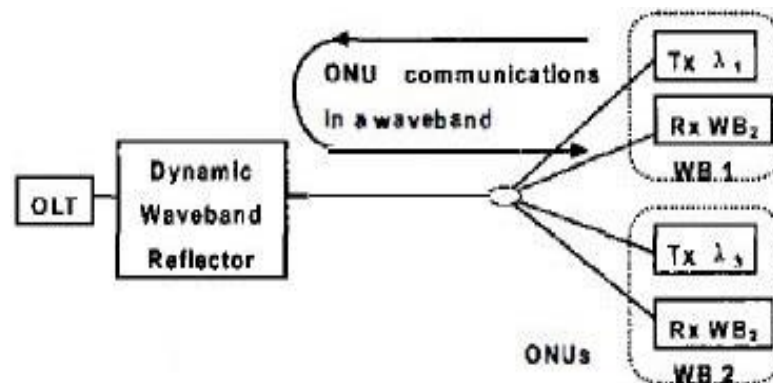


Figure 2.7  A Packet-Switched Waveband-selective PON Enabling Optical Internetworking [23]

## 2.3.5 Multiple Secure VPNs Using Electronic CDMA

In this scheme, each ONU is allocated a unique E-CDMA code, which is multiplexed with the data that is intended for the VPN and decoded by the one who has that unique code. As shown in the Figure 2.8, the system uses (N+1) x (N+1) SC to which N ONUs are connected via two distribution fibers. The transmitted E-CDMA signal is redirected to each ONU via second distribution fiber. The upstream transmission takes place at 1.3 μm while E-CDMA signal is transmitted at 1.5 μm.
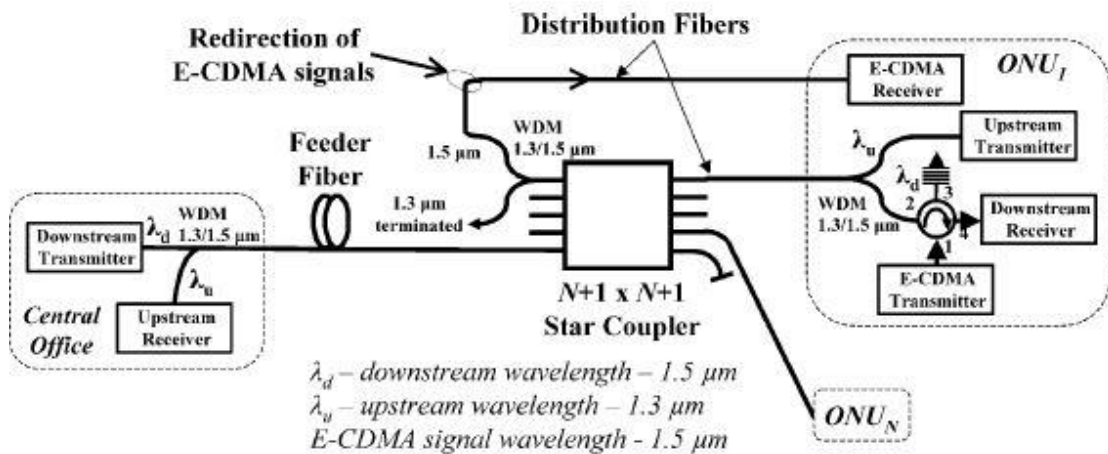
Figure 2.8  Multiple Secure VPNs Using Electronic CDMA [24]

To separate these, a CWDM coupler is used at the SC.   Several VPN transmissions can be possible using various electronic codes. Moreover, VPN transmission can take place at any time rather than specific time slot in TDMA and hence, alleviates the requirement of burst mode receiver. It also provides security of data at physical layer as it can only be decoded via a unique electronic code [24].

## 2.3.6  Multiple VPNs Using RF Subcarrier Multiplexing and Fabry– Pérot Laser Diodes
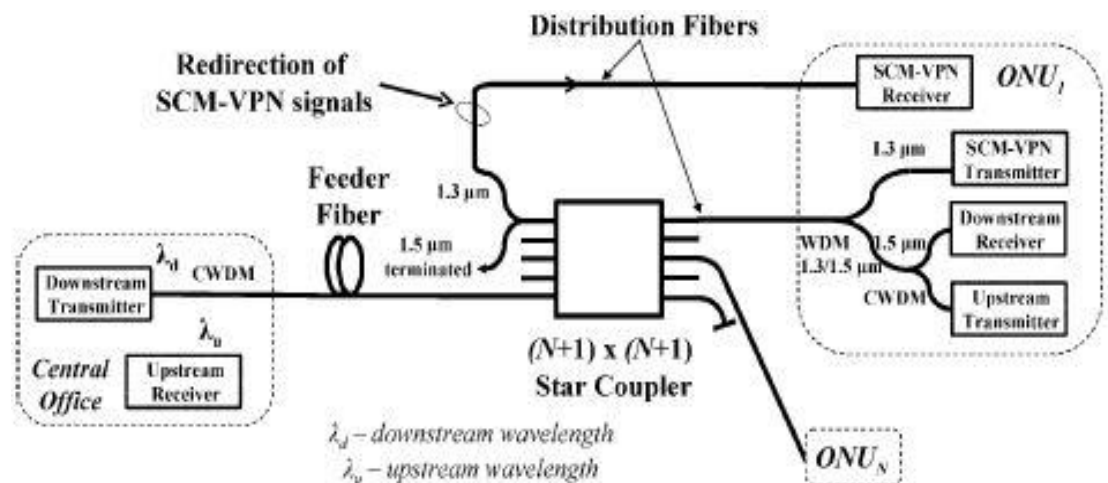


Figure 2.9  Multiple VPNs Using RF Subcarrier Multiplexing and Fabry–Pérot Laser Diodes [25]

In the previous architecture, the processing gain of E-CDMA signals imposes a limit on bandwidth of VPN traffic. The RN architecture of this scheme is almost similar to

the one discussed just before this. The only difference is in the technique of transmitting VPN traffic from ONU and receiving the same. Here, an RF SCM transmission of the VPN traffic has been proposed in order to get multiple VPNs in a single PON. The transmission of SCM-VPN signal is carried out using FP-LDs in the 1.3- m wavelength window whereas the upstream transmission is carried out using a DFB laser operating at 1.5- m wavelength window as shown in Figure 2.9. [25].

## 2.3.7 Internetworking Scheme for WDM Passive Optical Network based on Re-modulation Technique

In this, an internetworking scheme for WDM-PON using re-modulation of downstream DPSK signal using inter-ONU traffic has been discussed. By using the specific connection pattern of AWG and the channel shifting i/o property of AWG at RN, the inter-ONU traffic can be routed to all ONUs except one which transmits the traffic. Here, the data rate can be significantly increased up to 1 Gbps without any disturbance. [26].

