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# DESIGN AND INVESTIGATION OF NEXT GENERATION ACCESS NETWORK BASED ON ADVANCED OPTICAL CARRIER GENERATOR

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**FOR**
**THE DEGREE OF MASTER OF SCIENCE**
**IN**
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**BY**

**NAMARIQ RASHID KHAMMAS AL-KHAZRAJI**

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DESIGN AND INVESTIGATION OF NEXT GENERATION ACCESS NETWORK BASED ON ADVANCED OPTICAL CARRIER GENERATOR

By Namariq Rashid Khammas AL-KHAZRAJI

April 2022

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

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**Namariq Rashid Khammas AL-KHAZRAJI**

## ABSTRACT

# DESIGN AND INVESTIGATION OF NEXT GENERATION ACCESS NETWORK BASED ON ADVANCED OPTICAL CARRIER GENERATOR



Namariq Rashid Khammas AL-KHAZRAJI

Master of Science in Electrical - Electronics Engineering

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April 2022



Passive Optical Network (PON) was designed in this thesis. The design aim was to locate faulty line of service professionally without extra effort. In the literature, there were various PON-design methodologies. However, a design with less components and less faulty line tracking was a challenge. The suggested approach tried to overcome the leakage in the state-of-the-art, such that, the PON network would be able to serve forty-eight Optical Network Units (ONUs). At the same time, the design has to have the capability to distinguish the dropped line of service straightforwardly. The design in this thesis mainly depends on the Fiber Bragg Gratings (FBGs) to create six-groups, in each group, there are eight-branches. Each branch serves as an end-user/customer point. The capacity of fault location was achieved for ONUs distanced/located as far as 20Km from the Central Office (CO). There was only one Optical Spectrum Analyser (OSA) inside the CO. This OSA employed to monitor the whole network groups, i.e., forty-eight branches/ONU were screened inside the CO to predict the fault location. The system is built using the OptiSystem software package version 14.



**2022, 100 pages**

**Keywords:** PON network, All optical network, OptiSystem, Fiber bragg grating, OLT, ONU

## ÖZET

# GELİŞMİŞ OPTİK TAŞIYICI JENERATÖR ÜZERİNE DAYALI YENİ NESİL ERİŞİM AĞI TASARIMI VE İNCELENMESİ

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Nisan 2022

Bu tezde Pasif Optik Ağ (PON) tasarlanmıştır. Tasarım amacı, hatalı hizmet hattını ekstra çaba harcamadan profesyonelce bulmaktı. Literatürde çeşitli PON tasarım metodolojileri vardı. Ancak, daha az bileşene ve daha az hatalı hat takibine sahip bir tasarım zorluydu. Önerilen yaklaşım, PON ağının kırk sekiz Optik Ağ Birimine (ONU) hizmet edebilecek şekilde, son teknolojideki sızıntının üstesinden gelmeye çalıştı. Aynı zamanda tasarım, bırakılan hizmet hattını doğrudan ayırt etme yeteneğine sahip olmalıdır. Bu tezdeki tasarım esas olarak altı grup oluşturmak için Fiber Bragg Izgaralara (FBG'ler) bağlıdır, her grupta sekiz dal vardır. Her şube bir son kullanıcı/müşteri noktası görevi görür. Merkez Ofis'ten (CO) 20 Km'ye kadar mesafeli/konumlu ONU'lar için arıza tespit kapasitesi elde edildi. CO içinde yalnızca bir Optik Spektrum Analizörü (OSA) vardı. Bu OSA, tüm ağ gruplarını izlemek için kullanıldı, yani arıza yerini tahmin etmek için CO içinde kırk sekiz dal/ONU tarandı. Sistem, OptiSystem yazılım paketi sürüm 14 kullanılarak oluşturulmuştur.

**2022, 100 sayfa**

**Anahtar Kelimeler:** PON ağı, Tüm optik ağ, OptiSystem, Fiber bragg ızgara, OLT, ONU

## PREFACE AND ACKNOWLEDGEMENTS

Upon closer inspection of this significant work, we can discover that it comprises the efforts of a number of people. I want to express my gratitude to everybody from the depth of my soul, and to express that however much I cherish and respect their decision. A special thanks goes out to Prof. Dr. Halil Tanyer EYYÜBOĞLU for his assistance in the supervision of my thesis. I owe him a sense of gratitude for granting time and resources required to pursue a master's degree. I learned a great lot from him both intellectually and professionally, and I am grateful to him for his guidance. I am grateful to you, Dr. Yousif I. HAMMADI, for your constructive comments and ideas on my research. He is also a fantastic great inspiration and encouragement for me throughout this journey, and I am thankful to him for his assistance.

I give a debt of gratitude to all those who have assisted me to get to where I am presently. It is impossible to express my appreciation enough to my wonderful parents, and grandparents for all efforts and unquestioning support throughout my life.

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**Namariq Rashid Khammas AL-KHAZRAJI**

**Çankırı-2022**

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## LIST OF SYMBOLS

| | |
|---|---|
| Nˇ | Normalization factor |
| Ø | Phase |
| c | Speed of light |
| D | Group delay slope |
| E | Energy |
| f | Frequency in Hertz |
| i | Input port number |
| n | Number of input terminals |
| t | Time |
| X | Polarization (horizontal) |
| Y | Polarization (vertical) |
| α | Power attenuation coefficient |
| Δλ | Bandwidth |
| λ | Wavelength |
| λc | Center wavelength |
| τ | Group delay |
| ω | Frequency in radian per second |

**LIST OF ABBREVIATIONS**

| | |
|---|---|
| APON | Passive Optical Network based on Asynchronous Transfer Mode |
| ATM | Asynchronous Transfer Mode |
| AWG | Array Waveguide Grating |
| BER | Bit Error Rate |
| BPON | Broadband PON |
| CAGR | Compound Annual Growth Rate |
| CO | Central Office |
| DBA | Dynamic Bandwidth Allocation |
| DBG | Distributed Bragg Reflector |
| DSL | Digital Subscriber Line |
| DWDM | Dense Wavelength Division Multiplexing |
| EDFA | Erbium Doped Fiber Amplifier |
| EFT | Earlier Finished Time |
| EFT-VF | Earlier Finished Time with void filling |
| EPON | Ethernet PON |
| FBG | Fiber Bragg Grating |
| FDM | Frequency Division Multiplexing |
| FSAN | Full-Service Access Network |
| FTTC | Fiber to the Cabinet |
| FTTH | Fiber to the Home |
| G1 to G6 | First Group to Sixth Group |
| GPON | Gigabit Passive Optical Network |
| HDTV | High Definition TV |
| HFC | Hybrid Fiber Coaxial |
| IEEE | Institute of Electrical and Electronic Engineering |
| IP | Internet Protocol |
| IPTV | Internet Protocol Television |
| ITU | International Telecommunication Union |
| MPS | Main Power Splitter |
| NG-EPON | Next Generation of EPON |
| NG-PON | Next Generation PON |
| NG-PON1 | Next Generation PON stage 1 |
| NG-PON2 | Next Generation PON stage 2 |
| NLS | Nonlinear Schrödinger |
| ODN | Optical Distribution Network |
| O-E-O | Optical-Electrical-Optical Modifications |
| OLT | Optical-Line-Terminal |
| ON | Optical Null |
| ONT | Optical Network Terminal |

| | |
|---|---|
| OPM | Optical Power Meter |
| OSA | Optical Spectrum Analyzer |
| OTDR | Optical Time Domain Reflectometer |
| PC | Power Combiner |
| PON | Passive Optical Network |
| PS | Power Splitter |
| PSR | Power – Splitting Ration |
| QoS | Quality Of Service |
| SNR | Signal to Noise Ratio |
| sub-PS1 to sub-PS6 | Sub-Power Splitter 1 to Sub-Power Splitter 6 |
| TDMA | Time Division Multiple Access |
| TL | Tunable Laser |
| TWDM | Time and Wavelength Division Multiplexing |
| UHDTV | Ultrahigh Definition Televison |
| VOD | Video on Demand |
| VoIP | Voice over Internet Protocol |
| WBM | Weighted Bipartite Matching |
| WDM | Wavelength Division Multiplexing |
| WDM-PON | Wavelength Division Multiplexing Passive Optical Network |
| Wi-Fi | Wireless Fidelity |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WLS | White Light Source |

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# 1 INTRODUCTION

The field of optical fiber has seen significant growth in recent years, and there is no indication of it slowing down any time soon. With ever-growing data traffic, the need for bandwidth is expanding as well. However, the advent of high speed internet is the key motivator behind the development of new connectivity technologies that allow users to enjoy genuine broadband. It prompts telecommunications providers to seriously investigate the widespread deployment of optical fiber based communication systems in large numbers of locations. They must upgrade their connectivity, which are obviously becoming a constraint in concerns of bandwidth availability and must be replaced. As a result, the vast majority of telecom operators are presently retiring their old copper networks in favor of optical fiber systems.

The optical fiber is being brought close to the customer in order to provide speedier interconnections. If you are looking for a long-term solution, fiber to the home (FTTH) looks to be just the best option: if all of the customers are serviced entirely by optical fibers, it will be so much simpler to expand the bandwidth in the road (Al-Quzwini 2014, Rokkas 2015, Horváth *et al.* 2018). FTTH is a potential possibility for offering internet connections such as high definition television (HDTV), video on demand (VOD), and online gaming. Due to the rapid advancement of optical transmission equipment, the need for faster transmission speeds, longer transmission distances, and wider channel capacity has become much heavier in recent years (Cheng *et al.* 2021).

Customers' homes or the terminal site may be served via a fiber-optic network configured for FTTH distribution. Fixed telephone, data, and interactive TV are all supported by FTTH Triple Play services. For further information on this, see (Lee *et al.* 2011). It is common for providers to employ Gigabit Passive Optical Network (GPON) technology for FTTH installation. Most attention has been paid to determining how much Bit Error Rate (BER) may be avoided while doing performance tests on an optical network using software called OptiSystem.

An explanation of optical access networks will indeed be discussed in this section. The chapter begins with a short discussion of fiber connectivity and network design. Fiber access technology is offered as the ideal approach to supply fast broadband heavy multi-media applications in light of the significant limiting considerations in the access network portion. When it comes to innovation, the Fibre-to-the-x (FTTx, x-stands for anything) innovation is investigated extensively, focusing on the Passive Optical Network (PON), which includes several supporting configurations: Time Division Multiplexing PON, in other words, a time-based configuration, and Wavelength Division Multiplexed (WDM), which is a wavelength-based PON. The development of the optical access network is shown via the discussion of core components of several PON systems. When it comes to potential metro/access aggregation, long-reach optical access innovation is presented. After then, the chapter ends with a brief recap.

The contemporary world has been transformed by fiber optic connectivity. It has had a profound impact on our everyday lives, bringing about major changes in the worldwide communication systems. Because of the shrinking physical boundaries between people and information, social interactions are now much more accessible than ever before. Since optical fibers have supplanted copper wires in most major communication networks, they have become the dominant data transfer medium, due to their low attenuation, high bandwidth, and minimal radio interference (Lam 2011).

The frequent deployment of optical fiber communication systems worldwide is the result of a number of significant achievements. Throughout 1960, Maiman successfully demonstrated the functioning of a laser for the first time (Maiman 1960). It wasn't long before financially successful optical fibers began to take root (Kao and Hockham 1966): The first fiber to fulfill Dr. Kao's standards was manufactured by Corning in 1970, and the first live traffic was transmitted across fiber networks in the United States and the United Kingdom in 1975 (Venghaus and Grote 2017). Fiber optic lines were able to transfer vast amounts of data over intercontinental distances with the invention of WDM system in 1977 (Tomlinson 1977) and the Erbium doped fiber amplifier (EDFA) in 1987 (Mears *et al.* 1987). All of these pioneering efforts have brought us to this present age of global optical communications.

A lot of development has been made recently in broadband transceiver technologies. Continuous observations and world championships on outstanding transmission tests, field testing and industrial installations with amazingly capacity and/or very vast journeys (Nakazawa *et al*. 2010, Salsi *et al.* 2011, Foursa *et al.* 2013) have been documented. Clients are the driving force behind all of these new breakthroughs in both the scientific and commercial arenas. Digital technology advancements and the widely accepted Internet Protocol (IP) framework have initiated a unique description for formal telecom services, straddling the line between classic phone, Internet and television connections, and creating a "triple play" corporate model that includes voice, data and streaming apps. There are many competitive demands on resource demanding IP products of all kinds, which all assist to infrastructure development and expansion inside the near future as a result of service confluence.

Globally, the total number of connected devices is expected to increase from 3.9 billion in 2018 to 5.3 billion by 2023, representing a compound annual growth rate of 6%. Population-wise, this constitutes 51 percent of the world population in 2018 and 66 percent of global population penetration by 2023, according to the Cisco Annual Internet Report (Cisco 2020) as shown in Figure 1.1.

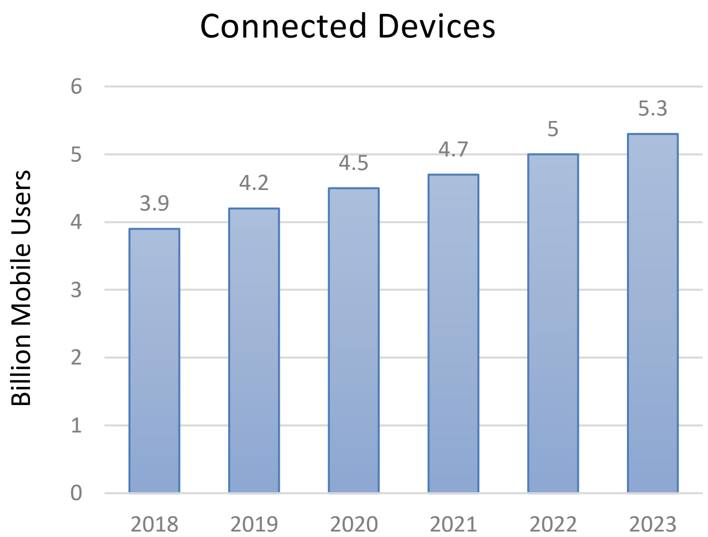


**Figure 1.1** Growth of connected devices from 2018 to 2023 (Cisco 2020)

In view of these developments, it is projected that the present telecommunications sector will be put under strain in the near future, necessitating the search for solutions. As a result, a number of investigations and discussions have been begun aiming to fabricate a developed photonics technologies, optoelectronic hardware, besides the possibility of amazingly powerful modulation patterns across the whole data transmission (Venghaus and Grote 2017, Cisco 2020). The access section of the network becomes the focal point of study in this thesis, and several unique technologies, as well as network architecture that is suited for next generation development, will be investigated.

The global communication network is a very complex system with many moving parts. The separation of such a system into numerous sub-networks on the basis of geography may be beneficial since the separate portions of the system often work with different functionality and varied needs (Chatterjee and Oki 2020). It is illustrated graphically in Figure 1.2 that the final design is comprised of long-haul/short-haul, metropolitan, and access networks. Figure 1.2 shows the final architecture. For this reason, the long haul (heart) infrastructures are referred to as the "backbone" of an entire data transmission since they enable data aggregation over great distances across cities, nations, and continents. In most situations, ultra-long connections stretch hundreds or even thousands of kilometers, with submerged cables in some cases spanning as much as 10,000 kilometers. Mesh network topologies are often used in network architecture to ensure that communication linkages between significant exchanges of information nodes are strong and reliable.

Metropolitan networks are used to link cities and areas that are separated by a smaller geographic range, such as a state or province. To acquire data from a large number of stations, the ring structure is typically employed to capture traffic across an area of tens of kilometers to long distances (central offices). Each central office extends its reach even farther, until it reaches the furthest point of the telecommunications network, which is the user properties. The idea of a metropolitan region may therefore be expanded to include a procedure of an inter-workplace metropolitan loop and a metro-access section (Ilyas and Mouftah 2003), which is often referred to as a combined metro network.

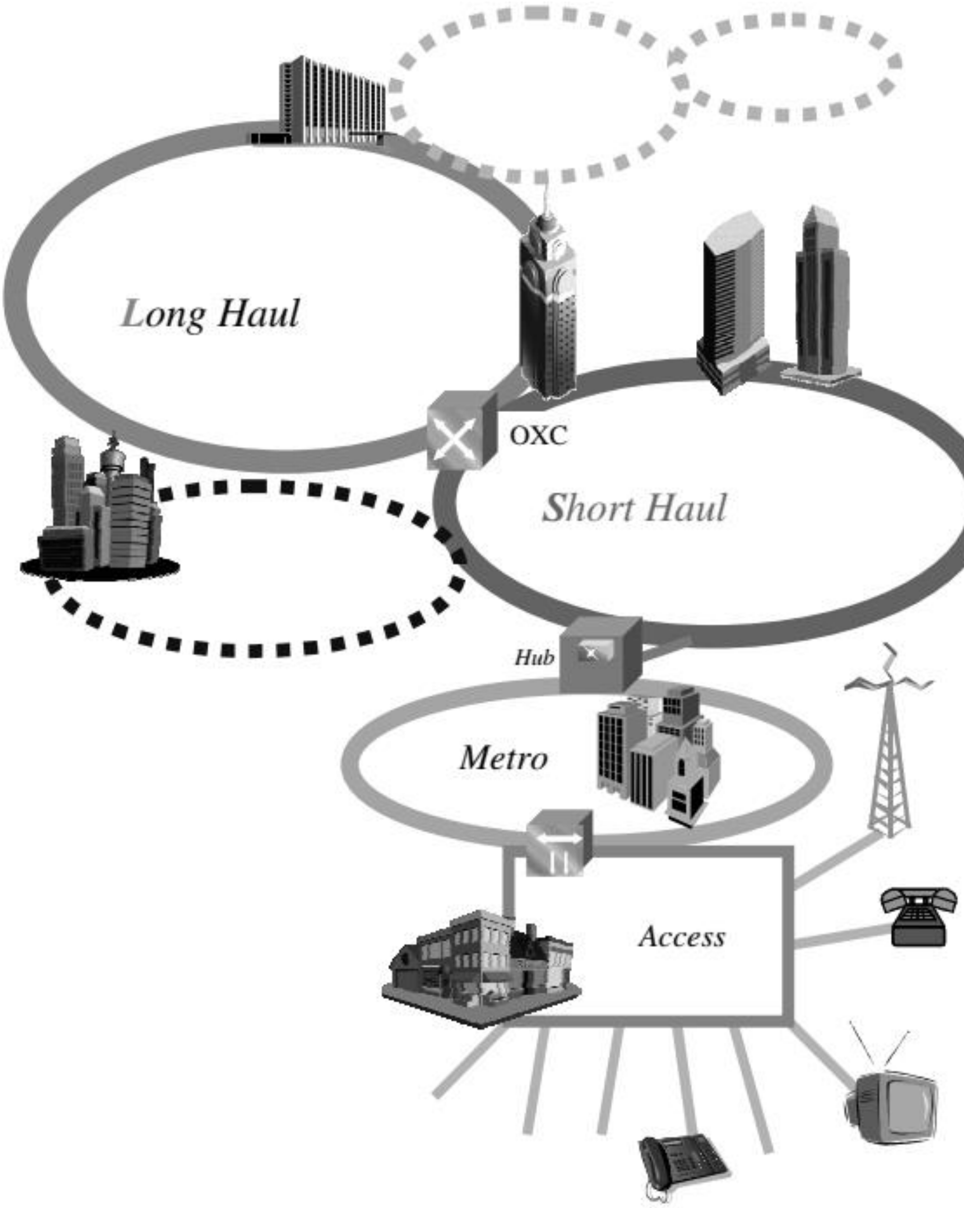


**Figure 1.2** A broad picture of the architecture of optical networks (including subnets for distribution, access/edge, metro-core, and long-haul) (Ilyas and Mouftah 2003)

The access network, last mile, or first mile of a telecommunications network, depending on the mode of transmission, is the final component of the system and provides fast actually very easy to end users. It connects the network's central offices with its users across distances of many tens of kilometers (residential or business). The access network is the "capillary" of the general telecommunications network, and it often incorporates sophisticated structures and a wide range of complex spatial deployments.