## 2.3.8 Optical VPN Connecting ONUs in Different PONs

In this paper, VPN communication among different PONs connected in two-stage tree topology i.e. super-PON architecture has been proposed. The lower stage is conventional WDM-PON which operates in burst mode for interleaving the upstream traffic and VPN traffic. Then they are combined using a passive coupler and transmitted to an OLT through a feeder fiber. The ONUs having same color in different PONs are grouped to form one VPN. A dynamic wavelength reflector is placed at the OLT, which is configurable to reflect VPN traffic back to ONUs of same group, resulting in link of ONUs in different PONs. Figure 2.10 shows the architecture of the proposed VPN. A 1xN SC at RN broadcasts the downstream traffic to each PON, where an AWG router separates the WDM channels so as to establish point-to-point connections to each ONU. As the PONs share the same group of wavelengths, upstream data from ONUs of the same color has to be TDM [27].
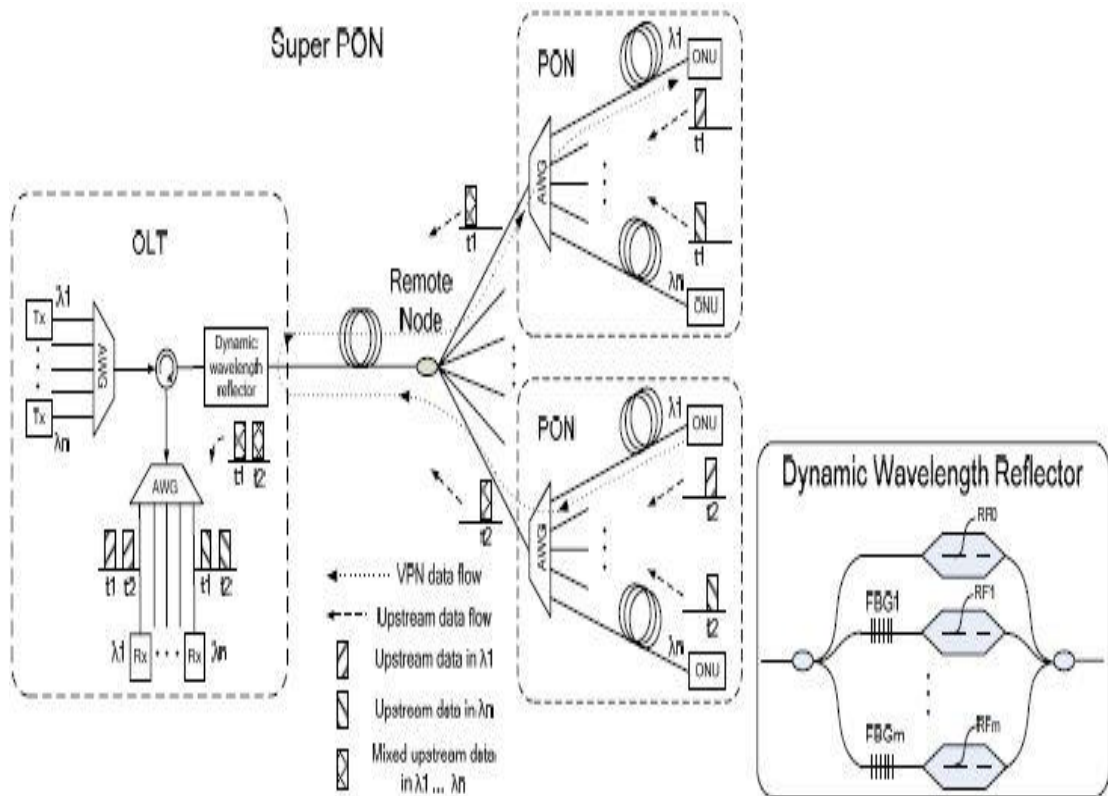
Figure 2.10 Optical VPN Connecting ONUs in Different PONs [27]

## 2.3.9 All-optical VPN and ONUs communication in optical OFDM-based PON system

Here, a novel scheme of simultaneous all-optical VPN and inter-ONU communications in optical OFDM-PON system has been proposed, Moreover, the all-optical intra-VPN/inter-VPN in one ONU group and in different ONU groups in the optical OFDM-PON system has also been achieved. In this, OFDM subcarriers have been divided into several sub-carrier bands for the traffics like one for the OLT band for the conventional traffic between each ONU and OLT, for the VPN bands for VPN traffic of different VPNs and for inter-ONU traffic the different ONU bands, etc. The allocation of subcarrier bands is scheduled by OLT, dynamically on the demand of ONUs. Guard bands are provided between every two subcarrier bands so as to separate each band in frequency. Each ONU modulates subcarrier bands with different kinds of data. The optical combiner (OC) combines these bands and directs towards OLT. At OLT, the upstream traffic gets split into two parts by optical splitter. One part goes to OLT receiver for demodulation. The other part goes to an OF, which

passes the signals in other bands while removing the signal in the OLT band. The output of the OF is combined with the OLT traffic by an OC. The downstream is directed towards the RN via the single mode fiber (SMF). At the RN, the downstream traffic enters a Comb of Filter (COF) bank which is used to extract the optical signals in different bands based on the bands allocation. Various signals are extracted and broadcast to respective ONUs [28].

## 2.3.10 Intra and Inter-PON ONU to ONU VPN networking using OFDMA in a Ring Topology

In this technique, a novel WDM-PON architecture, which supports ring-based physical layer VPN emulation over inter-PON and intra-PON, has been discussed. A virtual ring link has been established by using practical and low-cost Optical VPN Circulator Device (OVCD) as shown in the Figure 2.11.
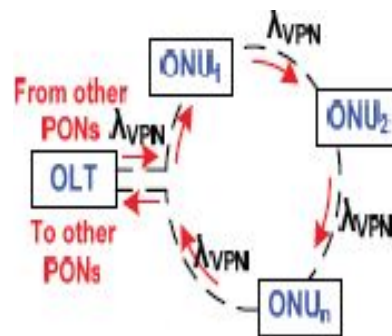


Figure 2.11  The virtual link for the VPN data transmission [29]

For the transmission of VPN traffic, the Orthogonal Frequency Division Multiplexed (OFDM) VPN traffic originating from other WDM-PON systems is combined with downstream traffic via CWDM filter at the CO. After transmission on fiber, the VPN traffic signal arrives at the ONU1 through the circulator and OVCD at the ODN. Having received control information and VPN data, ONU1 decides the subcarrier on which its VPN traffic data is carried, and generates an OFDMA signal, again and then sends it to the ONU2. In general, the VPN traffic wavelength passes through all the ONUs within WDM-PON, and eventually gets directed to other WDM-PON systems as well through the ODN and OLT. Therefore, both inter-PON and intra-PON ONU communications becomes possible [29].

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

In this paper, a flexible, two stage RN based architecture has been proposed that achieves overall broadcasting of inter-ONU traffic and/or subgroup communication. The architecture is shown in Figure 2.12.
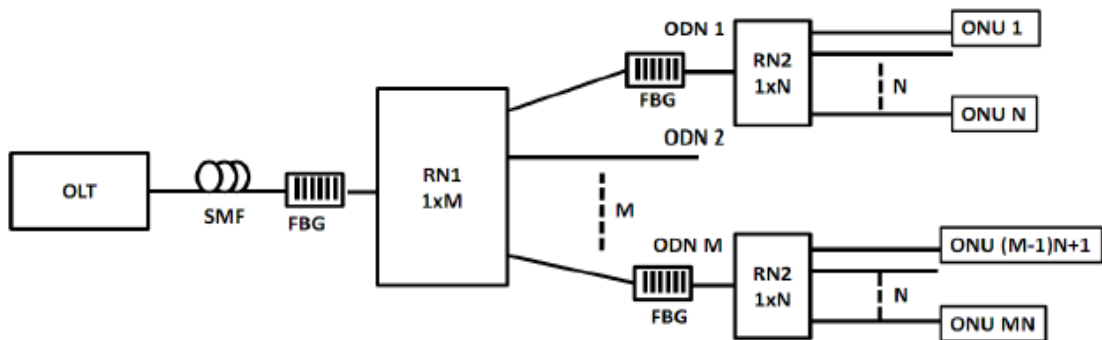


Figure 2.12  Overall/ Subgroup ONU Intercommunication based on Two Stage Flexible PON Network [30]

Here, two cascaded stages of remote nodes (RN1 and RN2) have been used. Splitting ratio of RN1 is 1xM and that of RN2 is 1xN. The architecture includes M ODN and each ODN has N ONUs. Each RN is equipped with a SC, thus each ONU can receive the wavelength transmitted from the OLT. In addition to this, an FBG is cascaded just before each RN. The FBG reflects back the ONU intercommunication data at a particular wavelength. Downstream and upstream transmissions take place normally. All the ONUs are equipped with tunable transceivers in order to transmit and receive specific wavelengths for ONU interconnection [30].

# Chapter 3                                    Proposed Architecture

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Before discussing the proposed architecture, let us discuss the simulation software used for the simulation i.e. OptiSystem. We have used OptiSystem 13.0 in our simulations. In the industries, where productivity with cost effectiveness is important for success, the outstanding OptiSystem can minimize the requirements of time and reduces the cost required for the design of optical systems, components and links. OptiSystem is a simulation package in the area of optical communication for the design, testing and optimization of practically any optical link in the physical layer of a vast spectrum of optical networks, which can be from video broadcasting systems in analog domain to backbone networks spanning to continents. It has been created to fulfill the needs of researchers, optical engineers, system integrators, students and many types of other users and it satisfies the demand of ever evolving photonics technologies for a strong yet handy to use tool for optical system design. It has a powerful simulation environment in which we can design systems using optical components in hierarchy. There is a provision for user-defined components and script language. We can model fiber optic communication systems realistically and it provides optimization and parameter sweeps also. There is a broad library of passive and active components. Its capability can be extended by adding user components and absolute interfaces to majorly used tools. This software is compatible with Optiwave's OptiAmplifier and OptiBPM, OptiGrating, etc. It contains MATLAB component also which enables user to call MATLAB in its environment. A user can design, test and optimize TDM/WDM or CATV network, SONET/SDH ring, transmitter, receiver, channel, amplifier, amplified system BER and calculate link budget.