These are the most basic access networks, which are mostly built on twisted-pair wire-based digital subscriber lines (DSL) and hybrid fibre-coaxial (HFC) technologies as their foundation (Kazovsky *et al.* 2011), these are primarily used for the transmission of broadband connections. These copper-based technologies are appealing because they make use of existing infrastructure to transport digital information transmission. A number of different DSL specifications exist, all of which are referred to as xDSL. These specifications make use of conventional telephone lines and provide access capacity in the tens of megahertz range while using regular telephone lines.

## [redacted] Motivation

The high-frequency cable network was initially developed by cable television carriers and is capable of delivering high bandwidth capabilities with a capacity of up to 1 GHz. The assured bandwidth per client, on the other hand, is very limited (Kazovsky *et al*. 2011), due to the fact that cable systems are shared-medium communications with an average network customer number ranging amongst 500 and 2000.

Due to these limitations in relation to the availability bandwidth and requirements accordingly, both DSL and HFC solutions are unable to supply good triple play services that need large amounts of bandwidth while also impeding growth prospects. Wireless fidelity (Wi-Fi) and worldwide interoperability for microwave access (WiMAX), despite the fact that they provide a more adaptable mobile access solution, despite their widespread usage, these technologies are severely constrained by the inconsistent wireless connection and their limited access range.

One of the most potential choices for forthcoming broadband connectivity is optical fiber, which is now being tested. Particularly in contrast to the relatively limited bit-rate-distance union of twisted pair communications and the frequency-dependent depreciation in coaxial cables, this technology has a number of advantages. In (Lam 2011, Venghaus and Grote 2017), a conventional single-mode fiber often experiences attenuation of a reduced amount of than 0.4 dB/km throughout the permitted transfer range of the spectrum (30 THz).

As a result, fiber access makes it conceivable to supply increased transmission services over vast distances whilst eliminating the use of sequentially cumulating power amplifiers in the challenging outdoor environment. (Kazovsky *et al*. 2011, Venghaus and Grote 2017) Universally perceived as the sole technology in the future, optical fiber access has the true promise of alleviating existing copper-based solutions' physical media limits while also reducing overcrowding in metro/access accumulation networks and completely eliminating barrier.

## [redacted] Problem Statement

When it comes to realistic deployments of PON-based FTTH, it will be vital to have the capacity of identifying and localizing fiber problems as soon as possible. Network service providers (also known as operators) need a way of bringing up and restoring service that is both quick and cost-effective. Customary debugging methodologies necessitate time- and money-consuming collaboration between the central office (CO) (network operations center or head end) and field engineers/technicians who use optical time domain reflectometer (OTDR) to conduct optical testing and locate fiber failures. OTDR is a time- and money-saving alternative to traditional processes. A critical characteristic of any telecommunications network is its survivorship, which pertains to the transmission capacity to resist equipment breakdowns and to continue delivering activities even when the system is disrupted. As a result, offering resilience versus outages is a critical need for far too many elevated networks. Due to the fact that these networks transport increasing amounts of data, the level of interruption caused by a network malfunction or attack grows more severe as time passes.

In comparison to a point-to-point network, diagnosing a defective passive optical point-to-multipoint network might be more difficult. It is necessary to totally shut down an FTTx (Fiber to –anything) network when a failure occurs on a point-to-point basis. It is therefore simple to terminate the fiber without negatively impacting the customer's situation. The wavelength division multiplexing PON (WDM-PON), on the other hand, contains several drop fibers after the distant node. Consequently, it may be essential to dispatch a workmanship to the optical network terminal (ONT) side in order for an OTDR pulse to be injected into the drop fiber. This strategy would need a significant investment of time and resources.

## [redacted] Research Problems

Voice, video, and data networks have all merged in today's communication networks. User quantity demanded year after year, according to the previously described developed applications and services. As a result, it is critical for telecoms companies and telecom operators to expand their network capacity, which is the probably the most crucial distinctive feature of broadband access networks. Peer-to-peer file transmission, video file transfer, and VOD services like YouTube and Daily Motion are examples of applications with high bandwidth requirements for both home users and corporate users, according to the FCC. Different resolutions of Internet protocol television applications are available, including standard definition television with 720x576 pixels per frame. Ultrahigh Definition TV, often known as 4k innovation with 4096x2160 pixels, the impending 8k specification, and three dimension TV are all examples of ultrahigh definition television. VoIP services such as Skype are examples of voice over IP (VoIP).

Designing a higher efficiency optical access network in accordance with PON standards is the primary research goal, since passive optical networks (point-to-multipoint) may extends for multiple kilometers. There may be numerous splitters, splicers or connectors, which may limit the diagnoses of the fault location in the PON network. To locate fault-location in PON network, it is substantial to send workers/technicians to the estimated location by the OTDR device. This operation is time consuming and expensive. Furthermore, the OTDR device itself has many limitations, to be flexibly used for the fault location detection.

## [redacted] Methodology

The methodology which will be conducted in this thesis is that a WDM-PON network will be built using OptiSystem software. The system consists of CO, transmission line (optical fiber), splitters and monitoring units. However, fiber brag grating (FBG) will be utilized, to make the main core of the PON network. Monitoring units are the OSA and the optical power meter (OPM).

The optical transmission line extends to at least 20Km. Then, the optical power splitter will be used to split the optical signal to six-groups. Each group will deliver the service to eight clients. The reflected signals will be combined, using the optical power combiner inside the central office, consequently, the output signal will be supplied to the optical spectrum analyzer, which belongs to the central office.

On the other hand, the PON network, to be designed in this thesis, will mainly base on the fiber brag grating element. That is, there will be six-groups, each group will be constructed using these fiber brag gratings, to generate eight branches. Hence, total served branches are 48. To construct these branches, there will be two fiber brag grating for each branch, where each fiber brag grating has distinct wavelength setting.

Moreover, the main optical power splitter will feed the next six-sub power splitters. In other words, there are seven power splitters, the first one is the main-splitter, which is accepting the optical signal from the optical fiber. The other six splitters are those connected directly after the main splitter. Hence, six-groups are properly constructed.

## [redacted]Thesis Layout

1- Each of the five chapters in this research has a subheading: The first chapter is a broad introduction to the subject matter. It covers why the issue was selected, the study's challenge, the assumptions, the aim, the construction, and the techniques employed to reach the intended conclusions are all discussed in this chapter.

2- A discussion of the theoretical foundations and system operation of the generic passive optical network will take place in the second chapter. Several researches have been conducted, and their techniques, as well as the pros and drawbacks of each study, have been analyzed in order to guarantee that the network proposed in this thesis is unique and original.

3- The theoretical knowledge, the system that was employed, the technique that was used, the computations, and the formulae that were used in the research are all presented in depth in chapter three. This chapter will also go into depth about the system pieces that were used and how they functioned together.

4- The analysis of the signal flow, as well as the findings, are presented in the fourth chapter. The validation process, which includes the use of an OSA and an optical power meter, will be explained in more depth later.

5- The goal of the thesis is restated in the fifth chapter; additionally the closing comments will be given in this chapter. The findings are given in broad details, and useful information is also supplied to people who will be working on this subject in the future as a consequence of their findings.

# 2 PASSIVE OPTICAL NETWORKS: THEORY AND REVIEW

## [redacted] Introduction

The PON model shown in Figure 2.1 is the most prevalent network design for implementing FTTx. At every intersection stage in the optical communication link, there really are no active components. When it comes to the CO, an optical transceiver device known as an OLT is used to facilitate communication between a backbone network and a delivery node, although a percentage of ONUs located either adjacent or underneath the user's room, in which case the ONU is termed to as an ONT, provide high - speed internet telecommunications services through a photonic console. The quantity of externally powered circuitry can be reduced by using an optically passively bridge to connect the OLT and ONUs. Given the close proximity of the customer's premises towards the remote network that contains the optical transmission splitting equipment, such as transmission dividers or wavelength controllers, which theoretically tie an OLT and ONU jointly. The optical distribution network (ODN) includes these branching devices, as well as the feeder and distribution fibers (Kazovsky *et al.* 2011).

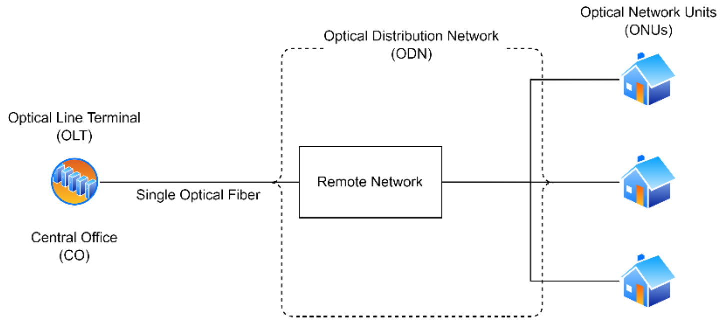


**Figure 2.1** A PON broad picture of the architecture of optical networks

## [redacted] Literature Review

A point-to-multipoint practical architecture is used by the PON system. The use of a single feeder fiber eliminates the need for a significant number of fibers, interconnections, and optical merges in the grid, making termination and space/cost savings possible at the central office. Lengthy deployments of huge equipment (an ONU may generally be between 10 and 20 kilometers from the CO) are also easier to install and maintain thanks to this technology. Active optical networks rely on electrical switching devices at the network's ends to regulate traffic allocation, while PON do not rely on optical-electrical-optical modifications along the essential component to control traffic distribution. (Larsen *et al*. 2010, Forzati and Gavler 2013). TDM (time division multiplexing) is now being used in the majority of commercial PON installations. Passive optical power splitters are used in a TDM-PON to realize the ODN. All of the downstream data is distributed to all ONUs in such a network; each ONU may pick its own chunk by identifying itself in the data frame with a unique identifier. Burst mode upstream delivery is reserved for ONUs in a distinct time frame. It is necessary to employ two separate wavelength bands for upstream and downstream traffic in order to minimize interference in the same feeder fiber. TDM-PONs use WDM technology in the same way. In contrast, the name "TDM-PON" (Lee *et al.* 2006) specifically allows the exchange of given bandwidths in a straight path, either downward or upwards. The procedure presented in this paragraph such as the one in Figure 2.2, which presents TDM-working PON's exemplary.

The TDM-PON infrastructure has a number of technical specifications. Data encryption is required in the downstream channel since broadcast communication is accessible to all users. The OLT (optical-line-terminal) and the ONUs must work together to prevent packet collisions during upstream transmission. Obtaining precise time-delay information between the OLT and each ONU requires the use of range and discovery as well as DBA (dynamic bandwidth allocation), which is a responsive tactic for ideal schedule distribution throughout other multiple ONUs. Range and discovery, as well as DBA, are also obligated (Kazovsky *et al.* 2011). The OLT must have a burst-mode receiver with quick synchronization capabilities in addition to organizing multi-user data from the upstream transmission

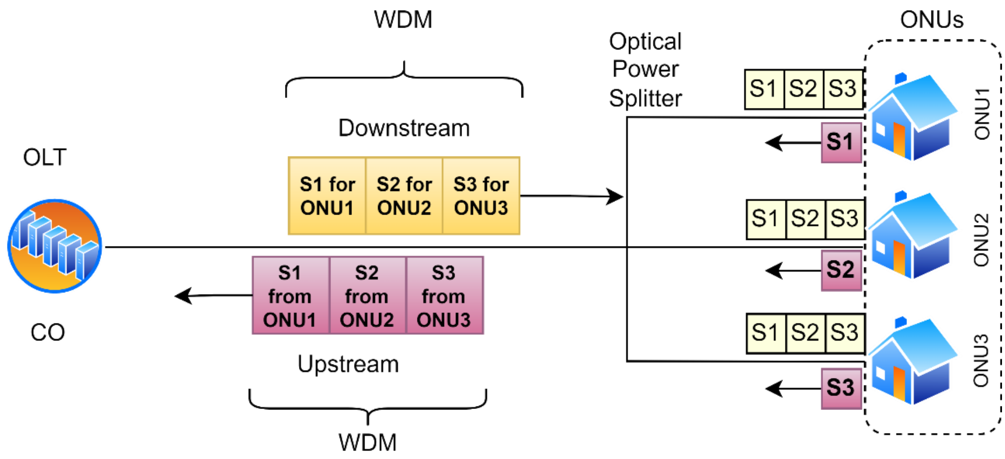


**Figure 2.2** Principles of operation of the typical time-based PON network, where S1 to S3 are time slots

If you do not have a burst-mode transmitter with good dependability, you risk causing intervention between other ONUs and a fatal breakdown integrity of the entire upward transmission chain. To begin with, "telephony on passive optical network" was coined in 1987 (Stern *et al*. 1987). Innovative contributions, such as excellent optical dividers and burst configuration communication devices, were developed and refined over a long period of time (Iannone and Reichmann 2010). Models based on asynchronous transfer mode (ATM) protocols were originally suggested in 1995 here by full-service access network (FSAN) taskforce, and in one of them was APON. ITU first accepted this in 1998, but in 2005, everything was amended to incorporate additional functions that were not originally included (ITU 2005).

A remastered edition of the technology is known as the broadband PON (BPON), and it is capable of providing downstream connection rates as high to 1.25 Gb/s as well as an upstream branch speed of up among 622 Mb/s. Owing to the BPON's ATM architecture, there are several aspects that preclude upcoming updates. As a result, FSAN and the ITU suggested the GPON in 2003 (the current version of which was ratified in 2008) (ITU-T 2008). Though straight back with BPON, the Ethernet standard is now included in GPON as an added benefit (Kazovsky *et al*. 2011).

Within both downstream and upstream routes, the GPON protocol defines line rates of up to 2.4 Gb/s in both orientations, but a 1.25 Gb/s upstream rate is most typically employed (ITU 2008). At the same time, an extra branch of the research group, the Ethernet in the First Mile Alliance, and a standards organization (the IEEE) have been working on the Ethernet equivalent of the elevated PON infrastructure. As a consequence, the IEEE 802.3 working committee standardized the Ethernet PON (EPON) in 2004 (IEEE 2007). Downstream and upstream data rates of 1.25 Gb/s are provided by the EPON standard, in symmetrical fashion. Current FTTx systems, such as EPON and GPON, are becoming more common in modern regions of the globe, particularly EPON dominating the Asian market and GPON being built primarily in the U.S. And other western European countries (Wong 2012).

ITU in collaboration with the FSAN in addition to the IEEE in collaboration including EFMA both produced elevated 10 Gb/s TDM-PON equivalents just several years back in response to the increasing expansion of Internet activities. The ITU-T G.987 series XG-PON (ITU-T G 2016) as well as the IEEE 802.3av 10G-EPON (IEEE 2010) are the two standards that have been adopted. In addition to delivering increased security and unique power saving characteristics (Wong 2012), XG-PON aims to provide complete interoperability with old PON architectures by delivering an urgent solution forward to next generation PON (NG-PON) systems.

As a result, PON initiation phase of the next era is now available (NG-PON1) (Vetter 2012, Nakamura 2013) is identified to as one of the XG-PON in certain circles. According to the XG-PON specification, polyphase flow transfer rates are defined: 10 Gb/s down, 2.5 Gb/s upstream, and 10 Gb/s symmetrical upstream and downstream, which are designated as XG-PON1 and XG-PON2, respectively. The 10G-EPON allows symmetric 10 Gb/s communication on either side, as well as asymmetric 10 Gb/s downstream transfer speeds paired with 1 Gb/s upstream information rates on the other side (IEEE 2010).

Multiple organizations have recently conducted field testing for both Next Generation PON (XG-PON or NG-PON) and 10G-EPON, and the results have been published (Jain *et al.* 2011, Fujiwara *et al*. 2012). 2013 saw the introduction of the first commercial deployment of XG-PON, which was tested on real customers by BT and ZTE. Despite these accomplishments, there are several difficulties related with these TDM-based PON systems that need to be addressed. It is possible that certain limits of the TDM technique may be reached as the demand for bandwidth continues to rise and specifications become more rigorous. Such restricting characteristics are derived from the fundamental aspects that are related to TDM technology which likely to impede the development of wideband light-based communication systems in the future (Grobe and Elbers 2008, Wong 2012). It is one of the most basic problems with TDM-PON technology that, despite time-sharing helps to reduce upstream collisions, it also means that the bandwidth capacity available towards each subscriber is shared. A common PON split ratio of 32 or 64 (ITU 2005, IEEE 2007, Grobe and Elbers 2008, ITU-T 2008, ITU 2008, Fujiwara *et al.* 2012, Wong 2012) is used, which means that only a small percentage of allocated bandwidth is really committed to the individual nodes (ONUs). With the significant reduction in power splitter performance, the system power budget suffers, restricting the maximum number of users or the range of systems that can be supported by a single device.

In addition, peak-hour data traffic has become the dominating traffic pattern in networks owing to the needs of video-rich video streaming. A data-centric network's statistical multiplexing benefit is predicted to be less beneficial now that the median Internet traffic has crossed (Barnett *et al.* 2018, Cisco 2020). TDM-PONs may not be able to handle peak-hour traffic with the DBA algorithm used to distribute resources across several users. There is a concern of where the infrastructure be having the capacity to maintain a good quality of service (QoS) for video-intensive multi-media applications, given the demand on customer load distribution.

Additionally, burst-mode transceiver in the ONU/OLT gets increasingly difficult as the information rate increases. Because each ONU recipient is required to function somewhere at aggregated downstream connection speed, the recipient throughput demand is substantially larger than its allocated connection speed. As a consequence, there is a decrease in the SNR (signal-to-noise-ratio) and an increase in the cost of upgrading (Lee *et al*. 2006)

### 2.2.1 WDM-PON networks

Because of its superior performance over current TDM/TDMA systems and ability to offer a long-term alternative, WDM-PON is a promising contender for NGA networks in the coming years (Wong 2012). Even for one transmission direction, the spectrum resource is shared in the wavelength domain in the WDM-PON infrastructure, a completely new network type. A wavelength gateway, as in an arrays waveguide grating (AWG) in the ODN, distributes wavelengths to different ONUs in accordance with their individual upstream and downstream transmission requirements, as shown in Figure 2.3. It is vital to remember that a large number of arrayed-waveguide gratings (AWGs) might well be employed in a cascaded fashion to further increase the extensibility of the network distribution system's distribution (Grobe and Elbers 2008, Kazovsky *et al.* 2011)

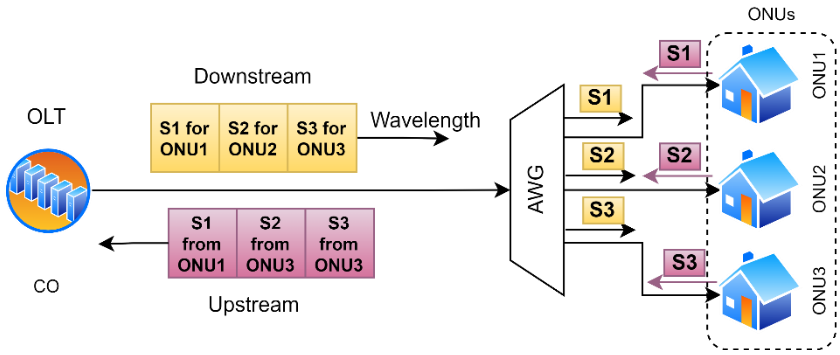


**Figure 2.3** Deployment of WDM-PONs potential configuration

As a WDM-PON attributes, the specialized wavelength combinations really construct a virtual channel across each OLT and each ONU, thereby offering point-to-point connection even if the physically point-to-multipoint infrastructure is in place. As in (Payne and Stern 1986), With the WDM-PON idea, initially introduced in 1986, throughput may be shared more effectively. For video-based applications that need fast response times and high QoS, WDM proper planning offers a better QoS and resource assurance than TDM-PON (Wong 2012).

Overall ODN waste of a WDM-PON is greatly decreased as a consequence of the wavelength routers replacing the power splitters, allowing for extended distribution lengths and/or a greater number of subscribers. Burst type transponders at the ONU or OLT eliminate the time splitting control difficulties associated with TDMA, allowing for protocol neutral operation and a reduction in recipient throughput requirements anywhere at the ONU. However, the WDM-PON has had some issues due to the ODN's usage of an AWG. First and foremost, the opportunity to distribute over the system has been wiped out, as has the DBA feature that allows users to utilize the excess capacity of other subscribers. This means that OLT and ONU broadcasters must use wavelength-specific broadcasters, although receptor wavelength-specificity is not required, since the ODN is responsible for channel selection in the new spectrally locked network.

Concerns have been raised about the cost-sensitive network access situation, whereby necessitates that each distant access site, which seems to be the ONU, be assigned a couple of wavelength-specific optoelectronics. An efficient cost-saving option is to prevent fixed wavelength equipment by making the ONU broadcasters colorless; that is to say, the same equipment may operate on several of the system's operational wavelengths to save money on expenses, operational, administrative, and support (Corning 2021). WDM-PON systems have yet to be widely deployed due to the high cost of its individual components. For the time being, no standards have been set on WDM-PON given the large use of this innovation in lengthy and metropolitan broadcasts.

There has been a field experiment in Austria (ADVA 2021) and a commercial deployment in Korea (Lee *et al.* 2007), although the economic consequences have yet to be reviewed. WDM-PON technology has, all in all, suffered its initial battle against TDM-PON equipment in the conventional access market and is only now searching for a new chance in the NGA market. Notwithstanding, development of WDM-PONs hasn't slowed down. As a result of these observations and debates, a number of low-cost ONU and OLT designs have been developed during the last decade (Feldman *et al.* 1998, Ponzini *et al*. 2009, Prince *et al.* 2012, Spiekman 2013). Starting from the ONU side, several fundamental ideas and major concerns will be briefly discussed in order to provide an overview of these research suggestions.

An identical Tunable Laser (TL) generator may be installed in each User equipment anywhere in a pre-specified broadcast range, allowing them to all use the same spectrum. For optimal system performance and cost-effectiveness, the TL may be modified either explicitly or implicitly. In (Jie Hyun *et al.* 2005, Suzuki *et al.* 2007, Wale 2011, Grobe 2013, Lee *et al.* 2013) are some of the TLs that might be used in the future, including external cavity laser, tunable distributed feedback laser array, multi-section distributed bragg reflector devices, and tunable vertical cavity surface emitting lasers.

To achieve complete colorless working in this method, the TL components must be expensive (Prince *et al*. 2012), as well as requiring wavelength stabilization or alignment between the lasers and AWGs (Grobe 2013, Moon *et al*. 2013). For the upstream wavelength allocation of the AWG, ONUs may modulate a wavelength-independent wideband light source rather than employing a laser. The method of spectral slicing is used to establish represent distinct channels for every customer by passing across various spectral regions of the Broadband light source (Spiekman 2013). This technique has many drawbacks, including a low power spending plan and a limited instrument reaching (Woodward, Iannone et al. 1998), a spectrum or data rate constraint owing to the related distribution cost, and higher intensity noise attributable to spectrum filtration (Spiekman 2013). a WDM-balanced PON's design suggests that the infrastructure's lower portion is equally important, and that the OLT's price and complexity must be extensively investigated as well (Smith 2009). OLT components cannot be exchanged across several ONUs throughout the WDM-PON, as in TDM-PON, in which an elevated transponder connects with numerous devices simultaneously.

As a result, the power loss of occipital elements rises as the density of optical transponders inside the CO grows. Operational and investment expenses for telecom companies were risen as a result of challenges such as building and operation among that equipment as well as space management in the CO. In a WDM-PON, the OLT is projected to account for nearly half of the total network cost (Borghesani 2010).

### 2.2.2 PON development

Despite the fact that some individuals don't really have access to potable water, they do indeed have connection to the Web. There are billions of individuals who use the Internet every day without thinking twice. Emails, file sharing, texting, cloud storage, video chats, online games, and streaming movies are all commonplace. With both the assistance of wavelength multiplexing, the overall capacity can attain tens of terabits per second. This connectivity is facilitated by the incredibly huge available bandwidth that is accessible in the central fiber networks utilizing comprehensible optical communication hardware that offers hundred gigabits per second data rates, 400 Gbps in 2018. One of the most essential aspects of a fiber network's bandwidth is indeed the ability of terminal to consume the vast amount of data (Ford 2018).

Optical fiber is now the best option for whichever anticipated data flow, notwithstanding the massive surge in Internet activity caused by mobile phones, tablet, as well as other handheld technologies (Steenbruggen *et al.* 2015, Falch and Henten 2018, Hernandez *et al.* 2019). Because of this, online services ought to be capable of providing extra bandwidth, particularly in light of the growing demand for bandwidth among end users, which is rising both in communication systems and core networks.

However, it was mentioned in chapter one, a PON based on ATM (APON) technology is the first PON standard to be adopted by ITU institute in 1998. They defined the full standard, which is based on ATM technologies and constructed on the principles of distributed computing. There are several big networks that use the ATM technology. An ATM network standard would allow for transmission and reception of voice services to be provided. Cells are used as transmission units in an ATM. In order to resolve issues with circuitry and packet switched networks, cells were created. Bits and packets are combined into a single cell-based data stream for delivery.

Cells are data units with a fixed size and generally low density. There are 53 bytes in an ATM cell (header, 5 bytes, and 48 bytes of information). Due to their hardware-only processing capacity, ATM exchanges can route cells quickly. Switches of this kind may be quite expensive. As a result, this technique's utilization has declined (Kim 2003). Using ATM infrastructures, clients may transmit data at speeds of up to 1.5 Mbps to 2.4 Mbps. Permanent or virtualized components may be used to allow connection. To ensure quality of service, ATM infrastructures are also capable of handling a wide range of data streams. Make certain, however, that error diagnosis or equipment breakdown monitoring is not allowed (Kim 2003). It was in the late 1980s when ATM technology began to take hold. The International Telecommunication Union (ITU) authorized ATM as a communication medium for a wideband integrated services digital network. For enterprises and end-users alike, ATM networks were originally designed to offer facilities for a wide variety of applications. An asymmetrical form of the APON has been developed in the second generation. An upstream connection speed of 622 Mb/s was available for usage by consumers. The data rate in the upstream remained constant at 155 Mb/s. Thirty-Two is the highest number of splits that may occur. For something like an individual user in this specific scenario, the highest downstream data rate is roughly 19.4 Mb/s (Kim 2003).

The highest split ratio remained unaltered in the third generation, which was uniform and had a download speed of 622 Mb/s (James and Fisher 2002). In order to save money, optical cables weren't really terminated at the residences of end users. Rehashing an existing metallic network, several end-users have been associated with a particular ONU. The count of ONUs linked to the optical tree structure became restricted to 64 as a consequence of downward data being provided to all ONUs upon that system. Using this method, the company's electricity expenditures may be minimized. APON's usual range was roughly 10 kilometers (Gagnaire and Stojanovski 2000).

In the 1990s, the first real-world validation of that kind of specification in operational life was completed. This technology has advanced greatly since the establishment of a complete service access network by telecom companies and telecom product developers in 1995 (Vetter *et al.* 2000, Chanclou *et al.* 2006). This endeavor has made major contributions to the advancement of this industry. It was in 1998 that the ITU began to standardize their institutions. Following the establishment of this specification, there has been a major acceleration in the creation of electro - technical elements, with the price of these elements having fallen dramatically, consequently increasing their presence. When the APON specification was introduced in 2001, it has become the solution that was being examined for the deployment of FTTH communication systems (Ringoot, Janssens *et al.* 2001). The original APON standard was 155 Mb/s; the highest hierarchical ration being 32. 32 terminals may be accommodated in the optical transmission bridge at full capacity; each user's channel speed is 4.8 Mb/s. At around that era, the first generation of DSLs was not a considerable advance, but it was capable of transmitting data at the same speed as ADSL, which had been widely deployed by then. The very first version would also have been unsuited for triple play service (James and Fisher 2002).

Proposals for future PON architecture was indeed underway at the time of the establishment of the APON specification. Assuming that infrastructure would keep increasing in extent, the study was conducted For large scale networks with a significant hub proportion, the AC50 photonic regional optical network research project concentrated on the improvement of new PON architecture (Voorde and Plas 1997). An optical communication system laboratory test was carried out in March 1997, which is a big network with an increasing transportation ratio. The Super-PON connection was tested in Brussels in 1998 for multimedia broadcasting. In order to obtain a maximum distance of 100 kilometers with the Super-PON, the overall hub ratio was set at 2048. 2.4 Gb/s for downstream and 311 Mb/s for upstream were enabled. It was predicted that the capacity could support 15,000 simultaneous connections. Linking more and more customers might be conceivable with a fiber to cabinet (FTTC) design (Phillips *et al.* 1998). It is recommended that SuperPON use ATM unit transmission as the basis for data transmission. Nevertheless, optical amplification is required. There is a suggestion that perhaps the downstream route might employ the EDFA. It is recommended to employ a semiconductor optical amplifier for upstream applications. Saw the need to quickly switch between channels so that related noise levels could be reduced (Phillips *et al.* 1998).

Recommendation G.983.3 (Sector 2001) defines BPON as the next specification of PONs developed by the ITU. Due to this advice being accepted in 2001, a new optical transmission technology called WDM was developed and put into use. The BPON protocol is backwards compatible with the APON protocol and uses that very same network throughput. PON s were the primary beneficiaries of the new standard's emergence of WDM (Filka 2009).

Several optical fiber wavelengths are used to transmit data in a wavelength multiplex scheme. At varying wavelengths, different optical signal sources emit light. If this method were not used, each signal would have to be sent individually through a different optical fiber, which would increase transmission costs. An optical fiber's transmission capacity may be greatly increased by using WDM multiplexing. WDM is the closest thing to frequency-division multiplexing in terms of technology (FDM). There are several frequency bands used in FDM. Different wavelengths are used for WDM broadcasts. Streams from many broadcasters need to be combined at the commencement of an optical route. There are multiplexers and demultiplexers employed for this function.

Wavelengths spanning 1500 to 1550 nm have been designated by the ITU as a new band for WDM. 1550 nm was utilized to transmit television signals (Abrams *et al.* 2005). In order to implement a wavelength multiplex, the wavelengths employed for the communication of a single fiber was altered. 1310 nm was chosen as a wavelength for the downward direction. 1490 nm was employed in the upstream direction (James and Fisher 2002).

The BPON network's gradual rollout has reached its pinnacle. The field of digital video has grown in the new century. In order to transmit high-definition digital signals, even the BPON standard's maximum achievable speed (622 Mb/s) would be inadequate, particularly when this bandwidth is divided across 32 individual consumers. Emergence of PONs has committed to building faster network throughput and the ability to link many terminals (Hood 2012).

Regulation G.984 of the International Telecommunications Union defines the GPON standard. G.984.1, which outlines the fundamental features of GPON systems, became adopted as the initial proposal in 2003 (ITU-T G 2003, Recommendation 2008). All contemporary communications services are supported by the GPON specification. As bandwidth requirements continue to rise, new PON standards have been developed. The ATM architecture, which was the foundation for the two preceding PON systems, has not evolved much.

The absence of transmission functionality is a key downside to this system. The ATM made it feasible to link to a multiplex network. In order for a multiplex link to work, there must be a source of information one that transmits to clients who have enrolled for that specific multicast group and are willing to receive the transmission. This information source must occur. The clients of this cluster member are permitted to retrieve information from a certain provider. Nevertheless, ATM technique does not allow for transmission from many locations. Streaming could be accomplished using multicast, where the receivers were types of nodes (Kim 2003).

To ensure interoperability with the BPON, ATM system was included into the GPON architecture. ATM usage was eventually phased off. But the advent of a new GEM encapsulation technique, that can also encompass arrangements of many communication protocol, most commonly Ethernet sessions, marks a big step ahead (Hood 2012). In contrast to the Ethernet-based EPON, the GPON specification is incompatible with it (Cale *et al.* 2007).

The creation of the protocol was indeed influenced by the demands of telecom operators, who insisted on the steady modernization of the devices that they had already delivered. Because BPON is capable of transmitting at different wavelengths than

GPON, they could not be implemented together in the same optical communication system, which presented an issue.

Although it would be feasible, it would be prohibitively expensive from an economic standpoint to create new network in tandem with the current transmission medium. In a similar vein, changing all ONUs placed at terminal locations or temporarily turning down the current communication system would be extremely impossible to do. Consequently, GPON wavelengths have really been safeguarded in order to allow for the progressive installation of the next series of PONs to be implemented. It was critical to include filters inside ONUs; such filters being intended to exclude a specific wavelength of light, allowing for a more seamless transformation technologies. The years 2008 and 2009 saw a significant increase in the size of GPON technology application (Hood 2012).

Faster communication speeds are now possible thanks to the new GPON standard, There are 1244 or 2488 Mb/s downstream and 155, 622, 1244 or 2488 Mb/s upstream options as indicated in (Recommendation 2008). However, it is possible to mix these rates. An asymmetric variation with a downstream rate of 2488 Mb/s and an upstream rate of 1244 Mb/s is the most prevalent choice. 155 and 622 Mb/s rates are supported by prior specifications, therefore backwards interoperability is guaranteed.

There are two wavelength bands that are allocated for transmission: (a) 1480 to 1500 nm downstream and (b) 1260 to 1300 nm in upstream direction. More wavelengths spanning 1550 to 1560 nm may be used to transmit video stream (Cale *et al.* 2007). The splitting ratio has been increased by a factor of two. Networks based on GPON may employ a proportion of 1:64, with an intended ratio of 1:128. For example, GPON's distance is 60 kilometers in logical terms and 10 or 20 kilometers in practical terms (Recommendation 2008).

A new class of ITU-defined standards called Next-generation PON (XG-PON) was added to Recommendation G.987 in 2010 (ITU-T G 2016). Nevertheless, G.987.1 is the first proposal in this group of specifications and was accepted in 2010. A Roman number, X, denotes a broadcasting rate of 10 Gb/s for the specification, which is called 10G-PON. It was only natural for FSAN to focus on the successor to the GPON specification as immediately as GPON got extended. FSAN and the ITU have already been working each other since 2007 to establish a new wave of PON.  It was their own major goal to specify the criteria for the NG-PON, which would have been finished in 2009 (Effenberger 2017).

Next-generation PONs, or NG-PON or XG-PON, have been separated into two sub-generations, NG-PON1 and NG-PON2, based on whether or not they can operate on a similar network architecture with previous PON benchmarks (Hajduczenia and Silva 2009). In the NG-PON project, a new definition was examined from 2012 to 2015, which is the NG-PON1. On the other side, the NG-PON2 research covered solutions that weren't even suited for adoption at this time. Coexistence between NG-PON and GPON is assured in the situation of NG-PON1.

A key benefit of that kind of togetherness is that moving to a new benchmark is simple and does not need large infrastructure changes or service interruptions for current end-user operations. While determining the most appropriate strategy for ensuring cooperation, the usage of TDM or WDM had been taken into consideration. New generation NG-PON stage 2 (NG-PON2) comprised technologies that have not been interoperable with prior standards, in contrary to the previously listed facts. An investigation found that new solutions or an overhaul of the ODN were needed, but neither could be implemented in the near future (Effenberger 2011).

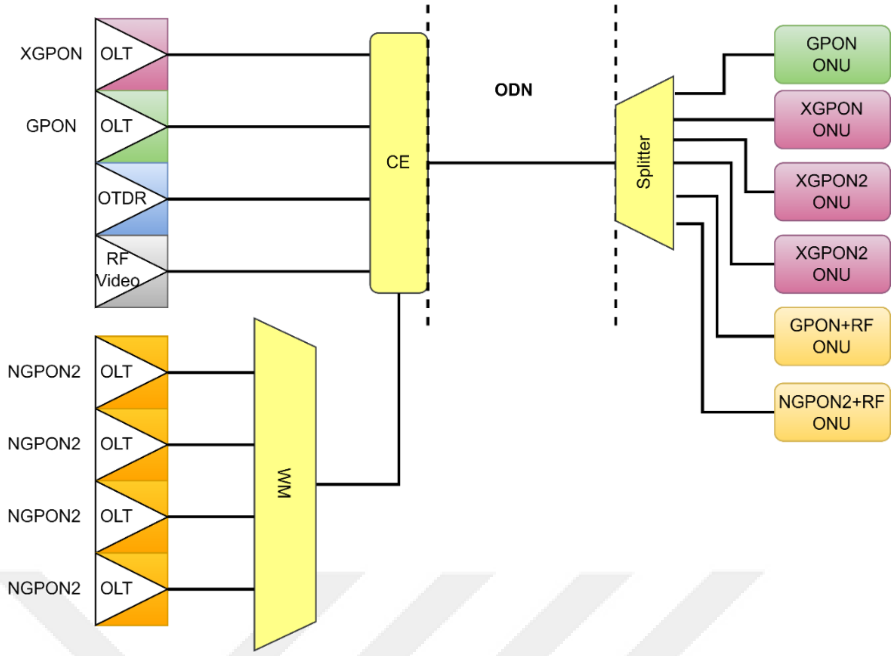


**Figure 2.4** NG-PON2 coexistence, a simple configuration

2015 saw the standardization of ITU-T G.989, the next iteration of PON stage 2. This standard combines TDM with WDM, which is a method of multiplexing signals based on wavelength, WDM. 4–8 wavelengths and a bandwidth of 10 Gbps per wavelength are supported by the NG-PON2. A single fiber provides 80 Gbps of overall network capability (Yi *et al*. 2019, van Veen and Houtsma 2020). With a 1:256 split ratio, the maximum distance is 40 kilometers. Backwards compatibility is achieved by the coexistence element (ITU-T 2013), as shown in Figure 2.4.

It was decided that the scheme XG-PON (Muciaccia *et al.* 2014) would have been the best possible choice for NG-PON1. Generally, XG-PON bieng subdivided into XG-PON1 and XG-PON2 depending on the transmission capacity they handle. Downlink transfer rates of 10 Gbps and 2.5 Gbps are supported by the XG-PON1 and XG-PON2, respectively, while the XG-PON2 is capable of supporting a 10 Gb/s bandwidth including both directions. Asymmetrical PON (XGS-PON) is also used for the XG-PON2 in order to emphasize its symmetric character (ITU 2016). This divide is mostly the consequence of market considerations. There has been little demand for the symmetrical solution, thus its progress was already put on hold (Hood 2012).

There are two wavelengths utilized for the downlink and uplink directions: 1575 to 1580 nm for the down and 1260 nm for the upward directions. To establish compatibility between the GPON and XG-PON specifications, a splitting ratio of 1:64 is required. In order to sustain the projected expansion, the system is required to transmit at a shortest distance of 20 kilometers; the highest potential communication range is 60 kilometers (ITU-T G 2016). For the sake of the previously described cohabitation, many wavelength choices are made were investigated during the creation of the XG-PON specification. It was pretty simple to choose the right wavelength for the downward direction. In the 1578 nm wavelength range, it was considered. This was a logical next step in the development of IEEE's 10 Gigabit EPON (10GEPON), which used the same wavelength. From the other arm, deciding on an appropriate upstream wavelength range was indeed a difficult decision, since there were four possibilities (Effenberger 2011).

For the upstream direction, NG-PON2 networks using Time and Wavelength Division Multiplexing (TWDM) employ a variety of ranges: wideband option 1524–1544 nm, reduced band option 1528–1540 nm, and narrow band option 1532–1540 nm. Second choice has to be made about the connection speed as well as the processing of the data. It was necessary to make a decision between commercially available SDH systems and Ethernet-based options. The research topic emerged at this stage in the selecting process: It is possible for XG-PON to operate well with 10GEPON specification because of the usage of WDM. Ethernet is the obvious option if this kind of cohabitation is needed. Nevertheless, it is doubtful that network operators would concurrently install XG-PON and 10GEPON to a similar internet infrastructure (Effenberger 2011).