## 3.1    System Configuration

We have proposed a Flexible Remote Node Architecture for Energy Efficient Direct ONU Internetworking in TDM-PON. Our proposed PON is assumed to be based on TDM-PON architecture. In the uplink, all ONUs share the same fiber through TDMA by transmitting the signal in a specified time interval, and in the downlink direction,

the OLT coordinates the ONUs to transmit frames specified for particular ONU in the specific time interval. As shown in Figure 3.1, the architecture consists of an OLT, a RN and number of ONUs. The OLT transmitter includes a continuous wave LASER, Pseudo random binary sequence (PRBS) generator, Non-return to zero (NRZ) pulse generator and Match-Zehnder modulator (MZM). The MZM modulates the LASER power with the NRZ converted PRBS and transmits in the downstream. An OLT receiver includes a Gaussian optical filter, PIN photo-detector, low pass Bessel filter and BER analyzer. The upstream signal wavelength is filtered by the filter, detected via PIN diode and analyzed by the BER analyzer. The ONU transmitter and receiver are same as that of the OLT except the Gaussian filter and LASER which is tunable in case of ONU in order to receive and transmit at the possible tunable wavelengths.
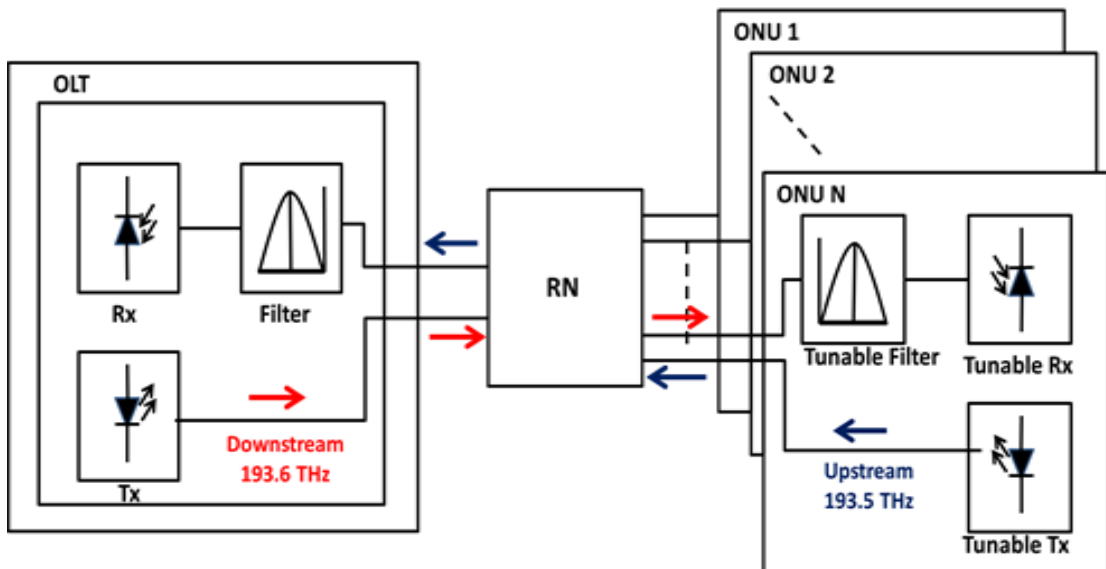


Figure 3.1   OLT and ONUs with Transmitter and Receiver

Now, if we consider the generalised proposed architecture each ONU in a network uses a specific wavelength $\lambda_u$ for upstream traffic and $\lambda_i$ for inter-ONU traffic. For downstream transmission, a specific wavelength $\lambda_d$ is used at the OLT. There are N - number of VPGs which can be formed by the same type of users in the network and each VPG consists of M ONUs (end users) as depicted in Figure 3.2, where M & N are integer numbers.
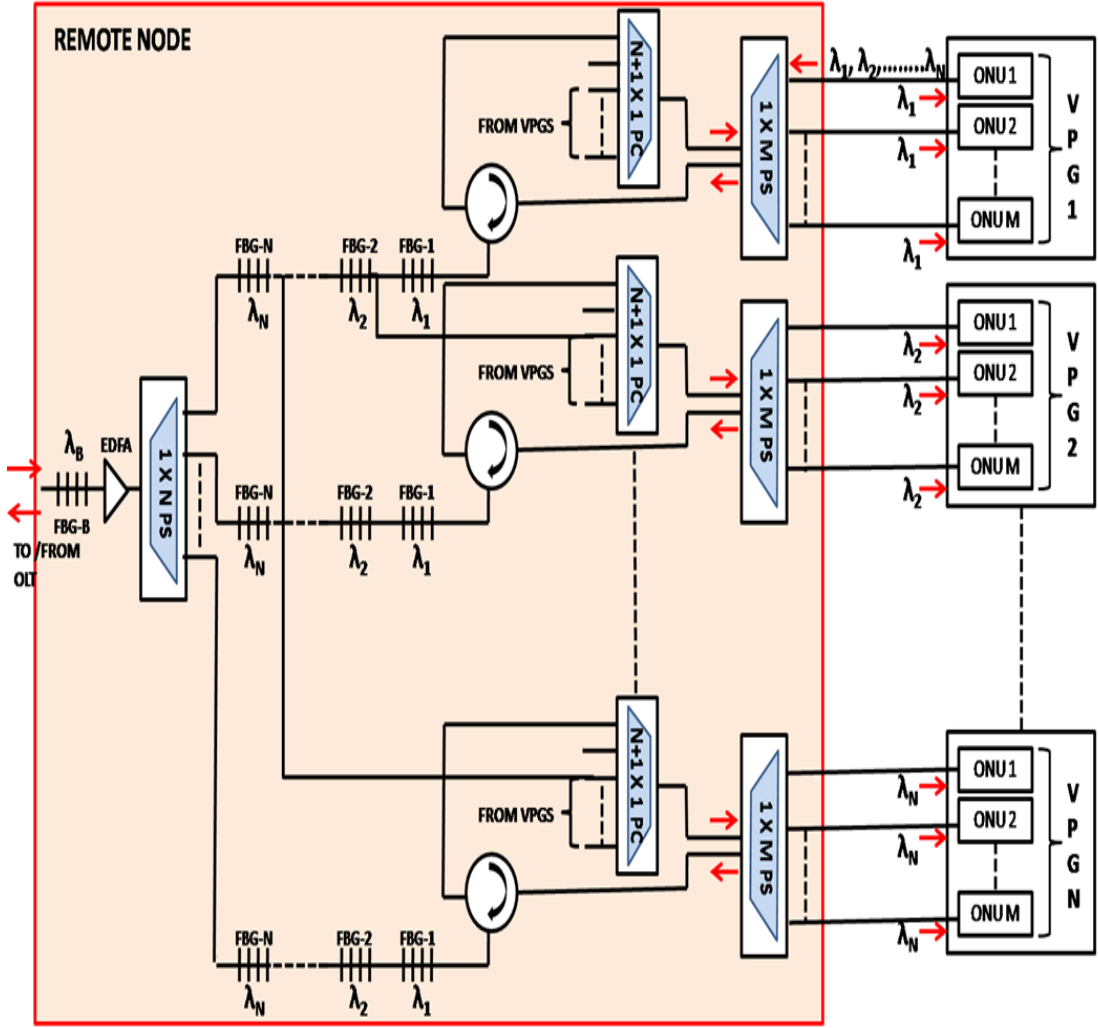
Figure 3.2 Generalized Configuration of Proposed Remote Node

We considered each VPG as a separate PON branch for privacy purpose, low requirement of power and easy power budget matching. To communicate with N VPGs, used wavelengths are $\lambda_i$ (i=1,2,…..,N) and are routed to particular VPG based on the wavelength configuration which can be obtained from equations (1), (2) and (3).

$$\lambda = \lambda_1 \; ; \; if \; s = d \tag{1}$$

$$\lambda = \lambda_1 + x * \omega \; ; \; if \; s < d \tag{2}$$

$$\lambda = \lambda_1 + [N - x] * \omega \; ; \; if \; s > d \tag{3}$$

Here, $s$ & $d$ are the source & destination VPG numbers, $\omega$ is the wavelength spacing between two consecutive wavelengths, $N$ is the total number of VPGs in the network

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and $x$ = Mod (source VPG number- destination VPG number).

The designed RN consists of N number of 1 x M bidirectional power splitters to broadcast the downstream as well as inter-ONU traffic and to combine upstream traffic, N number of (N+1) x 1 power combiners are also used to combine a regular downstream traffic via circulator and the N reflected inter-ONU traffic from all N VPGs. This circulator is also used to separate downstream and upstream signals to enable the proposed architecture for bidirectional communication. N number of FBG arrays (each array has N cascaded FBGs) are connected with each branch. As each branch has N cascaded FBGs, it is capable of reflecting N wavelengths. Here, the Bragg wavelength of FBG in the array is $\lambda_i$ for $FBG_i$ where i=1,2,.....,N. The wavelength used for the communication from one ONU from any VPG to the same VPG and that for the ONU from one VPG to the other VPG can be given by equations (1), (2) and (3).