XG-novel PON's capabilities incorporate steps to save electricity. An OLT supplied by a battery bank is designed to be as light as possible as in case of a main power outage, in order to extend the battery's life. The goal is to use as little electricity as possible while drawing power from the main source. If a consumer network device is no longer in use, it may be possible to deactivate it. If the client hasn't had any data to send, they may disable the broadcaster. When a client is not actively using the ONU, it turns off the transceiver, which saves the most electricity (Effenberger 2011).

In (Harstead *et al*. 2019), Competitive PONs capable of transmitting data at rates up to 10 Gb/s are typically relied on proven equipment from transportation and metro transportation networks. The datacentre architecture is being exploited beginning with 25G PON, which should be available shortly. Specifically, it is proposed that a basic design be used to allow the increased speed of 25 Gb/s at a low incremental expense to the existing 10G PON infrastructure, and that the use of costly optical amplifiers be avoided in order to maintain low costs associated. A description is given of the 25G PON wavelength scheme as well as cooperation possibilities with current PONs. Evaluation of the capabilities of TDM PONs to handle the 5G backend, midhaul, and front haul transportation use cases is carried out. The technical path for a potential 50G TDM PON is detailed throughout this study. The presentation includes an analysis of the primary problem of fulfilling PON losses estimates at 50 Gb/s with increased start wattage, as well as the economic dependency on signal power, among other things. Following that, there is a brief summary of new findings in the topic of coherence detection in PON schemes, and this will be critical for 100G PON deployment.

A study (DeSanti *et al.* 2020) showed that as an access technology, PONs have indeed been extensively utilized in communication systems for many years and are now the preferred technology for many providers, particularly whenever new equipment is required. In order to increase the performance of PONs, a considerable exertion was already expended throughout time. Additionally, the notion of a super-PON has been developed in addition to increasing the spread of PONs as well as the amount of customers they can aggregate. The process did never, unfortunately, result in any meaningful regulatory attempts or industrial implementations. The IEEE 802.3 Advisory Committee established the P802.3cs "Super-PON" Response Team in November 2018 to systematize a taste of super-PON that can reported that an increase optical accessibility of up to 50 km and an increased client connectivity of up to 1024 clients for every fiber across a PON. Several seasons later, under ITU-T Q2/SG15, a programme with some really similar goals got launched. Being part of ongoing sector networking protocols, this study provides the most recent developments, with particular emphasis on work being done by the IEEE P802.3cs Working Group and the engineering logic of some of the most significant choices that have been taken (DeSanti *et al*. 2020).

In (Zhang *et al.* 2020), the purpose was to evaluate significant elements that were discussed and selected prior to the introduction of the faster speeds PON recommendations throughout the Full Service Access Network and ITU-T SG15/Q2 before they were implemented. It examines the needs for an otherwise platform as well as the development of the ITU-T specifications papers that are relevant to the system under consideration. The major innovations required for the 50G-physical PON's and operational layers are also described in detail.

NG-EPON, the next generation EPON, has been standardizing in the IEEE 802.3ca Working Group lately, to accommodate different throughput needs. Enables ONU transmissions to ever be planned on several wavelength different channels in NG-EPON. The four 25 Gb/s wavelength lines may already be assigned to either of the 25 Gb/s channels, increasing system throughput to 100 Gb/s. When choosing an optimal routing methodology for the NG-EPON (100G-EPON) design, there are several technological considerations to address. One of the main goals of the study in (Hussain *et al.* 2017) is to provide relatively low network latency and accommodate frame re-sequencing in the scheduling of upstream available bandwidth in the NG-EPON. In this study, (Hussain *et al.* 2017), an online scheduling architecture with a gated service grant sizing criteria is shown. Experiments showed that the suggested approach was effective.

In the research (A. Mohammed and Hamdi Mansi 2019), Dense Wavelength Division Multiplexing (DWDM) is simulated and evaluated using a record of 16 channels with future channel spacing in accordance with ITU-T G.694.1 at 12.5 GHz for DWDM. This efforts have been made in order to bring a projected high bandwidth DWDM-PON infrastructure to fruition. As a result from these parameters, the upstream throughput may be increased to 2.5 Gb/s across a 25 km single-mode fiber cable while also delivering a notable overall BER of around 1×10-12 throughout the platform's inspection process. All of these performance metrics are obtained by optimum design of the cross-seeding Rayleigh Backscattering elimination approach, which is a kind of

Rayleigh Backscattering elimination. When contrasted to the cross seeding-related literature, this modification has been beneficial in lowering the overall cost.

Explosive growth of PONs raises the worldwide power consumption of communication network, which contributes to global warming. The goal of a study in (Khalili *et al.* 2020) is to reduce the amount of energy used by EPONs to a minimum. The authors offer an energy-efficient, distributed DBA technique that allows an ONU's transceiver to be turned off since there is no upstream or downstream activity in the network. When compared to centralized dynamic bandwidth allocation, the important focus is the combination of the benefits of distributed dynamic bandwidth allocation, which include a relatively small network latency especially in comparison to centralized DBAs due to less time being required to assign the propagation window, with energy efficiency characteristics, which come at the cost of longer delays associated with extended queue waiting times when transceivers are turned off. This method examines the waiting time of the ONUs in switching devices to rest status if there is no transmission or distribution activity in either direction of the system. Using this approach, they were able to reduce ONU energy usage over a broad variety of media demands whilst maintaining latency within a defined tolerance.

Upon this foundation of the wavelength cooperation between the ONUs, the NG-EPON structure may be divided into two categories: basic and advanced. Designing DBA methods that will be able to satisfy the development demands of network access is a critical job in the implementation of NG-EPON. In order to support TWDM-EPON, a variety of DBA methods were developed (Rafiq and Hayat 2019). It is still necessary to create and innovating appropriate DBA techniques on a given level, for example. In this research, they present a DBA method for NG-EPON that is focused on the QoS provided. Having respect to current techniques, they recently conducted a comparison analysis of the proposed DBA with Earlier Finished Time (EFT), Weighted Bipartite Matching (WBM), and EFT with void filling (EFT-VF). The findings reveal that the suggested DBA technique outperforms EFT, WBM, and EFT-VF algorithms in terms of average latency and average timeframe for NG-EPON when contrasted to the other three algorithms.

TDM-PONs, TWDM PONs, and WDM PONs with higher efficiency get a great deal of promise for usage as NG-PONs in developing broadband services for a wide range of applications, including telecommunications and videoconferencing. The employment of immediate detection methods and reduced parts in PONs makes propagation defects a significant limiting feature in their deployment. Transmission impairment compensation strategies, among both optical and digital solutions, are developed and proven for elevated TDM-, TWDM-, and WDM-PONs using a variety of different technologies. NG-PON systems, as well as the fundamentals of various compensation approaches, are discussed in (Zhang *et al.* 2019). Nonlinear intersymbol interference produced by imperceptible sideband, circumscribed modulation spectrum, in as well as quadrature asymmetry, dispersal, and square-law detection is compensated using filter type optical compensatory and Volterra type electrical compensation approaches, which was provided. Aside from that, the authors give evaluations and comparisons of the equilibrium outcomes of several optical- and electrical-domain compensation schemes, as well as their properties, qualities, and application.

## [redacted] Conclusions

PONs have unquestionably arrived, and fresh innovations assure that they might continue to exist for many generations to follow. New protocols for rising PONs have been developed, and other specifications are in the process of being developed. Designers spoke about a number of methodologies, ranging between expense options for everybody to modern examples that could still meet even the most demanding company requirements. They explained the data transmission between PON components: OLTs & ONUs, as well as the designs including all data packets sent over the network.

To minimize vendor dependence and lock-in, fresh public connectivity ideas advocated by megadata and hyperdata foundation firms must be explored for emerging innovations in PON implementation. It is possible to use public communications to guarantee that techniques are changed or moved to new hardware as necessary. Despite the fact that these new open patterns are not regulated, they cannot be ignored due to the fact that they have been surfacing in several regions of the globe, particularly in North America and Asia. It should be evaluated whether to enable new services including such precise time transmission or dispersed fiber monitoring. This new category of apps may not seem to be fit for a PON setting at first glance, but existing client needs plus fresh public techniques might avoid well-known prognostications from occurring.

Hence, it can be concluded that the investigation of a lost service in a specific line of service in a very simple and cost-effective approach can be introduced in this thesis. It is possible to locate the faulty line using simple passive components by dividing the serving spectrum into groups. Each group is further subdivided into serving lines (users). If the user did not reflect the signal, it means that its serving line has dropped. Moreover, if the whole group is lost, no signals will be reflected to the central office. Even more, the isolation wall that differentiates the groups is formed using the reflected signals from each group, where these reflected signals have the same wavelength in the specified group. This will be discussed extensively in the next few chapters.

# 3 DESIGN OF NEXT GENERATION ACCESS NETWORK BASED ON ADVANCED OPTICAL CARRIER GENERATOR

## [redacted] Introduction

APONs were the first PONs to be recognized, and they were used in the same optical distribution network layout that we are familiar with in contemporary networks, which was 21 years ago. As time passed, several PON networks became regulated and then became an integral element of the telecommunications industry. To supply services to many access points, a PON is a telecommunications network that use optical fibers and optical splitters to transmit data.

The data-centric needs of both residential and business networks may be met by a PON, which includes solely passive elements. The PON has contributed immensely in getting fiber to the home. In a conventional PON, the communication network is traced back to an OLT, which is typically located in a network head office or central entity. The optical power is divided across many transmission fibers by a splitter located at a distant node, and the services would then be transported over an optical feeder with a distance of up to 20 kilometers or more. All potential customers attached to an ONU get the light beam from the transmission fiber that transports the information to the ONU's endpoint.

In this chapter, PON system will be implemented using OptiSystem. However, at the beginning, the system structure will be presented in details and each block of the system will be discussed in details.

## [redacted] System Construction

Passive Optical Network which is suggested in this work consists of different parts; first part is the CO. The CO contains the transmitter and monitoring systems. Second part is the transmission line which is optical fibre of length 20 Km. last but not least is third part, which consists of Power Splitter (PS) and FBGs. The PS will split the incoming signal to six branches. In each branch there are another PS, (sub-PS), two FBGs in series to identify the branch frequency band as shown in Figure 3.1. In the next sections, each part of the proposed PON network will be detailed and show how to connect each part with other parts, then the results will be discussed later.

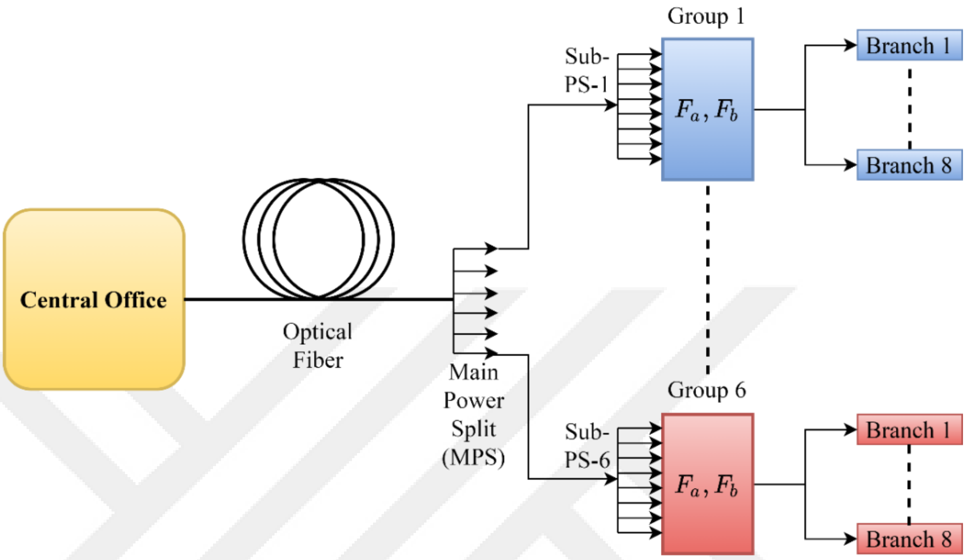


**Figure 3.1** Suggested PON system construction

The central office consists of transmitter (or signal source), OSAs, and one Power Combiner (PC) as input from the groups, as shown in Figure 3.2. The signal source should cover range of frequencies for six groups, each group (G) has eight branches. Therefore, an optical white light source was employed in this work, to operate the network. The OSA of the source (OSA (Source)) will be used to monitor the output signal and another OSA used to monitor the reflected signals from six groups, (OSA Reflected). Accordingly, there is one PC inside CO, this PC will be used to combine all reflected signals from the groups, and therefore from the branches, to investigate the faulty line, as will be seen later. Figure 3.3 shows the structure of the CO part as implemented in OptiSystem.

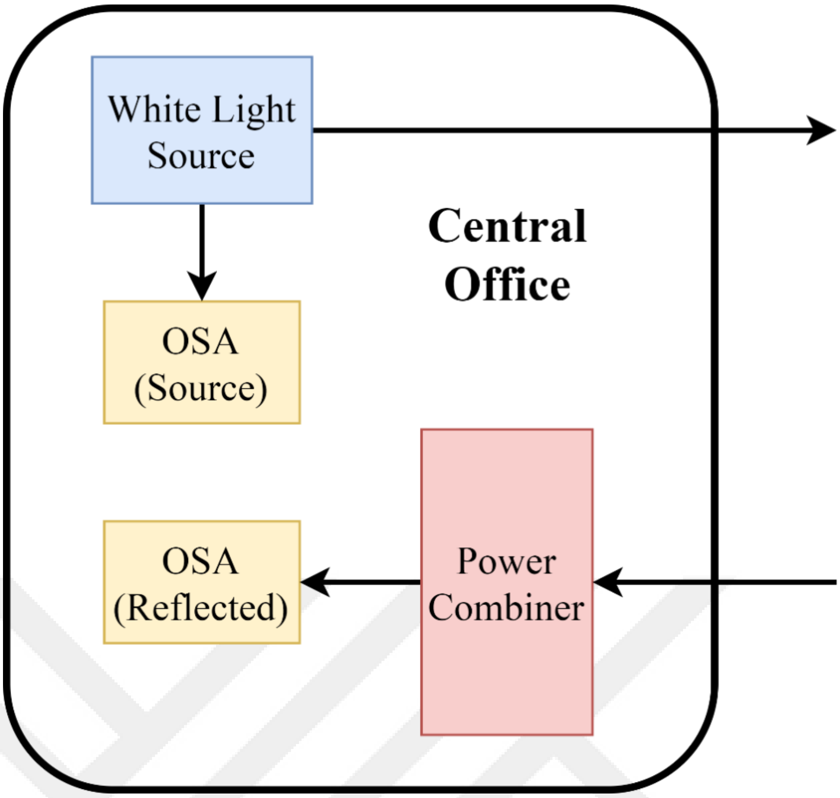


**Figure 3.2** Central Office equipped with passive components

After the central office, there is a transmission line, which is an optical fibre of length 20 Km. Thus, the optical fibre extends for 20 Km, starting at the central office until the Main Power Splitter (MPS). That is, the overall system infrastructure is presented. Before going deep in the implementation using OptiSystem, it is worth explain the employed components in the suggested organization of the system, then full implementation will be explained in this chapter. Consequently, the forthcoming subsequent sections will show the discussion of the light source, OSA, PC, optical fiber, PS, FBG, the OPM components, and the Optical Null (ON), respectively.

### 3.2.1 White light source

The function of the White Light Source (WLS) is to generate noise signal of type Gaussian. It has some an essential parameter to be set which is the central wavelength generation, which has been set to 1625 nm. The WLS icon inside the OptiSystem software is shown in Figure 3.3

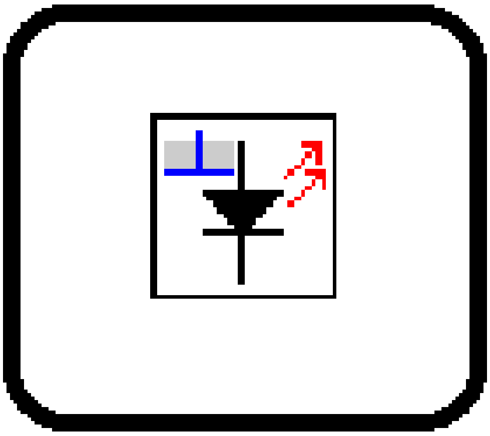

**Figure 3.3** Visual icon of the white light source component in OptiSystem software

### 3.2.2 Optical fiber component

Whenever the scalar situation is regarded, the optical fiber element approximates the transmission of an optical field in a single-mode fiber while keeping in view the dispersive and nonlinear impacts. When the random polarization situation of the signal is regarded, the optical fiber element approximates the transmission of an optical field in a scheme of two, coupled nonlinear Schrödinger (NLS) formulae. The optical samples transmissions are limited to a single frequency spectrum, which is why they are referred to as entire field (Agrawal 2001). Only the attenuation of the parametric transmissions and noise divisions is used. This component is depicted in Figure 3.4.

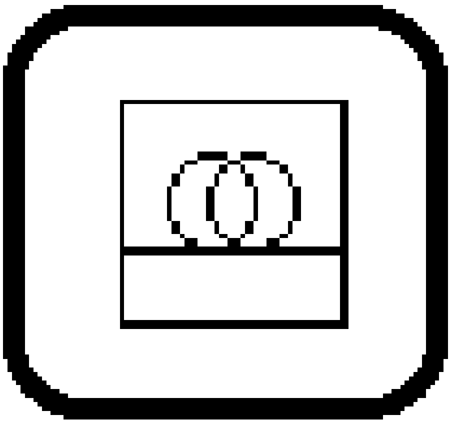

**Figure 3.4** Optical fiber component in OptiSystem software

There are two ports in this component, optical input and optical output. The important parameter to be set is the optical fiber length, which is set to 20Km in this project. Note that the attenuation was set to 0.2*dB* for each one-Km (0.2*dB*/Km).

### 3.2.3 Optical spectrum analyzer (OSA) component

Visualization of optical signals in the frequency domain is made possible by this tool. Power spectrum density, phase and dispersion for X and Y polarizations may be shown. There is only one port in this component which is the optical input. The OSA tool can be visualized in Figure 3.5.

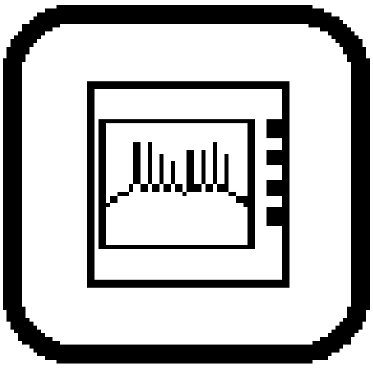

**Figure 3.5** Optical spectrum analyzer (OSA) component in OptiSystem software

### 3.2.4 Power combiner (PC) component

Depending on whether one or more frequency modes are present, the PC will merge the input fields through each frequency mode to produce throughput fields during every frequency mode. This PC is, actually, a user defined PC, in other words, this component allows user to define the number of input ports as shown in Figure 3.6. That is, the number of input ports should be set by the user to produce the combined signals in only one output port.

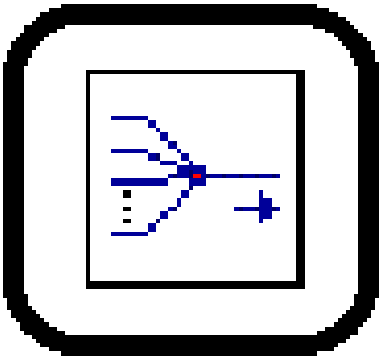

**Figure 3.6** User defined power combiner component in OptiSystem software

The output-combined signal can be formulated as,

$$E_{O,\omega,X,Y}(t) = 10^{-\frac{\alpha}{20}}\breve{N}(\omega,t)\sum_{i=1}^{n} E_{i,\omega,X,Y}(t) \qquad (3.1)$$

In this equation, n denotes the number of input terminals, α denotes the power attenuation, the polarization at time, t, is represented by the parameters X and Y, when the frequency mode is ω, and Ei,ω,X,Y(t) is the input signal from the port i. Eq. (3.1) is valid if all Ei,ω,X,Y(t) in the summation are phase synchronized. Moreover, the normalization factor was represented by $\breve{N}$(ω,t), which can be set according to the user defined parameters. For instance, if the "force power conservation" is disabled, then $\breve{N}$(ω,t) is reduced to,

$$\breve{N}(\omega,t) = \frac{1}{\sqrt{n}} \qquad (3.2)$$

By enabling the force power conversation option, $\breve{N}$(ω,t) became,

$$\breve{N}(\omega,t) = \sqrt{\frac{\sum_{i=1}^{n}\left|E_{i,\omega,X,Y}(t)\right|^2}{\left|\sum_{i=1}^{n} E_{i,\omega,X,Y}(t)\right|^2}} \qquad (3.3)$$

In this project, the number of ports n=12, and the force power conversation option is not utilized, thus, expression 3.2 is employed in the system. These settings are used for the PC presented inside the CO. Nevertheless, there are six-PCs inside each subsystem, which will be shown later in this chapter when building the system, these six-PCs are set similarly as in the PC of the CO, but the input ports are set to eight-ports. On the other hand, there are another six-PC at the output of each subsystem set as those inside the subsystems. These last six-PCs are used to combine the outputs of each subsystem for visualization only at the validation stage. In other words, they will be connected to six-OSAs in order to check the output of the six-groups generated by the FBGs (which will be discussed in the next subsection), as will be seen later.

### 3.2.5 Power splitter (PS) component

Power splitter that is ideal for optical communications that separates an optical input signal together into functionality number of output ports. Hence, there are one input port, optical, and a user defined output ports, N. The visualization icon of this component in OptiSystem is shown in Figure 3.7.

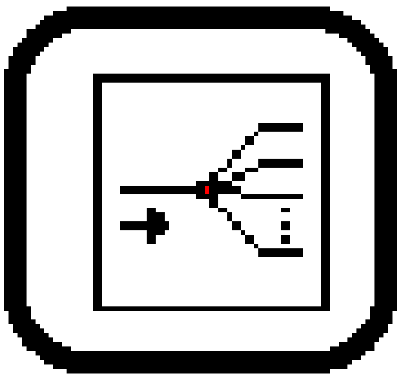

**Figure 3.7** User defined ideal power splitter component in OptiSystem software

However, from each output port, the signal can be determined in the following expression,

$$E_{out}(t) = \frac{10^{\frac{-\alpha}{20}} E_{input}(t)}{\sqrt{N}} \tag{3.4}$$

That is, there is an attenuation factor, α, will affect each output signal. Moreover, the power will be divided according to the power – splitting ration (PSR), which can be defined by the user. For instance, if N = 2 and the PSR is set to [0.6, 0.4], then the output of the first port is 60% of the total input power and the rest will be assigned to the second output port, 40%. In this project, N is set to 6, for the main PS (MPS), that is, the PSR was set to [1, 1, 1, 1, 1, 1], in other words, the input signal power will be divided equally to the six-output ports. This is according to the OptiSystem operational manual.

Not one PS was employed in this project, there are six more PSs that represents the six-groups. The settings of these sub PSs (sub-PS1, sub-PS2, sub-PS3, sub-PS4, sub-PS5, and sub-PS6) are N = 8 and PSR = [1, 1, 1, 1, 1, 1, 1, 1]. Thus, eight output ports and the input power will be divided across the eight output ports equally. This is called an ideal power splitter.

### 3.2.6 Fiber bragg grating (FBG) component

In optic fiber connections, fiber gratings have been critical elements, serving as filters, gain flatteners, and dispersion compensators, among other functions. FBG were quite desirable parts since, in addition in becoming passive, linear, and small, it also exhibits significant dispersion including both reflected and transmitted, making them extremely versatile. During reflective thinking, dispersion occurs whenever the border of the band edge changes with axial location anywhere along grating, as seems to be the case in regularly chirped or ramping gratings, among other situations.

A dispersed signal with distinct wavelengths is mirrored at various points in the grating, resulting in varying light path durations and the capability of adjusting for dispersion over extended distances. However, although the findings really far were rather good, the tests often need something like an optical circulator or a 3 *dB* coupler, as well as the development and manufacturing of intricate grating arrangements (Litchinitser *et al.* 1997).

In this project, an ideal dispersion compensation FBG is employed. However, there are three ports in this component: optical input port, output optical transmission port, and optical reflection port. Optimal chirped FBG developed for dispersion correction is approximated by this model. Nevertheless, the component should be properly set in order to function smoothly and correctly. The necessary settings are the center frequency/wavelength, bandwidth, insertion loss, depth, and the dispersion, parameters. On the other hand, there are two more parameters that are related to the noise, the noise threshold and the noise dynamic. Figure 3.8 displays the visual component of the ideal FBG in OptiSystem software.

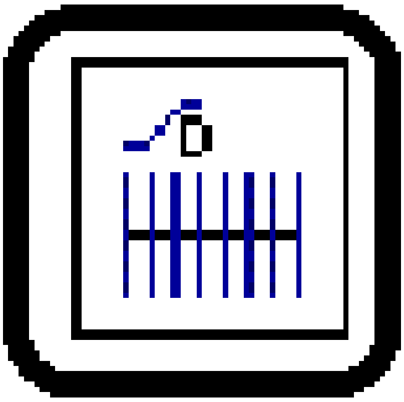

**Figure 3.8** Ideal dispersion fiber Bragg grating component in OptiSystem software

This type of FBG stands for a filter with a group delay that may be specified by the user. The transmission function of this FBG is as follows (Madsen and Zhao 1999):

$$H(f) = e^{j\emptyset(f)} \tag{3.5}$$

the frequency is denoted by f, where the phase of the function is represented by $\emptyset$(f). The definition of the group-delay can be formulated as (Madsen and Zhao 1999),

$$\tau(f) = -\frac{1}{2\pi} \cdot \frac{d\phi}{df} \tag{3.6}$$

and as a function of the wavelength, λ, the last formulae can be written as (Madsen and Zhao 1999)

$$\tau(f) = -\frac{\lambda^2}{2\pi c} \cdot \frac{d\phi}{d\lambda} \tag{3.7}$$

The speed of light is given as c. Now, assign the center wavelength (λc) and bandwidth (Δλ) together with the group delay slope D in s/m to define λ as in the following expression (Madsen and Zhao 1999),

$$\tau(\lambda) = \begin{cases} \tau_0 & \lambda \leq \lambda_c - \Delta_\lambda/2 \\ D \cdot \lambda & \lambda_c - \Delta_\lambda/2 < \lambda \leq \lambda_c + \Delta_\lambda/2 \\ \tau_{\lambda_c + \frac{\Delta_\lambda}{2}} & \lambda > \lambda_c + \Delta_\lambda/2 \end{cases} \tag{3.8}$$

Hence, the phase will be determined to correspondingly finding the transfer function of the FBG, as a filter. Last but not lease, the settings of this FBG are set to be: center frequency, will be defined in the next chapter due to its main effect on the proposed PON structure, the bandwidth is equal to 125GHz, insertion loss limited to 0*d*B, depth = -100*dB*, dispersion equated to -800*ps/nm*, noise threshold set to -100*dB*, and noise-dynamic is 3*dB*.

### 3.2.7 Optical power meter (OPM) component

This component is a simple tool to measure the optical power in the OptiSystem software. This tool can be seen in the OptiSystem software using the icon in Figure 3.9.

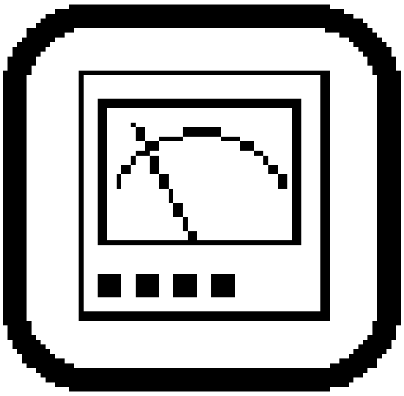

**Figure 3.9** Optical power meter (OPM) tool in OptiSystem software

Using this visualizer, the user may compute and see the mean/average power of light pulses in a variety of configurations. Power for polarizations X and Y may also be calculated using this tool. The OPM tool contains only one port, which is the optical input port. For each signal type, it may be choosing to show the overall signal power. The total of the sampled and parameterized signals is what will be gotten when the user picks the signal power.

To avoid confusion during calculating the powers in the next chapter, it is substantial to note that sampled signals, the average optical power during the simulation time frame is calculated by adding every one of the datapoints together and dividing the total number of observations by the number of samples. Because of this, the overall power that is presented will often be lower than the peak signal strength of the sampled data. Because of differences in the bit sequence pattern, transmissions connected to Bit Sequence Generators might exhibit varying optical strengths throughout simulations as well. In the case of noisy communications, each repetition of the transmission is seeded with a distinct randomly generated seed.

### 3.2.8 Optical null (ON) component

Simply, to get a zero optical signal, use this tool to function as a generator of an optical signal with a zero value. The ON has only one port represented by the output optical port of zero value. The tool inside the OptiSystem package can be seen in Figure 3.10. There are no more parameters to be set. That is, to use this component, it is only to select this component and connect its optical output port to the input of the required/next component, to behave as an input optical signal of value equals to zero.

The ON tool has been used in this project different times in different locations. This was conducted to investigate the various PON network performance and to help simulate a faulty line or a connection with bad function, particularly in-between the power splitters and as inputs to the utilized FBG of the designed PON network, of this project. This will be seen clearly in the next chapter, chapter four.

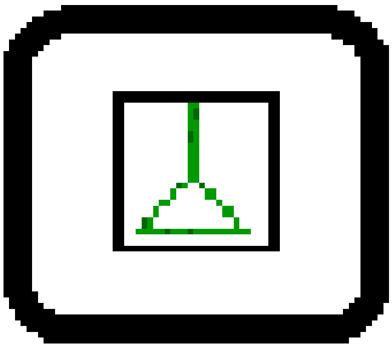

**Figure 3.10** Optical null (ON) tool in OptiSystem software

OptiSystem software package has many other components and measurements tools that are available for the designer. However, the scope of this project is limited to the components and tools that are just described in this chapter. The consequent sections will be dedicated to the utilization of these components/tools in the PON that will be configured in this project.

### [redacted] System Implementation

This section will discuss the implementation of the proposed PON network using the components and tools that are described in the previous section. In Figure 3.11, the CO can be seen as implemented in OptiSystem, which is the direct implementation of

Figure 3.2. Figure 3.12 is the block diagram figure showing all the suggested system, which is an expansion to Figure 3.1. Further, the direct implementation of the 20Km optical fiber can be seen in Figure 3.13.

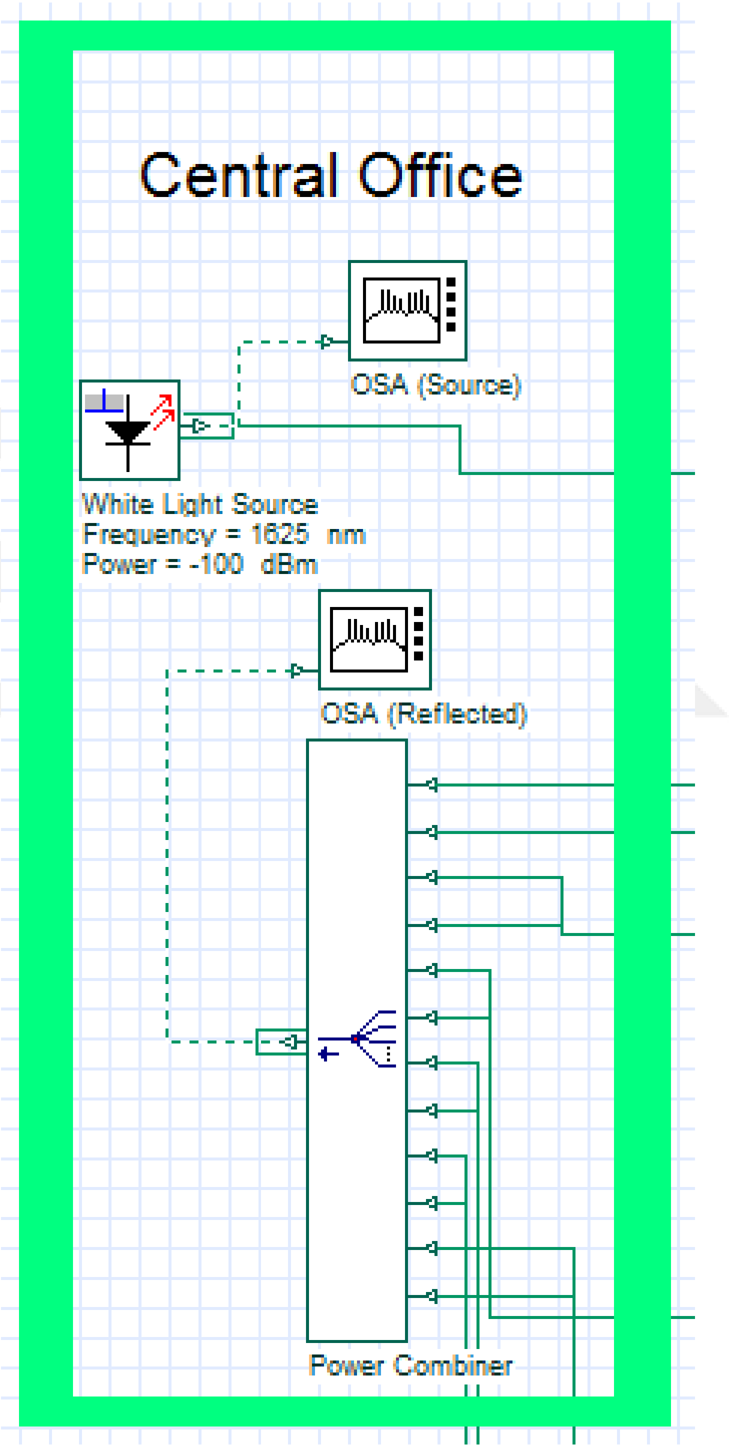


**Figure 3.11** Central Office (CO) as implemented in OptiSystem. It is shown that there are only one PCs which will combine all reflected signals

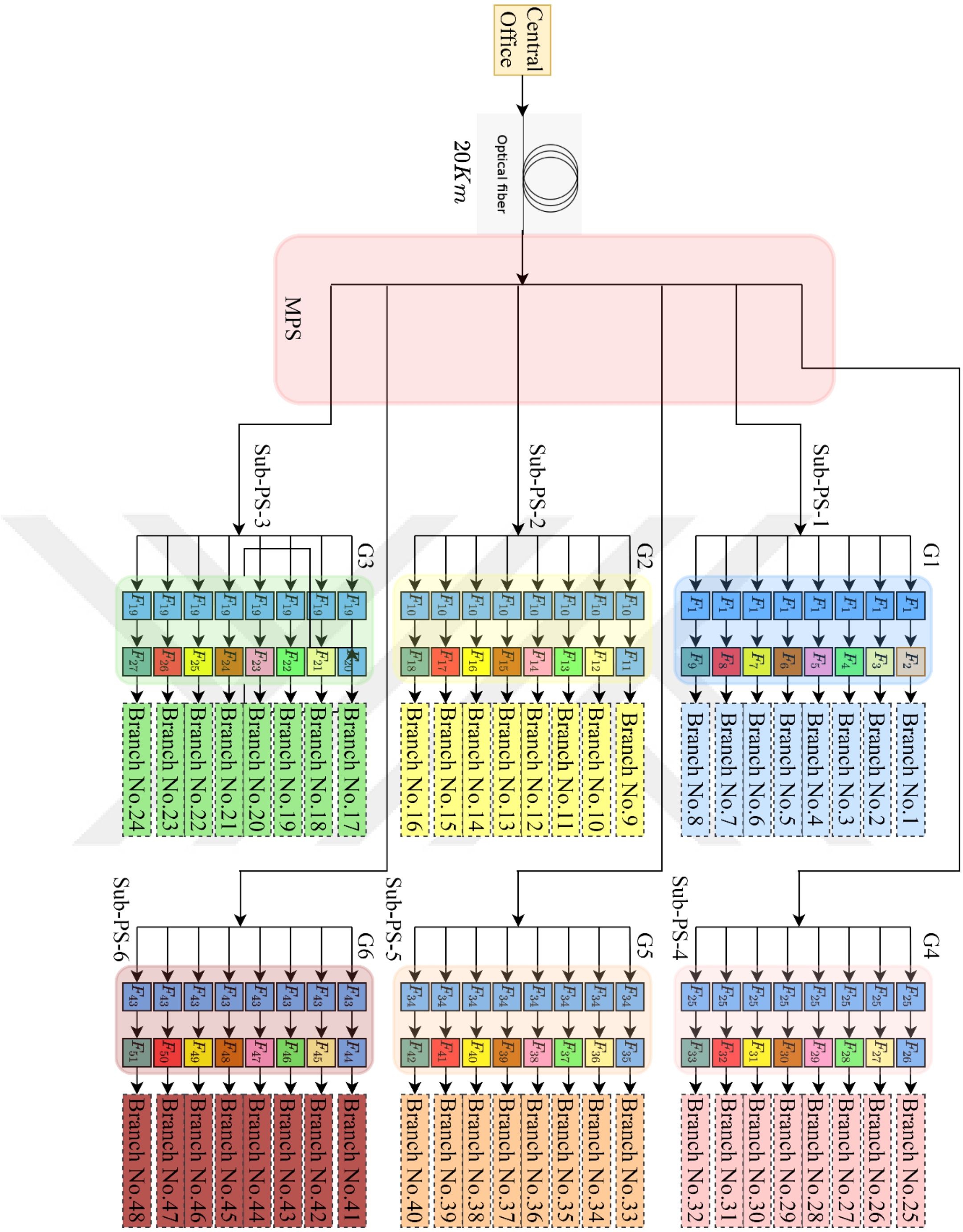


**Figure 3.12** PON showing the group combination procedure using different FBGs frequencies

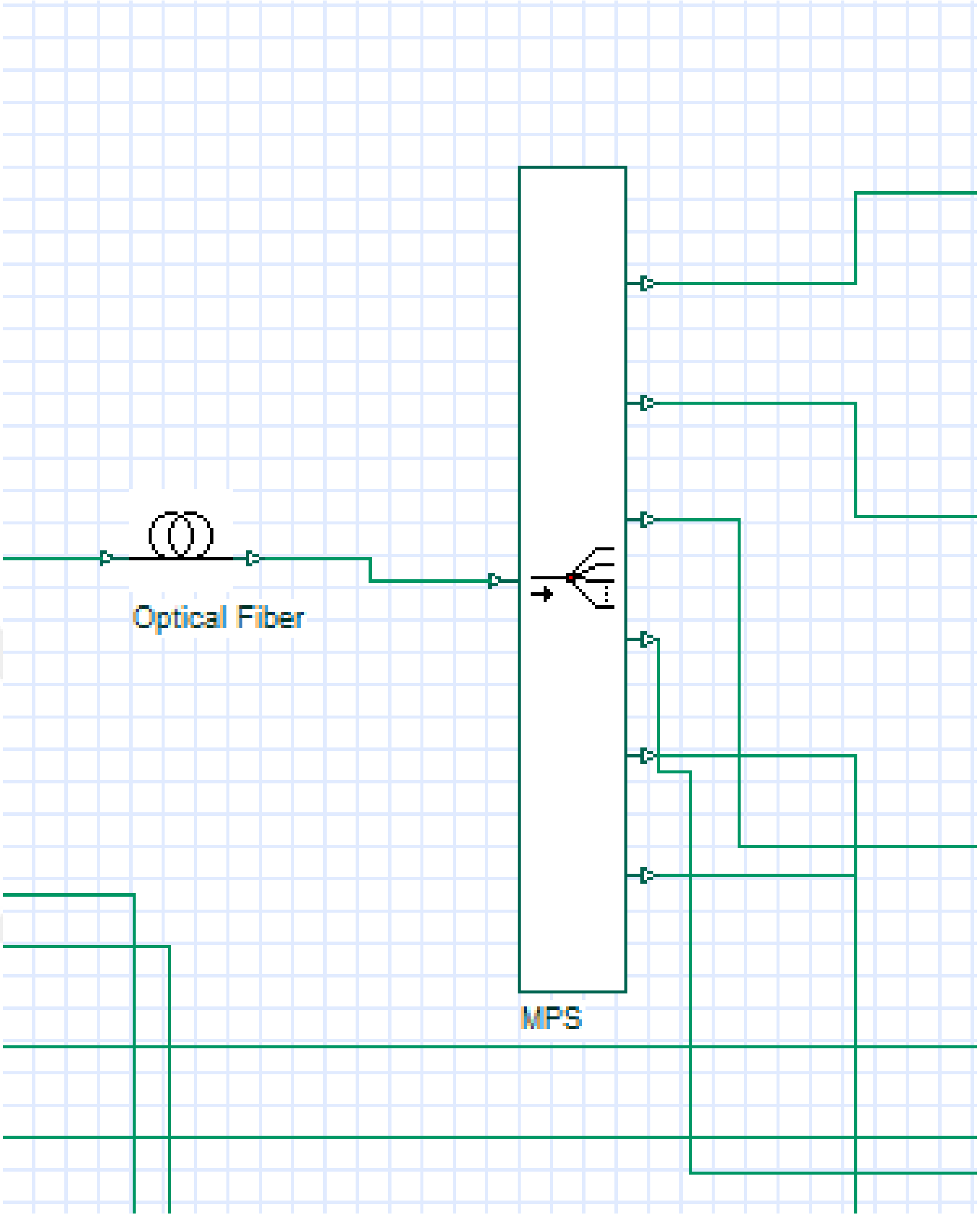


**Figure 3.13** Optical Fibre of 20 Km extended from the central office until the main power splitter

Consequently, after the transmission line, the optical fibre, the first power splitter is faced. This is called MPS, it is a one-to-six (1:6) power splitter. This power splitter will subdivide the signal into six groups. Each group, then, will be distributed to eight branches, which are the end units. However, the 1:6 MPS feds the incoming six-groups. Now, each group (G) will be constructed using a sub-Power Splitter (sub-PS). These sub-PSs are each one-to-eight splitters (1:8 power splitters). In other words, there are 6-subPSs, each one connects eight-branches to connect 48-branches to the CO. Figure

3.12 shows these details, while Figure 3.14 shows how they are connected in the simulated system using the OptiSystem software.