An FBG followed by 1xN power splitter is also used at the OLT side of RN for the overall broadcasting. Basically, Bragg wavelength of this FBG is set as $\lambda_B$ and all inter-ONU signals transmitted at $\lambda_B$ are reflected from it and broadcasted to all PON branches. An erbium-doped fiber amplifier (EDFA) is also used for the compensation of power losses and achieving the power budget easily. However, by using Duo-binary (DB) coding power budget may be further improved [31].

## 3.2    Simulation Setup and Working

To simulate the designed architecture, a PON architecture with four VPGs (N=4) has been considered here and simulated by using OptiSystem 13.0. Each ONU and OLT consists of one transmitter and one receiver for transmitting and receiving the signals respectively as shown in Figure 3.1. We also considered that each VPG has two ONUs (M=2) as shown in Figure 3.3. All ONUs are considered to be located within the distance of few hundreds of meters from the RN, connected to RN via optical fiber.

For the downstream transmission, OLT acts as a transmitter while ONUs act as receivers. At OLT, for traffic generation, a binary sequence of period $2^7$-1 (by default value) is generated randomly at 10 Gbps by using a PRBS NRZ generator and

modulated at frequency 193.6 THz by Mach-Zehnder Modulator (MZM). The output from MZM is given to the 20 km fiber having attenuation constant of 0.2 dB/km and dispersion of 16.75 ps/nm/km. After that, it travels towards the ONUs via EDFA and gets amplified so as to combat the losses, 1 x 4 PS, 3-port circulator, 5 x 1 PC and 1 x 2 PS. Therefore, downstream transmission is broadcasted to all the VPGs (ONUs) and received by all VPGs (ONUs). Insertion losses of PS and PC are calculated based on $3Log_2(K)$, where K being the number of ports. For example, for 4 port power splitter, the insertion losses will be 6 dB. At each ONU, downstream signal is received by the receiver consisting of a tunable filter to receive the possible tunable frequency, a PIN photodetector with responsivity of 1 A/W and dark current of 10 nA. A Low pass Bessel filter with cutoff frequency of 0.7 x Bit rate and a BER analyzer is also used to analyze the received signal for the quality of transmission. BER analyzer provides the value of BER, the quality factor and the eye diagram at the rate of transmission. The simulation parameters are listed in Table 3.1.

Table 3.1 Simulation Parameters used in Optisystem 13.0

| Component | Downstream | Upstream | Inter-ONU |
|---|---|---|---|
| Data Rate (Gbps) | 10 | 2.5 | 2.5 |
| Modulating Frequency (THz) | 193.6 | 193.5 | 193.1, 193.2, 193.3, 193.4 & 193.9 |
| Fiber Length (km) | 20 | 20 | Varies from 0.1 to 0.4 |
| Fiber Attenuation Constant (dB/km | 0.2 | 0.2 | 0.2 |
| Fiber Dispersion (ps/nm/km ) | 16.75 | 16.75 | 16.75 |
| Cut-off Freq. of Low Pass Bessel Filter | 0.7xBit rate | 0.7xBit rate | 0.7xBit rate |

In case of upstream transmission, ONUs act as transmitters and an OLT act as a receiver. The traffic for upstream is generated at 2.5 Gbps and is modulated at 195.5 THz in a similar manner as explained above for the downstream transmission. Here, for the simulation purpose we considered only one ONU is transmitting.

While in actual scenario, multiple ONUs may transmit the upstream signal and OLT will receive in the TDMA fashion. The traffic travels through 1 x 2 PS, 3 port circulator, FBG array, 1 x 4 PS and EDFA. This upstream signal is passed through 20 km optical fiber and received at OLT via receiver having a filter, a PIN detector, Low pass Bessel filter and a BER analyzer.

Flexible RN architecture with direct inter-ONU communication capability is shown in Figure 3.3, in which we have used four 1 x 2 PSs, four 5 x 1 PCs and four circulators. For the redirection of inter-ONU traffic, four FBG-arrays of four cascaded FBGs are used. The Bragg wavelengths of FBG-arrays are considered as $\lambda_1$, $\lambda_2$, $\lambda_3$ and $\lambda_4$ ( i.e. 193.1 THz, 193.2 THz, 193.3 THz and 193.4 THz) for FBG 1, FBG 2, FBG 3 and FBG 4, respectively. The reflected wavelengths from every array are connected to the particular PC according to the wavelength assignments based on (1), (2) and (3) as shown in Table I. For ease of understanding, these wavelengths are shown with different colors i.e. red color for transmission from VPG1, yellow from VPG2, green from VPG3 and blue from VPG4 in Figure 3.3.

Table 3.2  Wavelength Assignment for Four VPGs

| Destination VPG →  Source VPG ↓ | VPG 1 $\lambda$ (THz) | VPG 2 $\lambda$ (THz) | VPG 3 $\lambda$ (THz) | VPG 4 $\lambda$ (THz) |
|---|---|---|---|---|
| VPG 1 | 193.1 | 193.2 | 193.3 | 193.4 |
| VPG 2 | 193.4 | 193.1 | 193.2 | 193.3 |
| VPG 3 | 193.3 | 193.4 | 193.1 | 193.2 |
| VPG 4 | 193.2 | 193.3 | 193.4 | 193.1 |

For the inter-ONU communication, we considered that ONU 1 from VPG 1 is transmitting at wavelength 193.1 THz ($\lambda_1$) as shown in Figure 3.3. This wavelength will reach up to FBG 1. As the Bragg wavelength of FBG 1 is 193.1 THz and FBG reflects any signal at its Bragg wavelength, it reflects this wavelength. Based on the wavelength assignment given in the Table I, this wavelength is transmitted to VPG 1 only as indicated by red arrow in Figure 3.3. Hence, here we are achieving intra-VPG communication i.e. within VPG itself. Now, for the inter-VPG communication, we considered that the same ONU 1 is transmitting at wavelength 193.2 THz ($\lambda_2$) as shown in Figure 3.4. This wavelength will reach up to FBG 2. In the same manner as previous case, it will be reflected from FBG 2. Based on the wavelength assignment, this wavelength is transmitted to VPG 2.
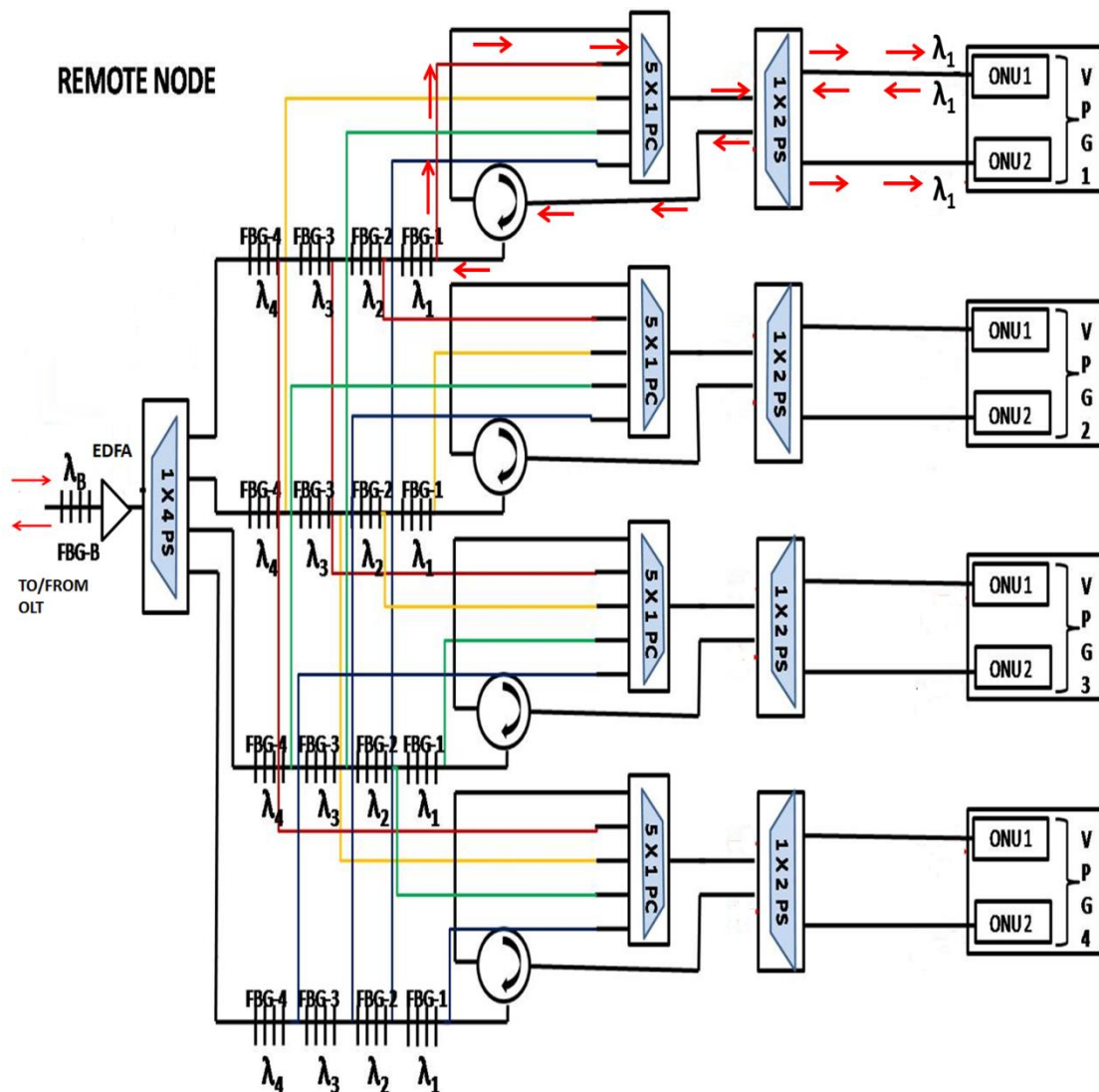


Figure 3.3 Design of Remote Node considered for Simulation showing Internetworking within VPG (intra-VPG communication)
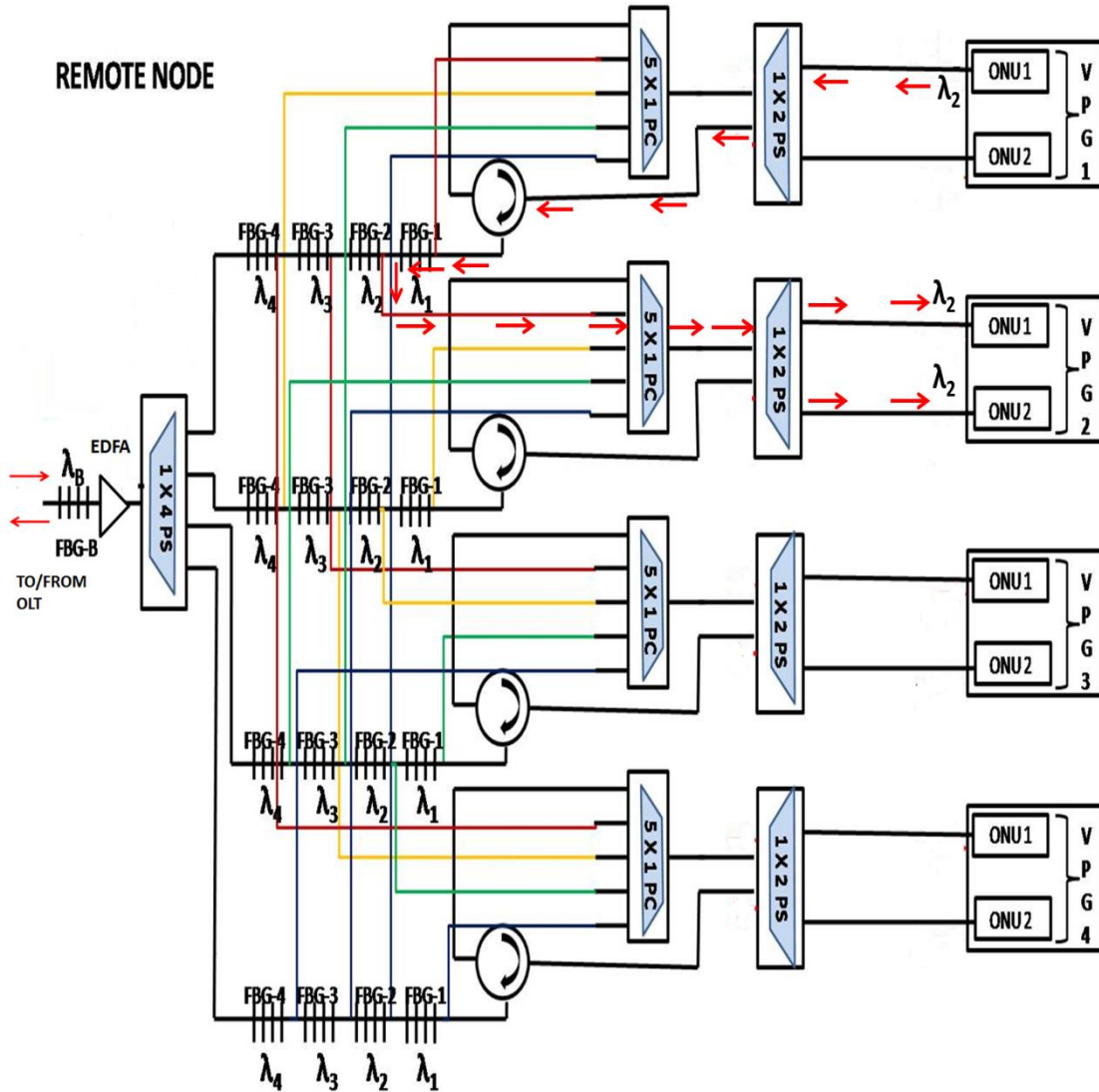
Figure 3.4   Design of Remote Node considered for Simulation showing Internetworking with other VPG (inter-VPG communication)

Hence, here we are achieving inter-VPG communication i.e. with other VPG. Similarly, based on wavelength transmitted by any ONU from VPG 1, communication with the other VPGs is also possible on other wavelengths as shown in Table I. In general, any ONU from any VPG can communicate with all ONUs of any VPG including the transmitting VPG also. That means, intra-VPG as well as inter-VPG communication is possible in this architecture.

In addition to this, for the overall broadcasting, FBG located at RN towards OLT side performs an important role. It has Bragg wavelength 193.9 THz ($\lambda_B$). If any ONU

located in any VPG transmits at 193.9 THz as shown in Figure 3.4, this wavelength will be reflected from this FBG and coming back to the power splitter, gets split and broadcasted to all four PON branches (VPGs). Thus, all VPGs and hence, all ONUs available in the network receives that wavelength. We achieve overall broadcasting in this way in this architecture.
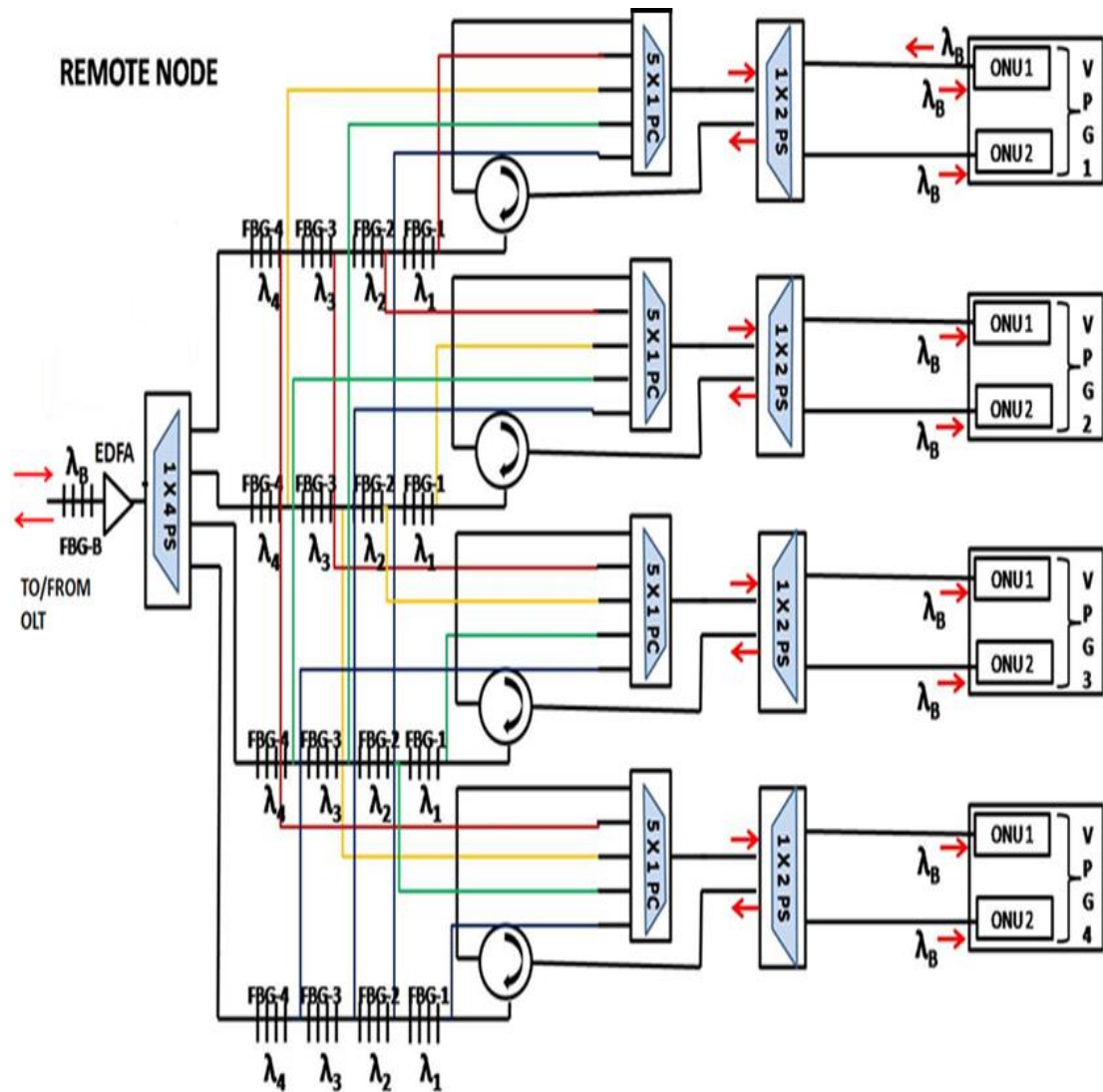