Groups are constructed by using couple of FBGs, the first FBG used as an edge while the second as an indicator. If there is a fault in this line, the second FBG will reflect nothing, hence, the faulty line is identified as will be seen later.

Figure 3.15 shows the first group (G1), it can be seen that there are eight-branches in this group. Thus, two cascaded FBGs will produce the first branch, the second branch is produced using the same frequency of the first FBG with different frequency than the second FBG of the first branch, as shown in Figure 3.15. consequently, the third branch is generated using third frequency, while the first FBG is still the same as that of the first FBG of the first and second branches, and so forth for the other branches. Thus, there are two columns of FBGs.

There are eight FBGs in each column, according to the number of required branches. The first column FBGs holds the same wavelength, $F_1$, and the second column FBGs have different wavelengths, $F_2$, $F_3$, $F_4$, $F_5$, $F_6$, $F_7$, $F_8$, and $F_9$, as shown in Figure 3.15. So, $F_1$ and $F_2$ produce the first branch, $F_1$ and $F_3$ give the second branch, until the eighth branch, which is built around $F_1$ and $F_9$ as shown in Figure 3.15. Agreeing to this phenomena, the first column will behave as an edge to distinguish the first group from other groups in the OSA of the CO, as will be explained later.

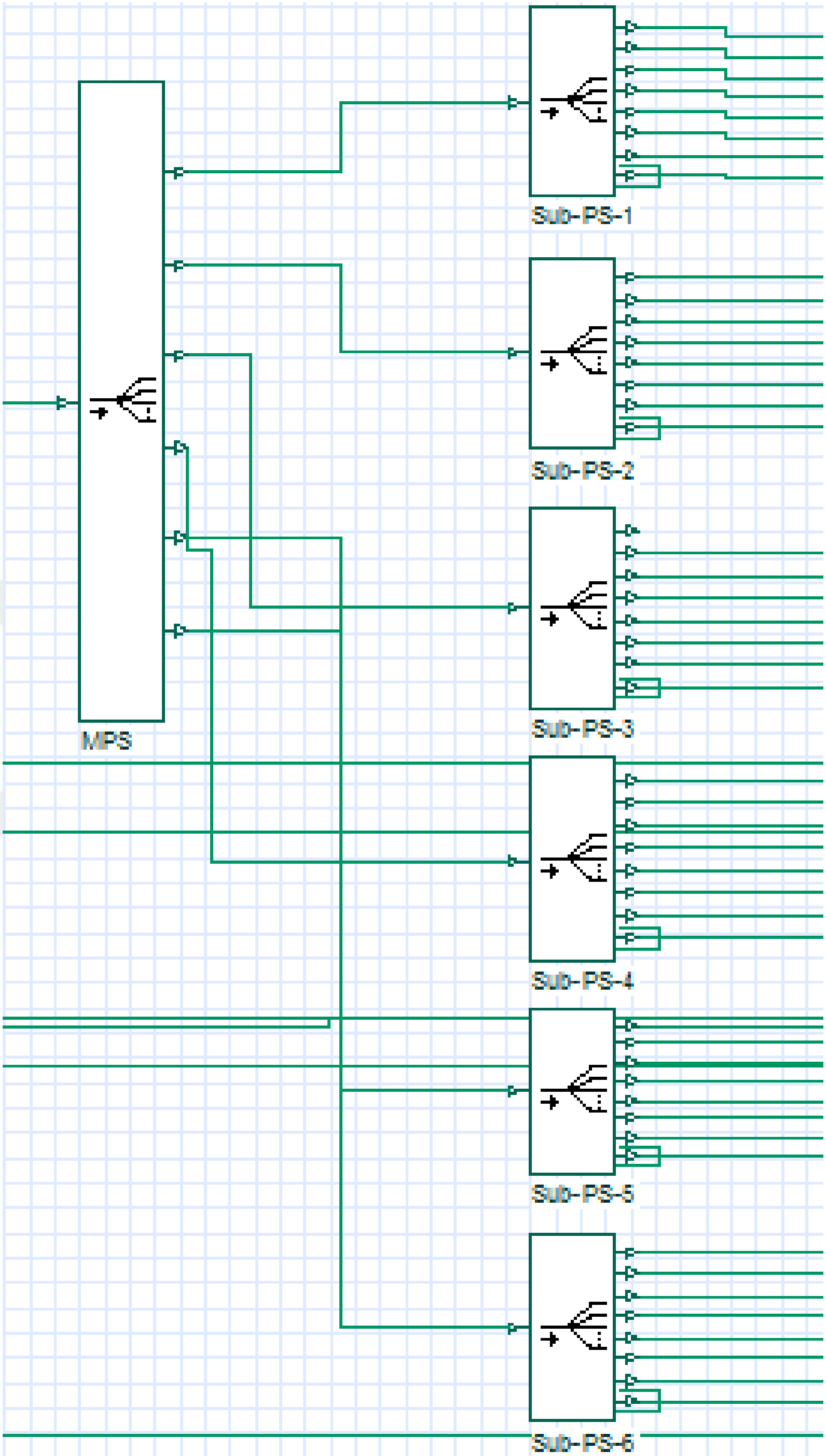


**Figure 3.14** Six sub-PS units, each sub-PS feds eight branches as connected in the OptiSystem software

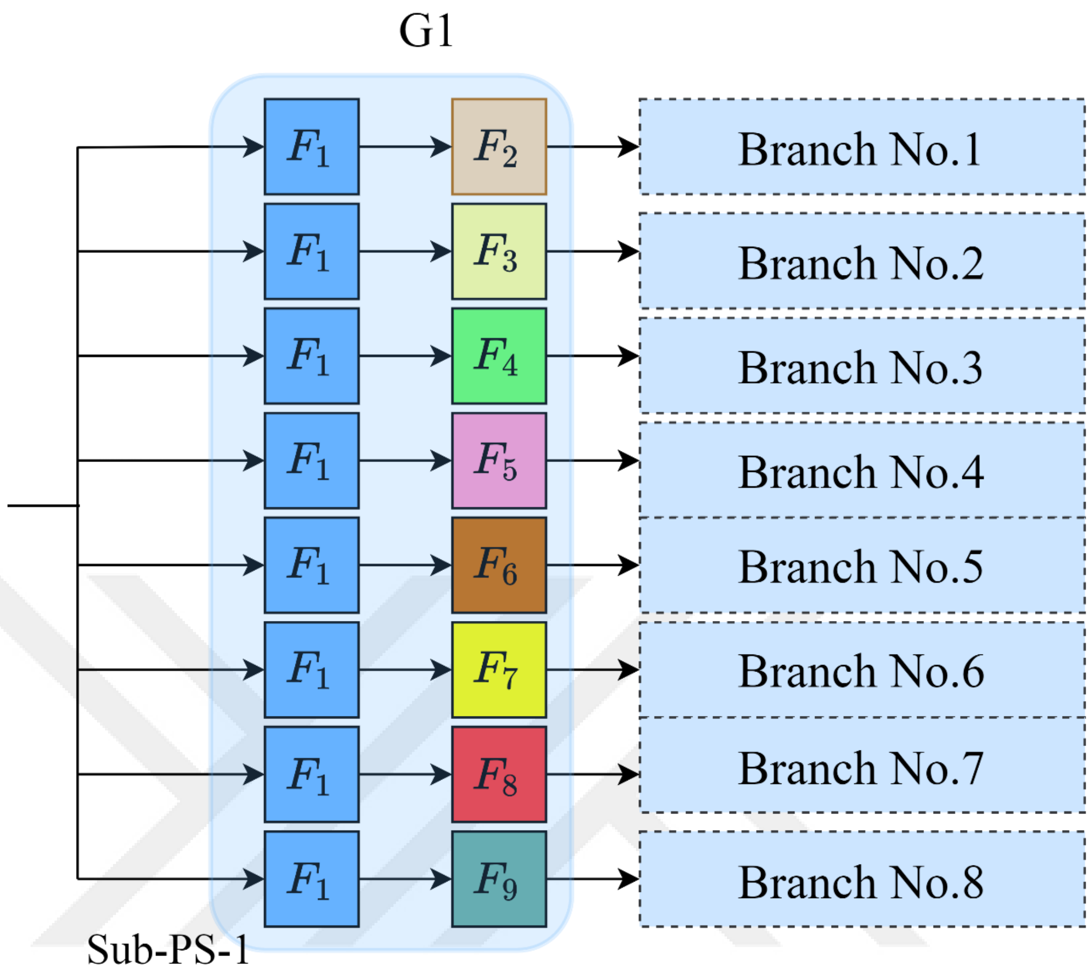


**Figure 3.15** FBGs combined as first group. The output of first two-cascaded FBGs stands for the first branch

Figure 3.16 shows the OptiSystem implementation of the configuration described in Figure 3.15. It is shown that the first column FBGs in Figure 3.16 was set to one wavelength, 1558 *nm*, while the second column FBGs are set to 1560 *nm*, 1562 *nm*, 1564 *nm*, 1566 *nm*, 1568 *nm*, 1570 *nm*, 1572 *nm*, and 1574 *nm*, to correspond to the first branch to eighth branch, respectively. All reflected wavelengths from the first column will be added to each other, because they will be combined in one power combiner, as shown in the down right corner of Figure 3.16.

These combined reflected signal components will be seen later in the central office as an edge or isolator between groups. The second column, as stated above, has different wavelengths for each FBG, though, the combined reflected wavelengths will not be added to each other, but they will be a train of signals neighbouring each other, due to their consecutive wavelengths.

Table 3.1 lists all utilized frequencies in the suggested system, for instance, in the first row in Table 3.1, there are branches 1, 9, 17, 25, 33, and 41 belonging to groups G1, G2, G3, G4, G5, and G6, respectively. Second row contains branches 2, 10, 18, 26, 34, and 42 corresponded to groups: G1 to G6, respectively, and so on for the other branches. In other words, G1 occupies wavelengths 1558 *nm* to 1574 *nm* in spacing of 2 *nm*, where the first wavelength is the isolation edge and the other wavelengths identify the branch numbers as shown in Table 3.2.

**Table 3.1** Wavelength configurations for the constructed groups and branches

| **Branches** | **Group Wavelengths (in *nm*)** | | | | | |
|---|---|---|---|---|---|---|
| | **G1** | **G2** | **G3** | **G4** | **G5** | **G6** |
| 1, 9, 17, 25, 33, 41 | 1560 | 1578 | 1596 | 1614 | 1632 | 1650 |
| 2, 10, 18, 26, 34, 42 | 1562 | 1580 | 1598 | 1616 | 1634 | 1652 |
| 3, 11, 19, 27, 35, 43 | 1564 | 1582 | 1600 | 1618 | 1636 | 1654 |
| 4, 12, 20, 28, 36, 44 | 1566 | 1584 | 1602 | 1620 | 1638 | 1656 |
| 5, 13, 21, 29, 37, 45 | 1568 | 1586 | 1604 | 1622 | 1640 | 1658 |
| 6, 14, 22, 30, 38, 46 | 1570 | 1588 | 1606 | 1624 | 1642 | 1660 |
| 7, 15, 23, 31, 39, 47 | 1572 | 1590 | 1608 | 1626 | 1644 | 1662 |
| 8, 16, 24, 32, 40, 48 | 1574 | 1592 | 1610 | 1628 | 1646 | 1664 |

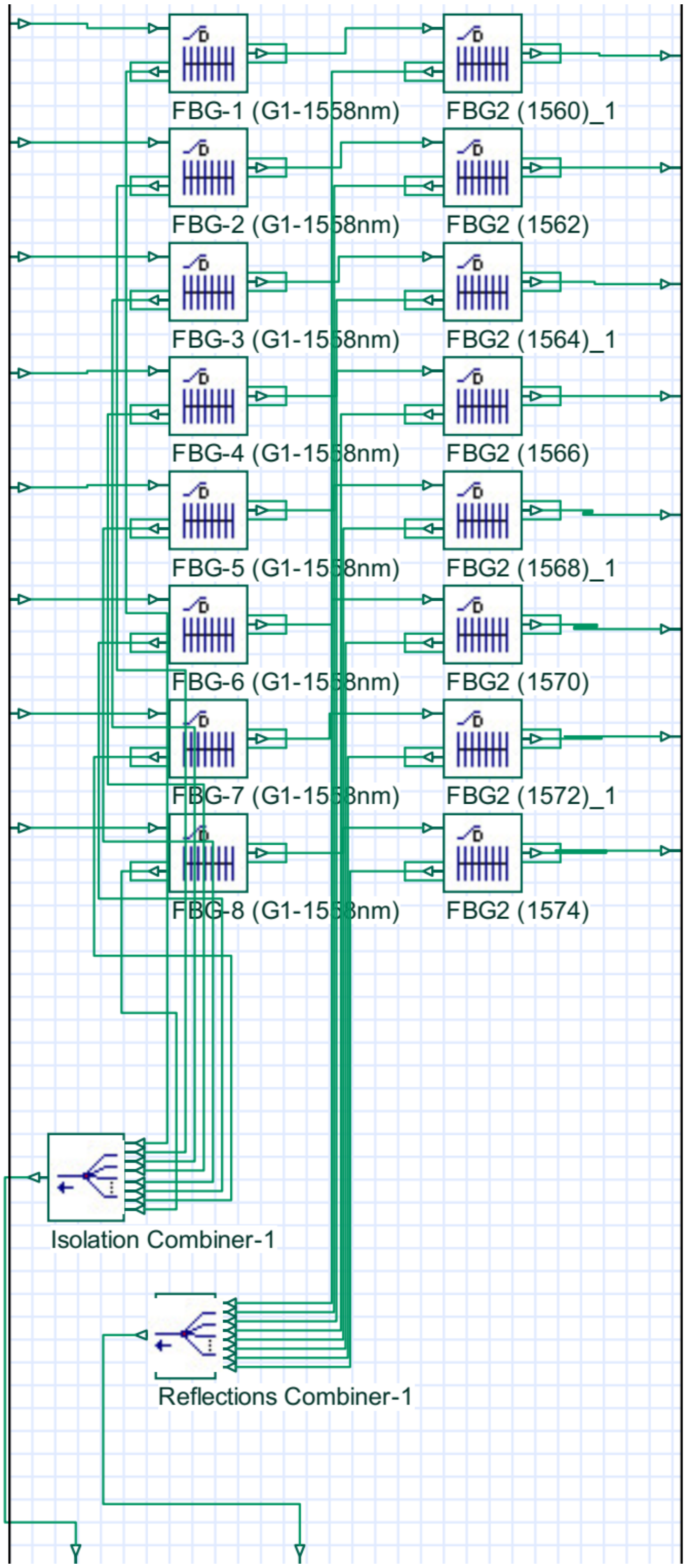


**Figure 3.16** Implementation of first group combination in OptiSystem

**Table 3.2** Wavelength configurations G1 FBGs

| Branch No. | First Group (G1) wavelengths (in *nm*) | |
|---|---|---|
| | First FBG | Second FBG |
| 1 | 1558 | 1560 |
| 2 | 1558 | 1562 |
| 3 | 1558 | 1564 |
| 4 | 1558 | 1566 |
| 5 | 1558 | 1568 |
| 6 | 1558 | 1570 |
| 7 | 1558 | 1572 |
| 8 | 1558 | 1574 |

Moreover, Table 3.3 shows the wavelengths configuration of the second group. Where the isolation edge wavelength is 1576 *nm* and the faulty identifying frequencies are start at 1578 *nm* and ending in 1592 *nm* spaced by 2 *nm*, corresponding to the first branch in the second group (G2) to the eighth branch, respectively, or it can be said that G2 branches are ninth to eighteenth, as stated in Table 3.4, and as implemented in the simulation software in Figure 3.17.