Figure 3.5   Design of Remote Node considered for Simulation showing Internetworking with all VPGs (overall broadcasting)

In this chapter, the results obtained by using OptiSystem 13.0 are discussed. In order to analyze the proposed architecture, performance for back to back (B2B) and 20 km fiber has been considered here for the upstream as well as downstream transmission. We also observed the inter-ONU transmission performance for different ONUs. The plots for bit error rate (BER-Ratio of bits received in error to the total bits transmitted) versus Received power are obtained for downstream, upstream and inter-ONU traffic and depicted in Figure 4.1, Figure 4.3 and Figure 4.5, respectively. From all the plots it can be inferred that the value of BER improves with increase in received power and we are getting the waterfall like curve.

From Figure 4.1 and Figure 4.3, it can also be observed that there is a power penalty of around 0.5 dB and 0.2 dB respectively for downstream and upstream transmission because of Rayleigh backscattering and other nonlinear effects occurring in optical fiber. The value of downstream power penalty is higher than upstream power penalty as the downstream data rate is higher than the upstream data rate.
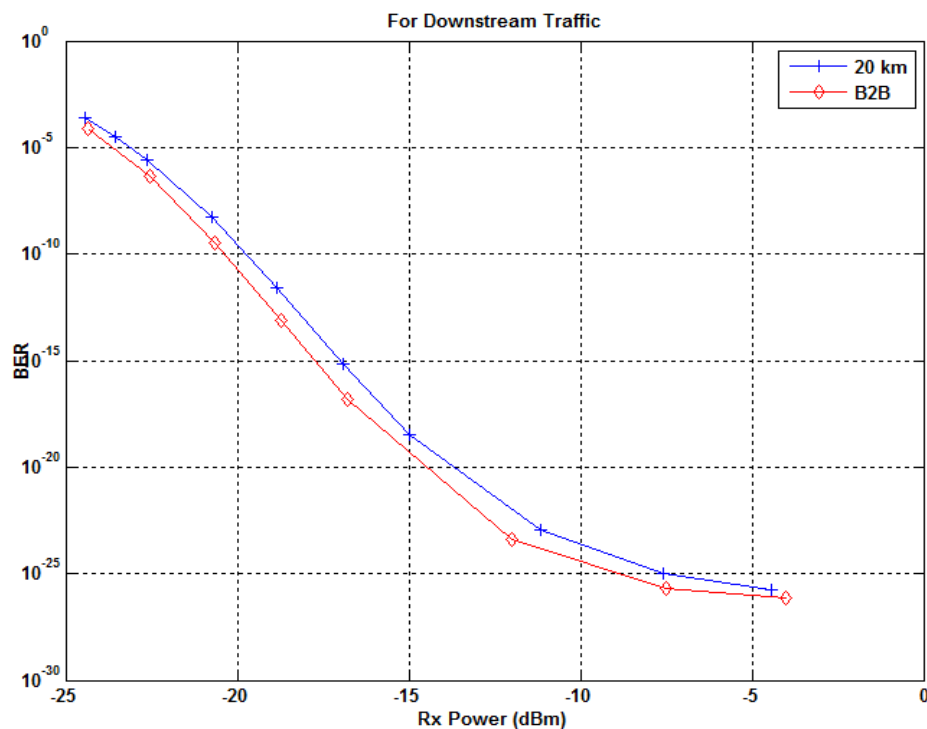
Figure 4.1 For the case of Downstream transmission at 10 Gbps

We have provided the eye diagram also for the reference to see the quality of reception for downstream, upstream and inter-ONU communication in Figure 4.2, Figure 4.4 and Figure 4.7, respectively at the value of BER equal to $10^{-9}$. Here, we can observe the clear eye opening. In ideal case, eye diagrams would be like rectangular boxes. But in practical case, communications are not so perfect, results in the transitions that do not line perfectly on top of each other, and an eye-shaped pattern results. The dissimilarities in amplitude and timing from bit to bit make the eye opening to shrink.
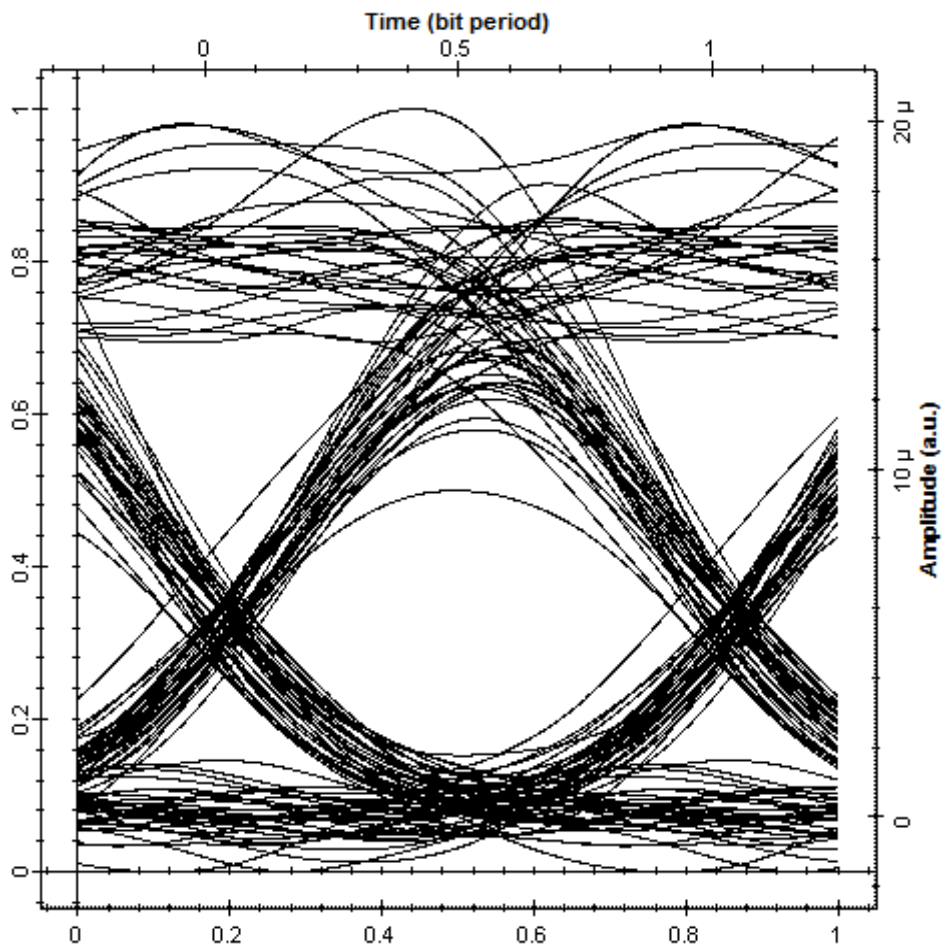


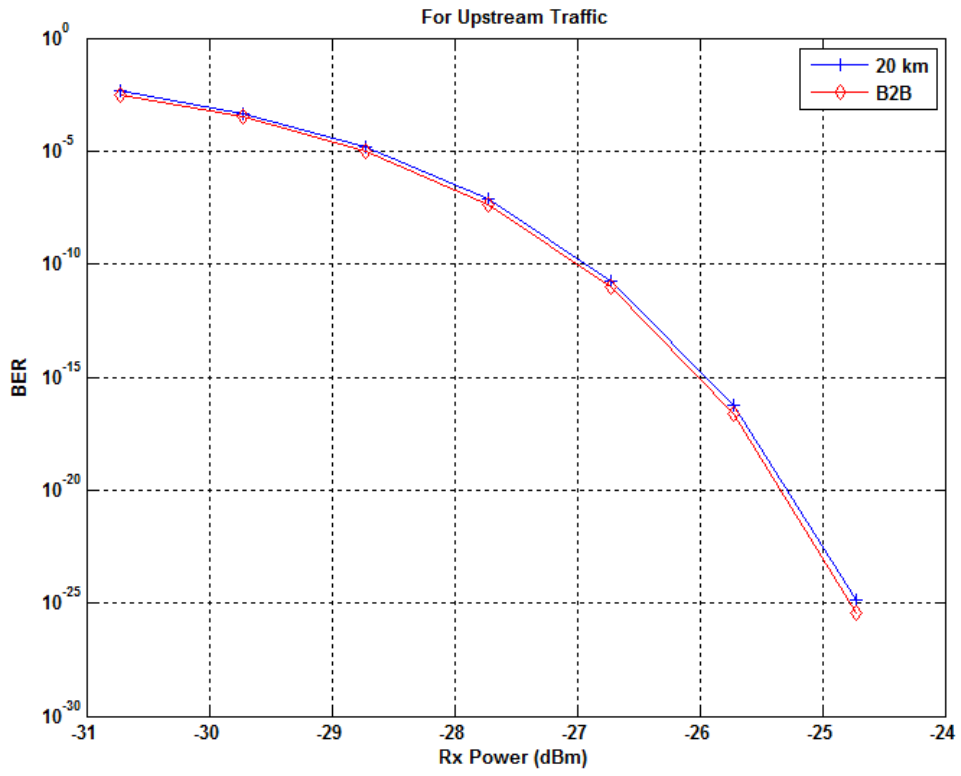Figure 4.2 Eye Diagram for the downstream communication at BER of $10^{-9}$

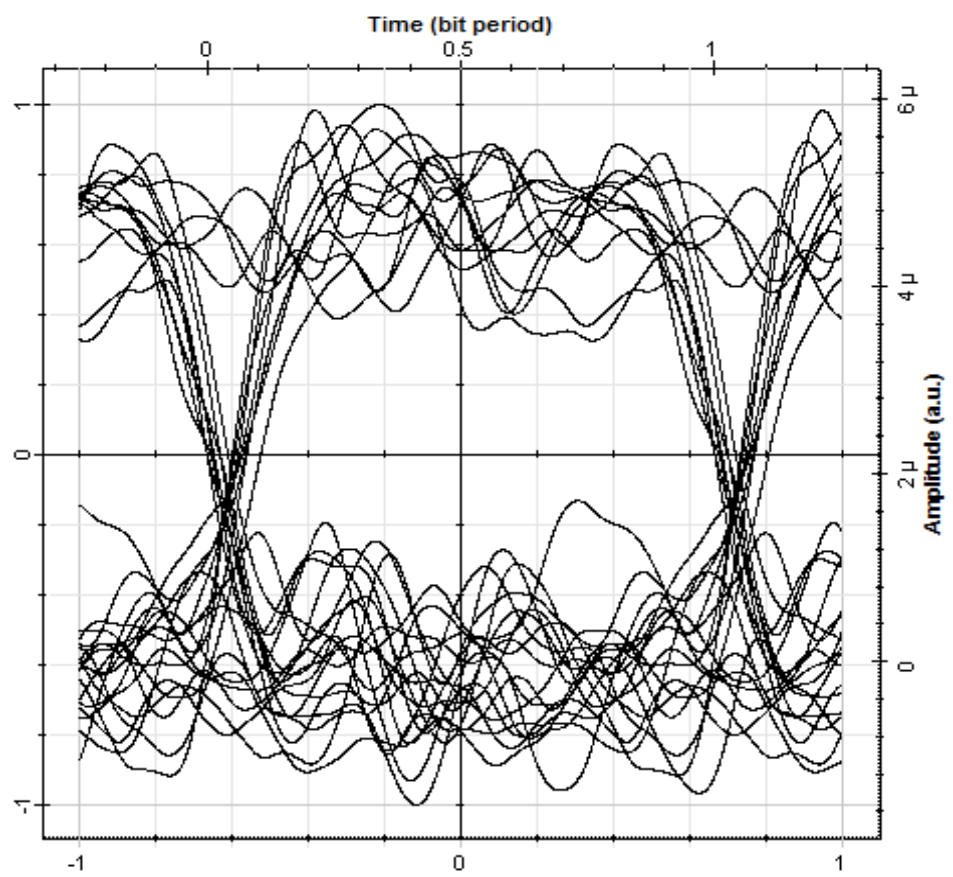Figure 4.3 For the case of Upstream transmission at 2.5 Gbps



Figure 4.4  Eye Diagram for the upstream communication at BER of $10^{-9}$

Figure 4.5 shows the BER performance of Inter-ONU communication for transmission of data from ONU1 to all other ONUs in the network at four different wavelengths; 193.1 THz, 193.2 THz, 193.3 THz and 193.4 THz for VPG 1, VPG 2, VPG 3 and VPG 4, respectively. Due to the almost same fiber length between RN and ONUs i.e. within 100 m to 500 m, the achieved BER is almost same for all the transmissions for same received power. Figure 4.6 shows BER performance of the inter-ONU communication from ONU 1 of VPG 1 TO VPG 2, separately for ease of understanding. If we compare the inter-ONU transmission with upstream transmission and downstream transmission, it is inferred that inter-ONU communication requires least amount of received power for the same BER performance. This is due to the fact of avoiding the nonlinear effects occurring in the fiber due to reflection from the RN itself. Alternately we can say, for inter-ONU transmission, less input optical powers may serve the same BER performance. Therefore direct inter-ONU transmission reduces the overall power consumption. Also, direct inter-ONU communication provides the opportunity to reduce the latency and utilizes the bandwidth efficiently as it is not transmitted to the OLT with upstream transmission and back to the destined ONUs with downstream transmission.
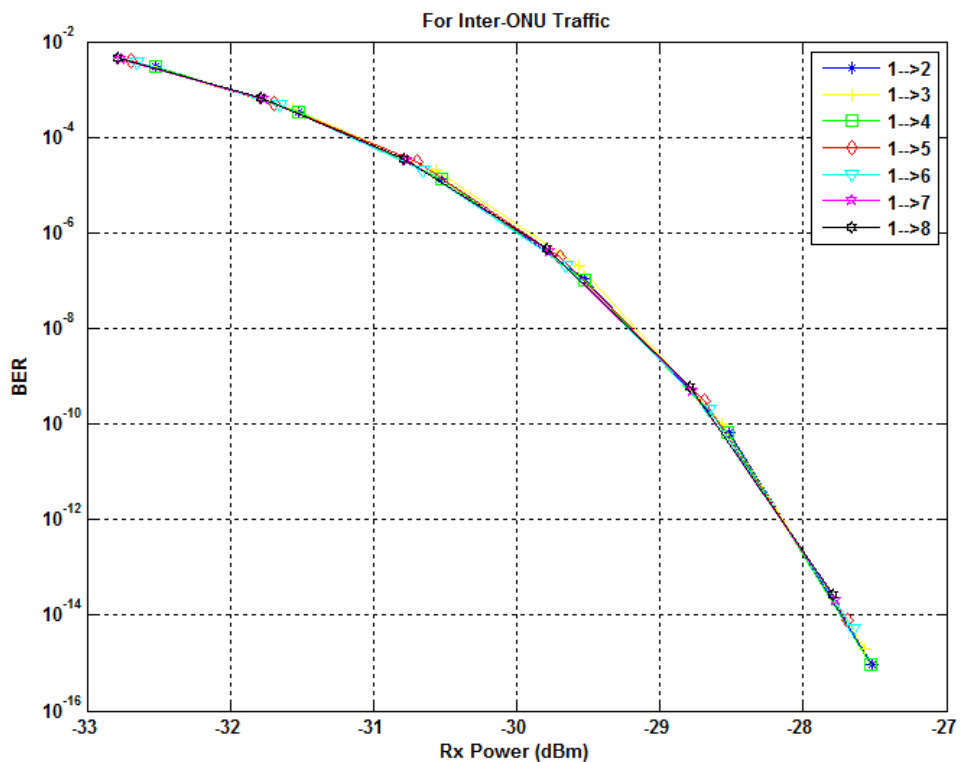