**Table 3.3** Wavelength configurations G2 FBGs

| Branch No. | | First Group (G2) wavelengths (in *nm*) | |
|---|---|---|---|
| | | First FBG | Second FBG |
| 1st in G2 | 9 | 1576 | 1578 |
| 2nd in G2 | 10 | 1576 | 1580 |
| 3rd in G2 | 11 | 1576 | 1582 |
| 4th in G2 | 12 | 1576 | 1584 |
| 5th in G2 | 13 | 1576 | 1586 |
| 6th in G2 | 14 | 1576 | 1588 |
| 7th in G2 | 15 | 1576 | 1590 |
| 8th in G2 | 16 | 1576 | 1592 |

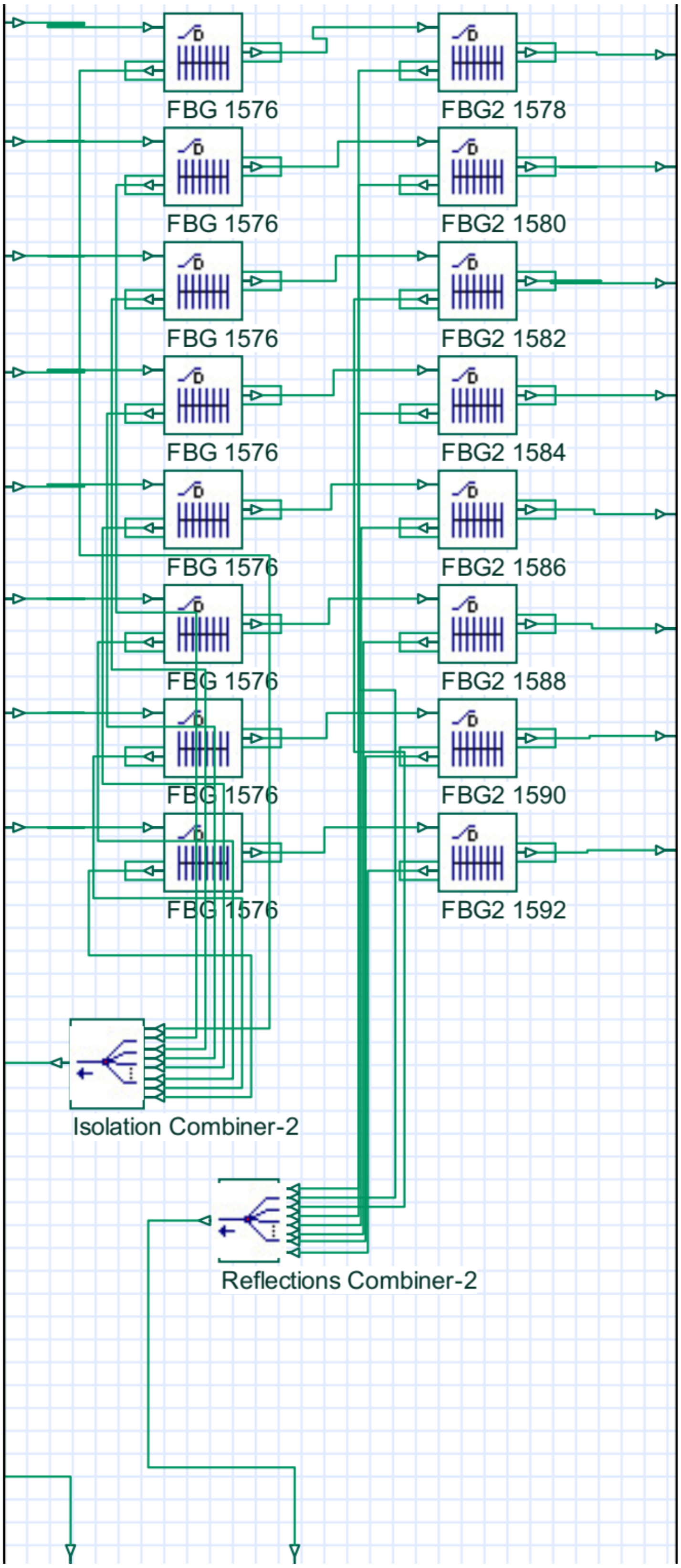


**Figure 3.17** Implementation of second group combination in OptiSystem

Table 3.4 lists all the wavelengths used to construct the third group (G3). The first FBGs-column of the third group reflects the constructing addition of the wavelength 1594 *nm*, by the power combiner as shown in Figure 3.18, while the second column of the FBGs reflect the wavelengths 1596 *nm*, 1598 *nm*, 1600 *nm*, 1602 *nm*, 1604 *nm*, 1606 *nm*, 1608 *nm*, and 1610 *nm*, corresponding to the first branch to eighth branch of the third group, respectively, as shown in Table 3.4 and Figure 3.18.

**Table 3.4** Wavelength configurations G3 FBGs

| Branch No. | | First Group (G3) wavelengths (in *nm*) | |
|---|---|---|---|
| | | First FBG | Second FBG |
| 1st in G3 | 17 | 1594 | 1596 |
| 2nd in G3 | 18 | 1594 | 1598 |
| 3rd in G3 | 19 | 1594 | 1600 |
| 4th in G3 | 20 | 1594 | 1602 |
| 5th in G3 | 21 | 1594 | 1604 |
| 6th in G3 | 22 | 1594 | 1606 |
| 7th in G3 | 23 | 1594 | 1608 |
| 8th in G3 | 24 | 1594 | 1610 |

Thus, there is two power combiners for each group. The first power combiner is utilized to combine the isolation edge frequency of the specified group, while the second power combiner is employed to combine the faulty lines identifying wavelengths for the same group. The reflection, then, are two lines from each group, the first reflected line is for the isolation edge wavelength and the second line represents the identifying combined wavelengths. These reflected lines will be monitored in the central office, using a dedicated OSA in the central office, OSA (Reflected), as shown in Figure 3.2 and its implementation in the simulation depicted in Figure 3.11. The working of these FBGs and their corresponding power combiners will be clearly seen later in the results and discussion of the next chapter.

In Table 3.5, the configuration wavelength of the FBGs are listed. It is clear that there are eight branches, sequenced from 25, which is the first branch in the fourth group, and ends with the branch sequenced 32, which is the eighth branch in the fourth group (G4). Hence, for the first branch in G4, Branch No. 25 in the suggested PON system, the reflection wavelength, which is for the identification of the faulty line, is 1614 *nm*, second one is 1616 *nm*, third is 1618 *nm*, fourth was 1620 *nm*, fifth branch reflection wavelength is 1622 *nm*, the sixth reflection is 1624 *nm*, and finally Branch No. 32, which is the last branch in the fourth group, the reflected wavelength is 1628 *nm*.

**Table 3.5** Wavelength configurations G4 FBGs

| **Branch No.** | | **First Group (G4) wavelengths (in *nm*)** | |
|---|---|---|---|
| | | **First FBG** | **Second FBG** |
| 1st in G4 | 25 | 1612 | 1614 |
| 2nd in G4 | 26 | 1612 | 1616 |
| 3rd in G4 | 27 | 1612 | 1618 |
| 4th in G4 | 28 | 1612 | 1620 |
| 5th in G4 | 29 | 1612 | 1622 |
| 6th in G4 | 30 | 1612 | 1624 |
| 7th in G4 | 31 | 1612 | 1626 |
| 8th in G4 | 32 | 1612 | 1628 |

On the other hand, the isolation wavelength, the edge, will be reflected from all of the branches of the fourth group, but from the first FBG of each branch combination, as shown in Figure 3.19. In other words, there are eight reflections, one from each FBG in the first column of the fourth group configuration. The isolation wavelength was 1612 *nm*. However, the powers of these eight reflections will be added to each other in the power combiner. Thus, the power will be constructed to build the edge, which will be clear in the central office OSA, therefore, it is easily to recognize the third group from the fourth group. Note that the reflected wavelengths from the second column of the fourth group will be combined in their corresponding power combiner, which will be connected to the central office.

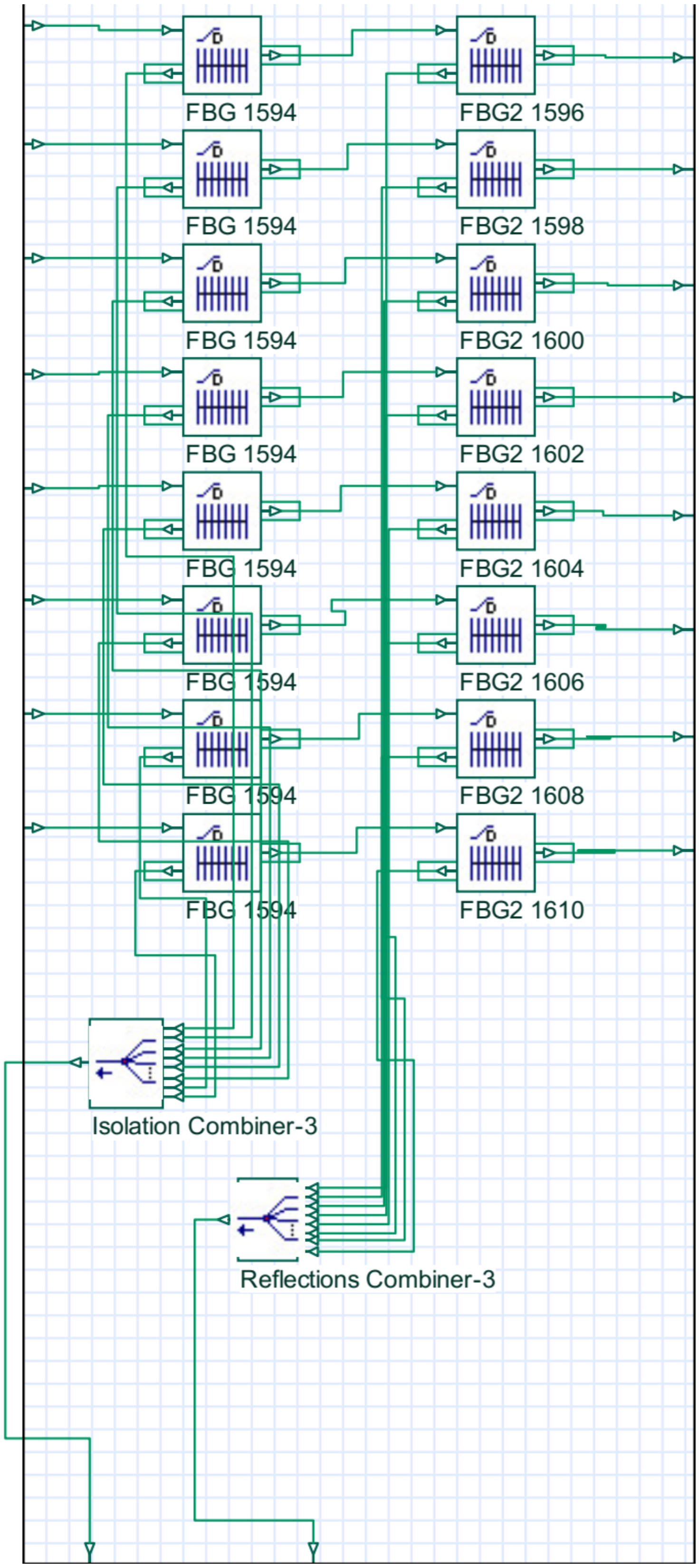


**Figure 3.18** Implementation of third group combination in OptiSystem

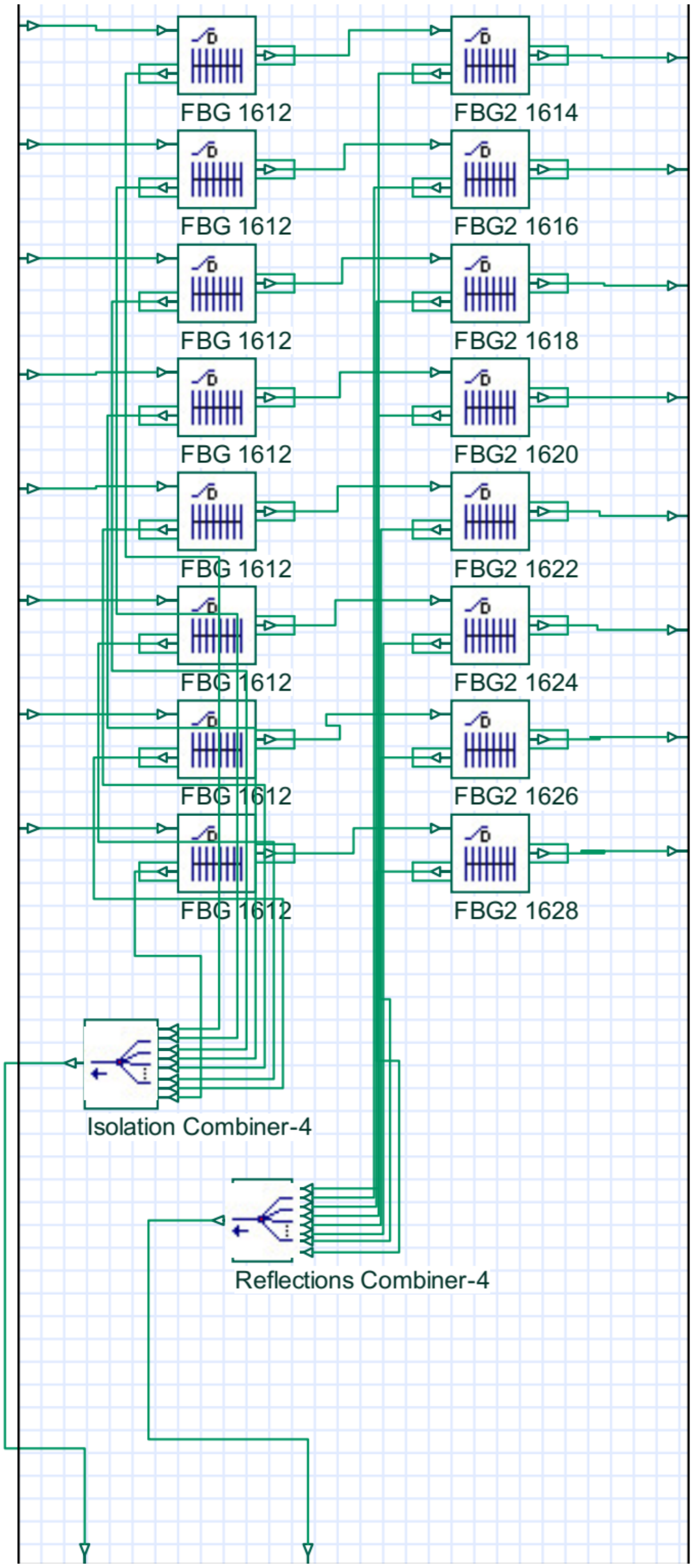


**Figure 3.19** Implementation of fourth group combination in OptiSystem

It is worth that to say the reflected wavelengths from the first column of the first group will be used to distinguish the start of the first group in the CO-OSA (Reflected), the reflected wavelengths from the first column of the second group will be used to isolate the first group from the second group. Consequently, the reflected wavelengths of the first column of the third group will be added to each other to build up the isolation edge to recognize the third group among the second and fourth groups. In this methodology, the monitoring operation in the central office, through the OSC (Reflected), will be simple and easy to find the fault branch and to which group it is belonging to.

Subsequently, the fifth group (G5) is also introduces eight branches. That is, the eight branches are Branch No. 33 consequently to Branch No. 40. Where Branch No. 33 stands for the first branch in G5, and consequently up to Branch No. 40 refers to the eighth branch of G5. Following this configuration, the first branch reflected wavelengths pair are (1630, 1632) *nm*, second branch wavelengths are (1630, 1634) *nm*, and wavelengths pairs (1630, 1636) *nm*, (1630, 1638) *nm*, (1630, 1640) *nm*, (1630, 1642) *nm*, (1630, 1644) *nm*, and (1630, 1644) *nm*, for the third, fourth, fifth, sixth, seventh, and eighth branch, respectively.

The isolation-edge wavelength in this group, G5, is 1630 *nm*, which will be combined, using the power combiner of this group, from eight FBGs which are the first column of the FBGs fifth group combination, as listed in Table 3.6 and as shown in Figure 3.20. Thus, and as implemented in the previous groups, the combined powers of the wavelength 1630 *nm*, will makes up the isolation edge of the fifth group, so that, it is possible to find the fifth group in between other groups, as will be seen later in the results of the next chapter, chapter five.

All of the previous and next groups operation will be discussed in details and at some locations of the groups, the optical null signal generator will be added. The connection of this optical null generator will help to locate the faulty position. The location recognition of the faulty line in an easy approach is the main aim of this project.

**Table 3.6** Wavelength configurations G5 FBGs

| Branch No. | | First Group (G5) wavelengths (in *nm*) | |
|---|---|---|---|
| | | First FBG | Second FBG |
| 1st in G5 | 33 | 1630 | 1632 |
| 2nd in G5 | 34 | 1630 | 1634 |
| 3rd in G5 | 35 | 1630 | 1636 |
| 4th in G5 | 36 | 1630 | 1638 |
| 5th in G5 | 37 | 1630 | 1640 |
| 6th in G5 | 38 | 1630 | 1642 |
| 7th in G5 | 39 | 1630 | 1644 |
| 8th in G5 | 40 | 1630 | 1646 |

Additionally, the second column FBGs reflected wavelengths, which are starting at 1632 *nm* in step of 2 *nm* and stopping at wavelength 1646 *nm*, will be combined using the G5 second power combiner, as shown in Figure 3.20. Though, there are two reflected lines to the central office, from G5, the first is the isolating, edge wavelength, which will be used to identify the fourth group from the fifth group, and the second line will show the eight reflected wavelengths for faulty branch identification.

This group, G5, is distanced from the central office by the same distances of the four previous groups. This is not only for the five previous groups, it is also implemented for the next group, G6, which represents the last group of the suggested PON configuration in this project.

This procedure will be repeated for the last group, G6, where the isolating, edge or wall, wavelength of the sixth group is 1648 *nm*, and the reflected wavelengths from this group, G6, are 1650 *nm* to 1664 *nm* spaced by 2 *nm*, corresponding to Branch No. 41 to the last branch, which is Branch No. 48, as listed in Table 3.7 and as shown in Figure 3.21. That is, the isolating wavelength will be combined from eight reflected wavelengths from the eight FBGs of the first column of the last group, while the other reflected wavelengths will be combined to recognize the faulty branch in this group at the central office.

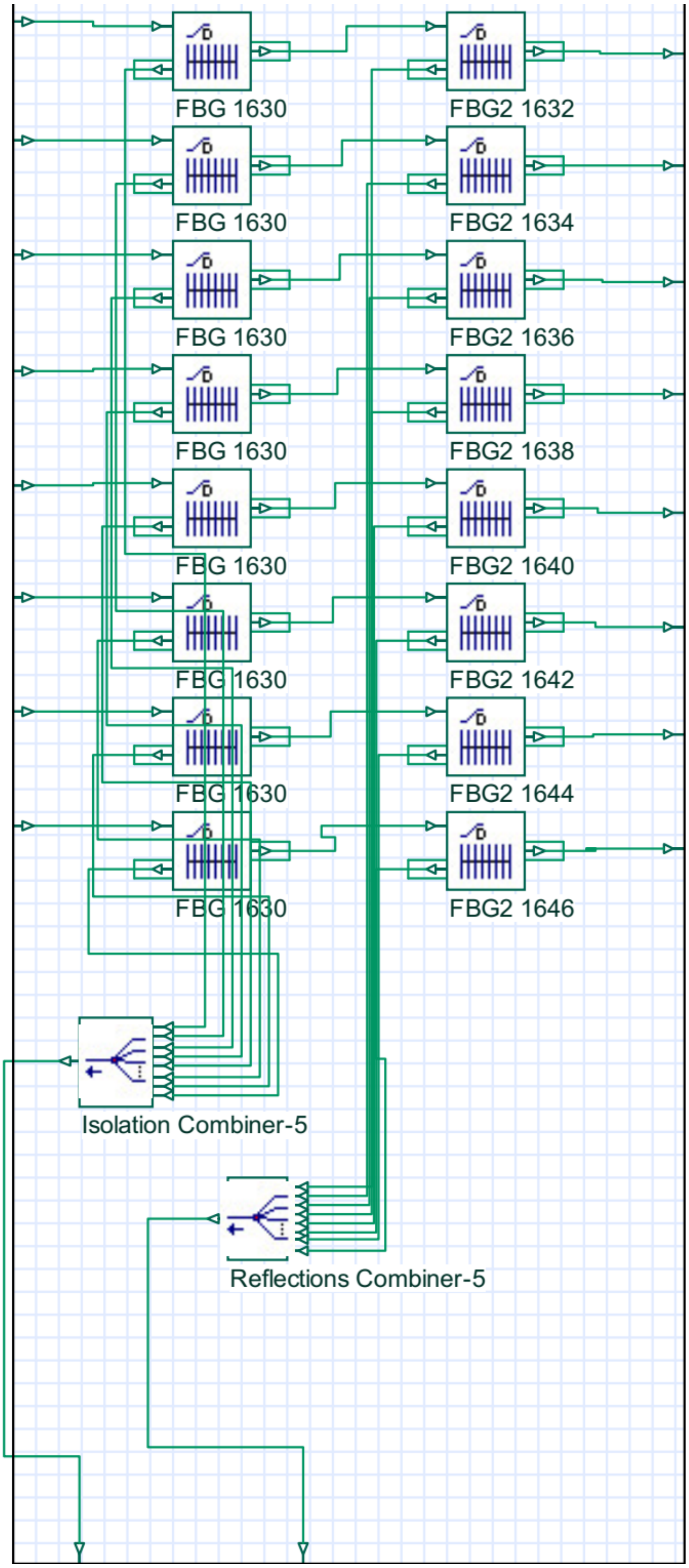


**Figure 3.20** Implementation of fifth group combination in OptiSystem

**Table 3.7** Wavelength configurations G6 FBGs

| Branch No. | | Sixth Group (G6) wavelengths (in *nm*) | |
|---|---|---|---|
| | | First FBG | Second FBG |
| 1st in G6 | 41 | 1648 | 1650 |
| 2nd in G6 | 42 | 1648 | 1652 |
| 3rd in G6 | 43 | 1648 | 1654 |
| 4th in G6 | 44 | 1648 | 1656 |
| 5th in G6 | 45 | 1648 | 1658 |
| 6th in G6 | 46 | 1648 | 1660 |
| 7th in G6 | 47 | 1648 | 1662 |
| 8th in G6 | 48 | 1648 | 1664 |

Nevertheless, it can be seen in Figures 3.16 to 3.21, that the two power combiners, Isolation Combiner-1 to Isolation Combiner-6 combined reflections of the first FBGs of each first column of the six groups, G1 to G6, respectively. Furthermore, there is the second power combiner in each of the eight groups called Reflections Combiner-1 to Reflections Combiner-6 for G1 to G6, respectively. The Isolation Combiner reflects the edge wavelength combination to put something like a wall between groups in order to make the monitoring as simple as possible. On the other hand, the Reflections Combiner combines the eight reflected wavelengths of the eight branches of each group. These reflections will be monitored in the central office as explained previously, as shown in Table 3.8.