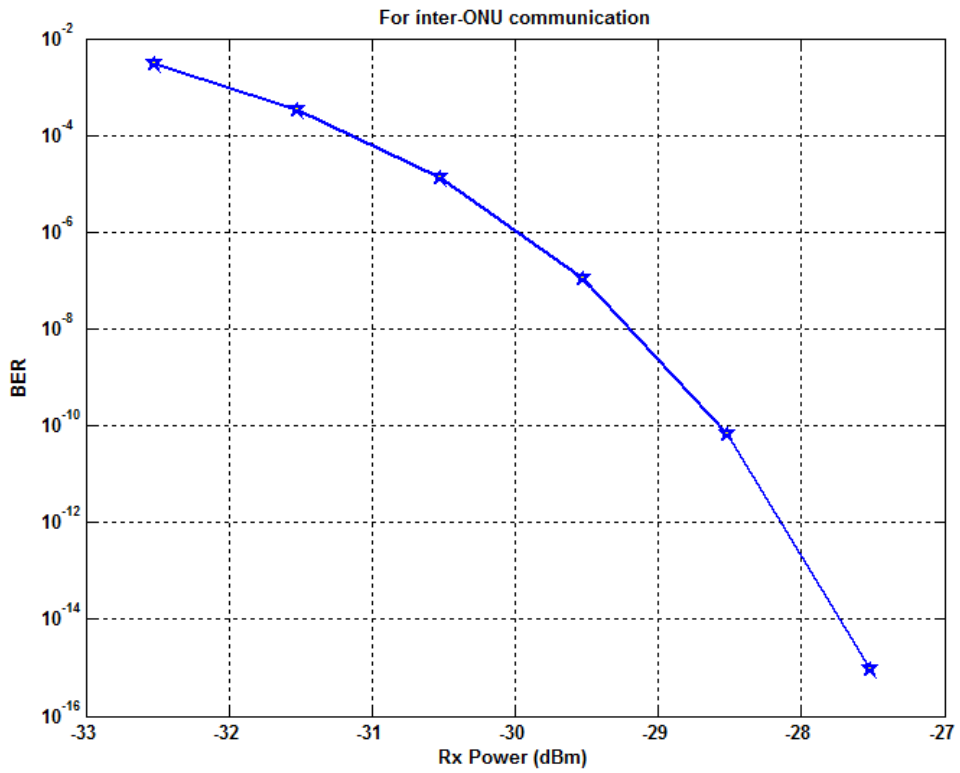Figure 4.5 For the case of Inter-ONU transmission at 2.5 Gbps

Figure 4.6 For the case of inter-ONU communication from VPG 1 to VPG 2
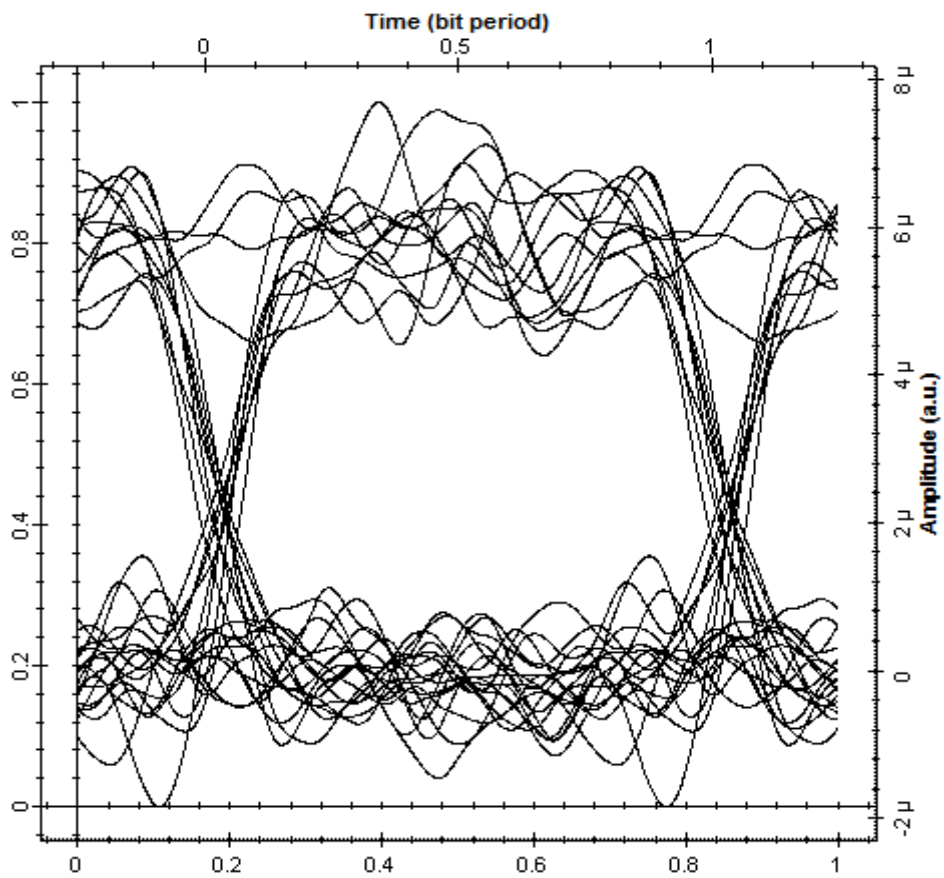


Figure 4.7  Eye Diagram for the inter-ONU communication at BER of $10^{-9}$

The spectrum of received signal for overall broadcasting at 193.9 THz for inter-ONU communication is shown in Figure 4.8.
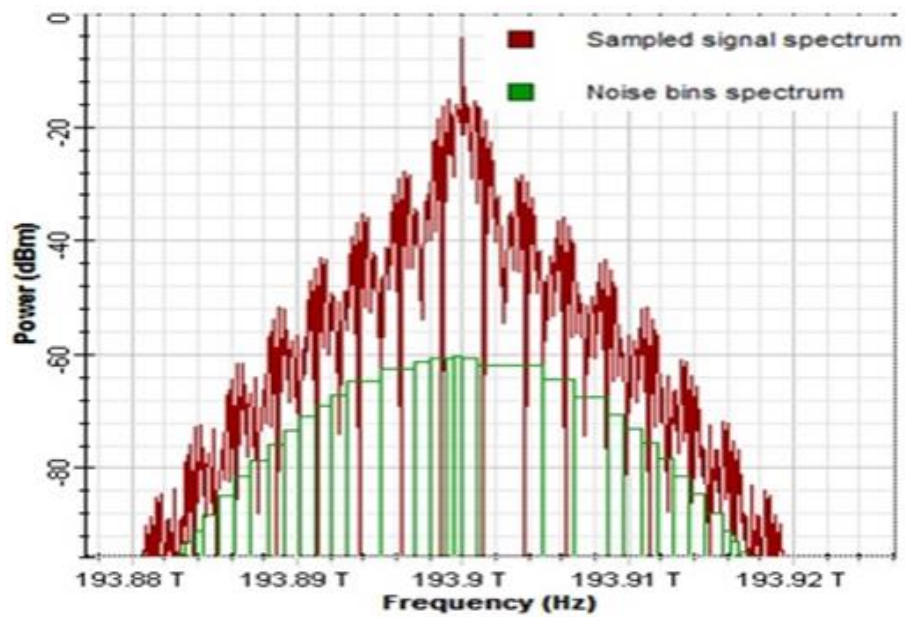


Figure 4.8 For Inter-ONU transmission, received spectrum at ONU 1 of VPG 1 for overall broadcasting at 2.5 Gbps

In this case, ONU1 of VPG1 is transmitting and all other ONUs of all VPGs are receiving. Any other ONU available in the network from any VPG may transmit in a similar manner and have overall broadcasting. The figure also shows that the received power may easily fulfill the required power budget to meet the receiver sensitivity for the good BER performance.

# Chapter 5       Conclusion and Future Scope

In this thesis, we proposed a flexible RN architecture which provides simultaneous downstream, upstream and inter-ONU transmission. By using this architecture, direct internetworking from one ONU to other ONUs located within the same VPG or other VPGs is achieved, which provides efficient resource utilization such as power and bandwidth. Proposed architecture also reduces the transmission latency among ONUs for inter-ONU communication. The performance of the proposed architecture is verified with the simulation results by OptiSystem 13.0. It provides a good BER performance for downstream, upstream and inter-ONU transmission. Moreover, in case of inter-ONU communication we are getting less BER for the same received power as compared to upstream and downstream transmission.

This work can be extended by modifying the architecture in such a way that it provides direct ONU communication for the case of one-to-one case means from any ONU in any VPG to any ONU in any VPG, also.

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