**Table 3.8** Power combiners in G1 to G6

| Group No. | Isolation Combiner No. | Reflections Combiner No. |
|---|---|---|
| G1 | Isolation Combiner-1 | Reflections Combiner-1 |
| G2 | Isolation Combiner-2 | Reflections Combiner-2 |
| G3 | Isolation Combiner-3 | Reflections Combiner-3 |
| G4 | Isolation Combiner-4 | Reflections Combiner-4 |
| G5 | Isolation Combiner-5 | Reflections Combiner-5 |
| G6 | Isolation Combiner-6 | Reflections Combiner-6 |

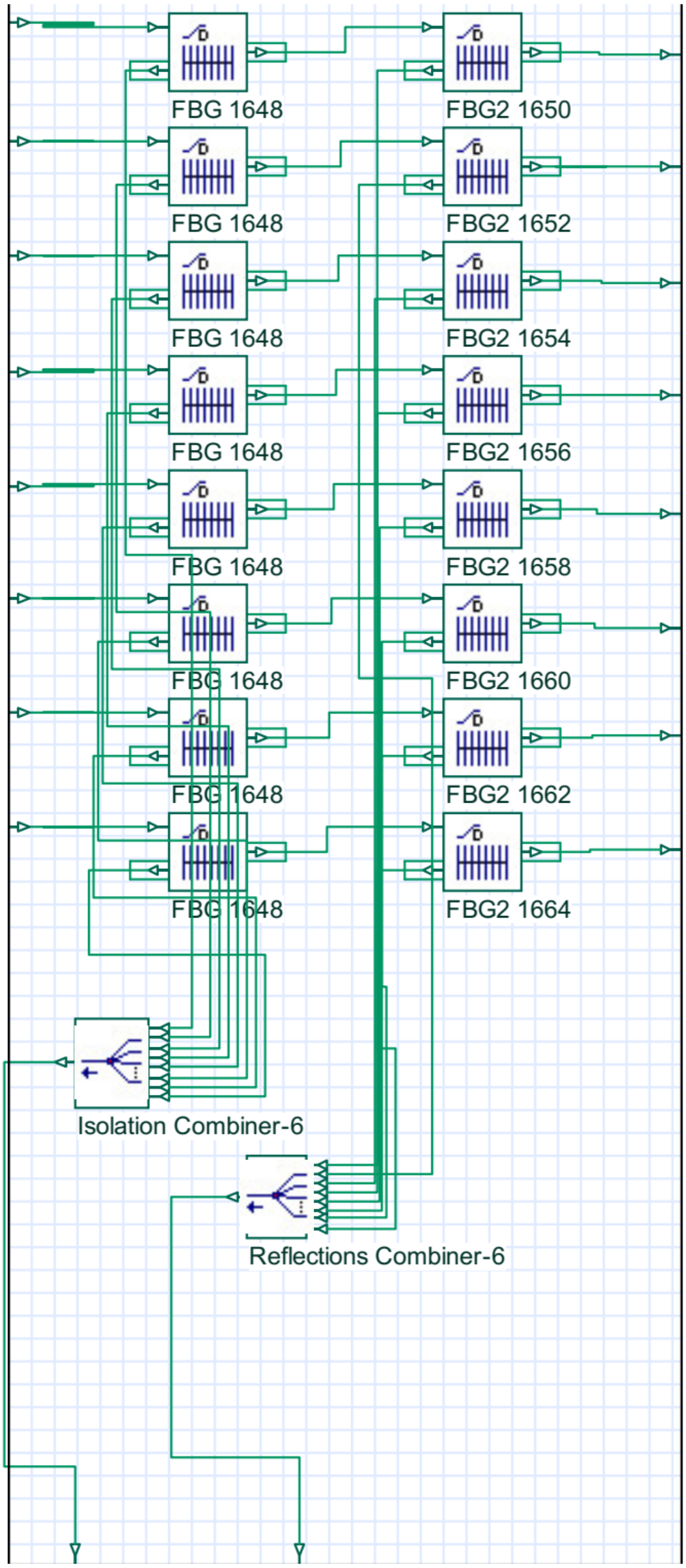


**Figure 3.21** Implementation of sixth group combination in OptiSystem

## [redacted]Conclusion

To conclude and simplify the above discussions, in section 3.3, it is necessary to follow up the following points coherently:

• It can be observed clearly from Figure 3.22 that all of the previously discussed component parts are connected with each other. That is, the central office consists of signal source, which is a white source signal, a power combiner, and two OSAs, one for the displays the source signal and the second depicts the reflected signals from the eight groups of the passive optical network components. Further, there is an optical fibre of 20 Km length connects the central office by the main power splitter.

• Next, the main power splitter is connected to the six sub-power splitters. Each sub-power splitter constructs one group of eight branches. Therefore, each sub-power splitter, then, splits its input line to eight branches, i.e., 1:8 power splitter.

• Each group configured using sixteen-FBGs arranged in two columns, eight FBGs in each column. The first column of each group reflects the same wavelength, called isolation wavelength, hence, there are eight isolation lines will be connected to the central office. Meanwhile, the second column of each group reflects eight distinct wavelengths, as stated previously. Then, there are 48-reflected wavelengths to identify the 48-branches.

• Suppose there is a fault branch, any branch, then, to identify the faulty branch, the OSA (Reflected) in the central office will be used. Thus, the isolation wavelengths working as walls to simplify the observing process. Thus, between each two walls, there are eight reflected wavelengths corresponding to its specific group. If one of these wavelengths is missing, then and simply, the worker could identify which branch is down by finding the group walls and counts the number of the missing wavelength.

- Last but not least, an additional OSAs are added for the simulation study in this work. Then, it is required to combine the eight branches of each group. Thus, the first group combined using the power combiner called Checking Power Combiner-1 and it is connected to Checking OSA (G1) as shown in Figure 4.14. Hence, there are additional eight Checking Power Combiners, and eight Checking OSAs, for the first group to the eighth group, respectively, as drawn in Figure 3.22.

- Power combiner in the central office is simply 12-to-1. This is because there are six-groups, each group reflects two combined groups of wavelengths. The first combined group is from the first column of each group. The second reflected combined signals group is coming from the second FBGs of each group, in other words, from the second column from each group. That is why, the power combiner has twelve input signals.

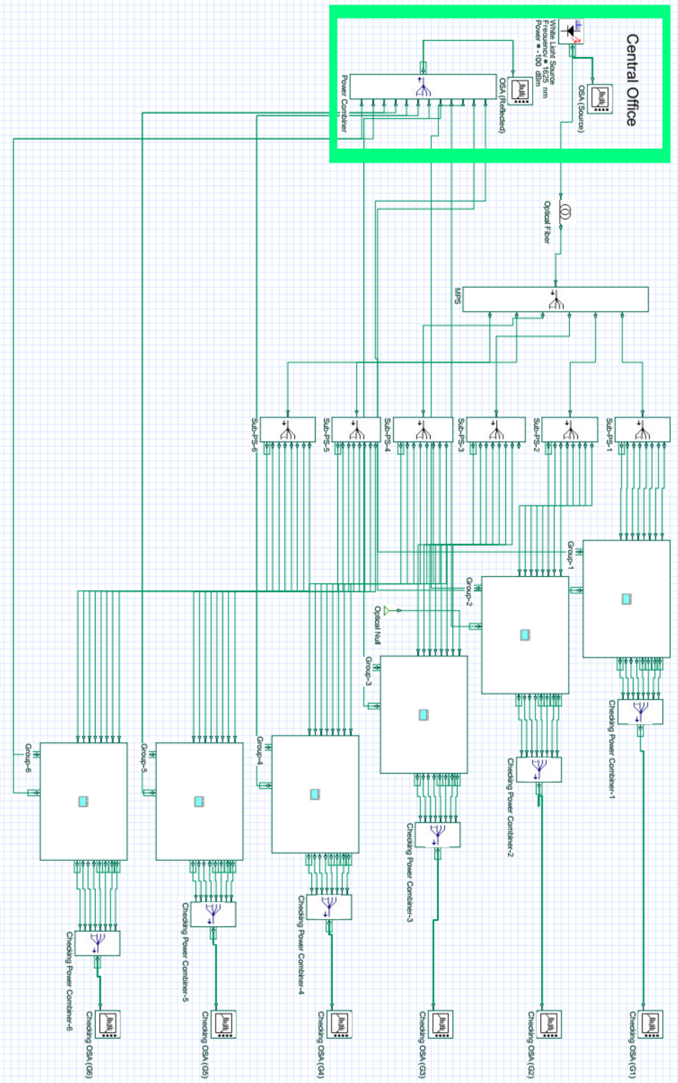


**Figure 3.22** Suggested PON implementation in OptiSystem

# 4 SYSTEM OPERATING RESULTS AND DISCUSSIONS

## [redacted] Introduction

This chapter is dedicated to presents the simulation of the proposed PON. The system configuration, which is shown in the last chapter in Figure 3.22, will be simulated. All of the parameters will be set properly in this chapter to get the aimed results.

## [redacted] System Settings

In this section, simulation using OptiSystem will be conducted. In Table 4.1, the general system parameters and quantities are listed. The employed source a white light source with total output power of 1.652 *W* or 32.182 *dBm*. The optical fibre transmission line length is 20 *Km*. The optical fibre dispersion is 16.75 *ps*/*nm*/*Km* with 0.2 *dB* losses in each one kilo meter.

According to this scenario, total losses across the optical fibre is 0.2×20=4 *dB*. Further, the main power splitter power ratio array is [1 1 1 1 1 1], in which the power will be divided by six, then, the output of each port will be total input power divided by six, as will be shown later in the next section. Moreover, the sub-PS-1 to sbu-PS-6 power ratio array is [1 1 1 1 1 1 1 1], therefore, the output power in each port is the total of its input power divided by eight.

The central office power combiner has twelve inputs, as stated previously. Additionally, there are two power combiners in each group configuration and sixteen FBGs to configure the group combinations. This is clearly illustrated in Figure 3.22, which is, in fact, the implementation of the whole suggested PON in this project.

**Table 4.1** General System parameters settings and quantities

| **Parameter** | **Value Set** |
|---|---|
| White Light Source total power | 1.652 *W*, 32.182 *dBm* |
| Optical Fibre losses | 0.2 *dB*/*Km* |
| Optical Fibre length | 20 *Km* |
| Optical Fibre dispersion | 16.75 *ps*/*nm*/*Km* |
| MPS power ratio array | [1 1 1 1 1 1] |
| sub-PS-1 to sub-PS-6 power ratio array | [1 1 1 1 1 1 1 1] |
| Power combiner in the CO input ports | 12 |
| No. power combiners in each group | 2 |
| No. of FBGs in each group | 16 |

Before discussing the results, it is worth explaining the optimal display in the OSA (Reflected) in the central office. This can be seen clearly in Figure 4.1. That is, the first wavelength, which is a combination of the first FBGs of the first column of the first group combination, is 1560 *nm*, hence, this wavelength is the first isolation frequency comes from the first group. Thus, the remaining number of wavelengths are 47, which starts after the isolation wavelength, and stops at wavelength 1664 *nm*, with spacing of 2 *nm*. Accordingly, it can be observed that the other isolation wavelengths are 1576 *nm*, 1594 *nm*, 1612 *nm*, 1630 *nm*, and 1648 *nm*, corresponding to the second, third, fourth, fifth, and sixth group, respectively.

More specific, the first group wavelengths are 1560-1574 *nm*, second group wavelengths 1578-1592 *nm*, third one are 1596-1610 *nm*, and 1614-1628 *nm* belonging to the fourth group, the fifth group wavelengths are 1632-1646 *nm*, and the last group, G6, wavelengths are 1650-1664 *nm*. These wavelengths are spaced by 2 *nm*, in other words, the spacing between each reflected frequency and its neighbour is 2 *nm* only. This will simply be used to identify the faulty branch as will be seen consequently.

As an implementation for Figure 4.1, Figure 4.2 shows a pre-inspection of the results, that are discussed previously explained in Figure 4.1. Thus, Figure 4.2 shows how will be the isolation wavelengths and the branches. Hence, without fault of any branch view can be seen in Figure 4.1 and Figure 4.2 shows its OptiSystem output view.

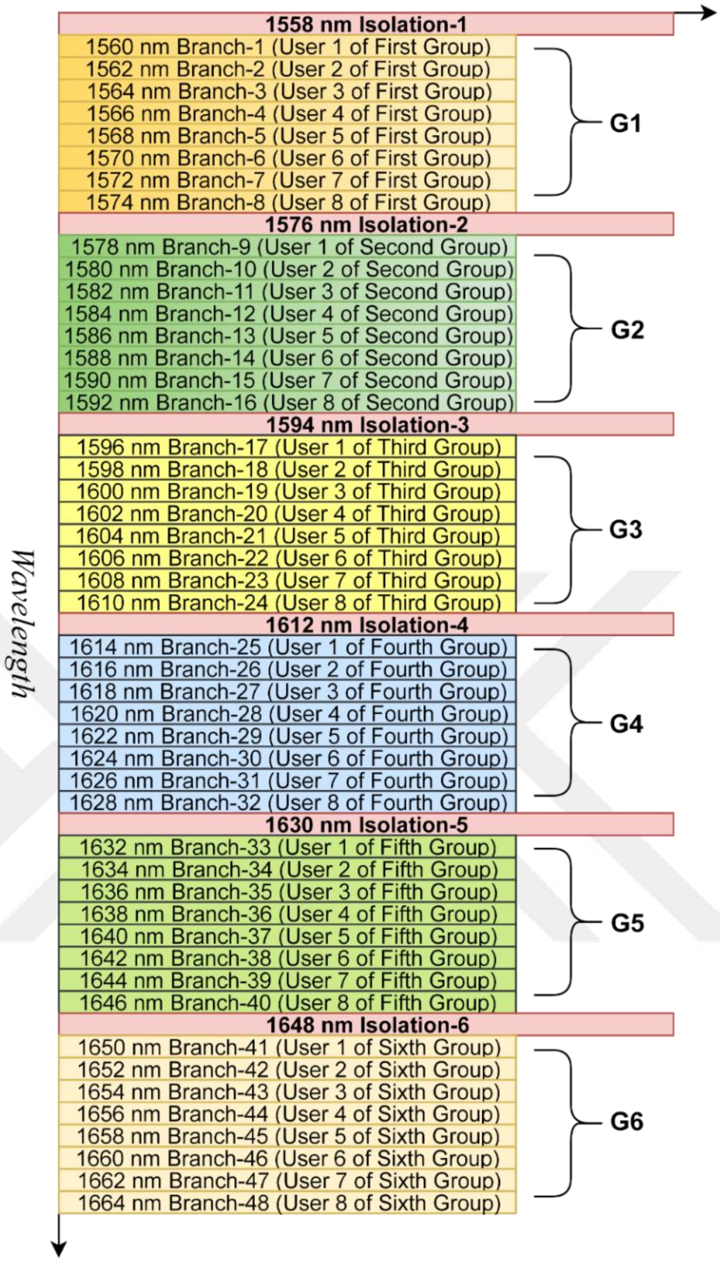


**Figure 4.1** OSA (Reflected) optimal display in the central office

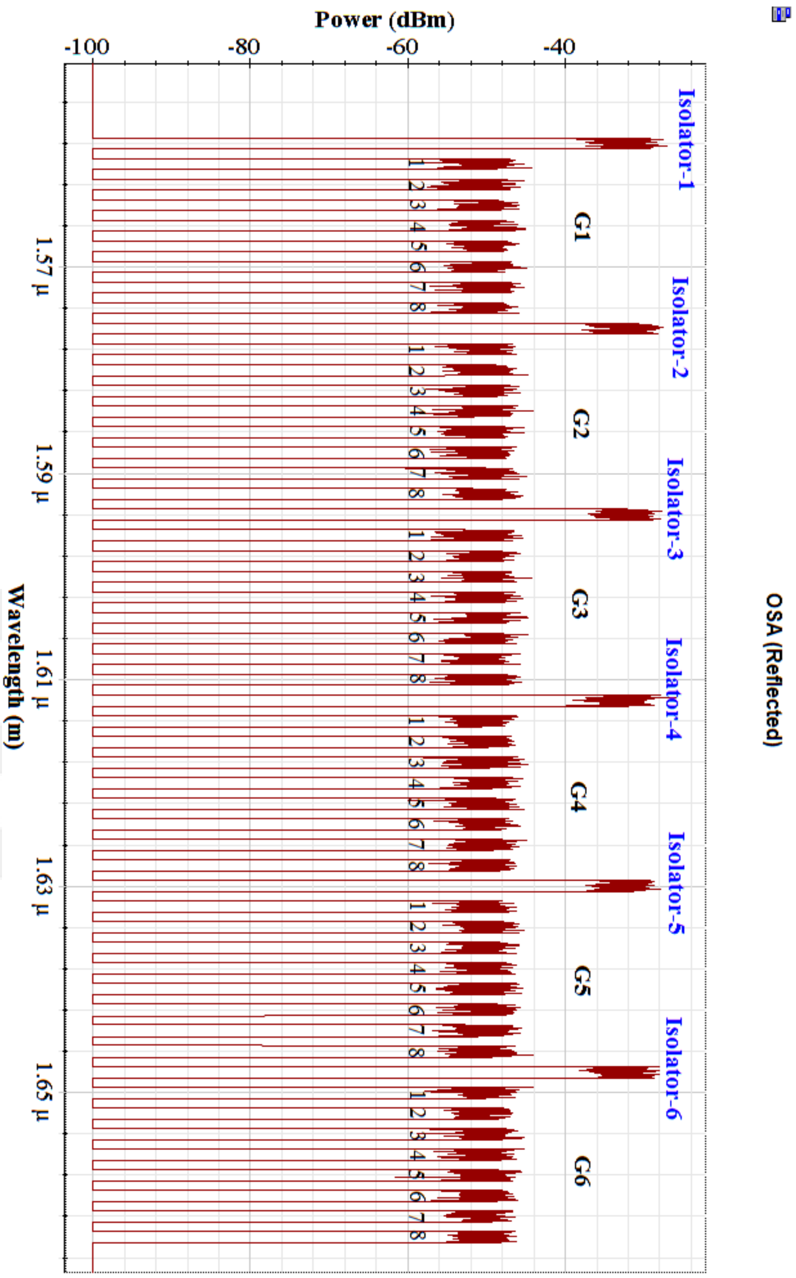


**Figure 4.2** Signal waveform at the central office OSA (Reflected), an optimal (without faulty branches) view

## [redacted] Results and Discussion

Although the last Figure, Figure 4.2, is part of the results, however, it was important to introduce it in the previous section to show some necessary facts. Now, talking in terms of powers, the total output power from the white light source is 1.668 *W*, 32.222 *dBm*, as shown in Figure 4.3. This power fed to the 20 *Km* optical fibre transmission line, then, the total power at the output of the transmission line is 28 *dBm*, or 664.045×10-3 *W*, which ensures the power drop of 4 *dB* in the optical fibre, as shown in Figure 4.4.

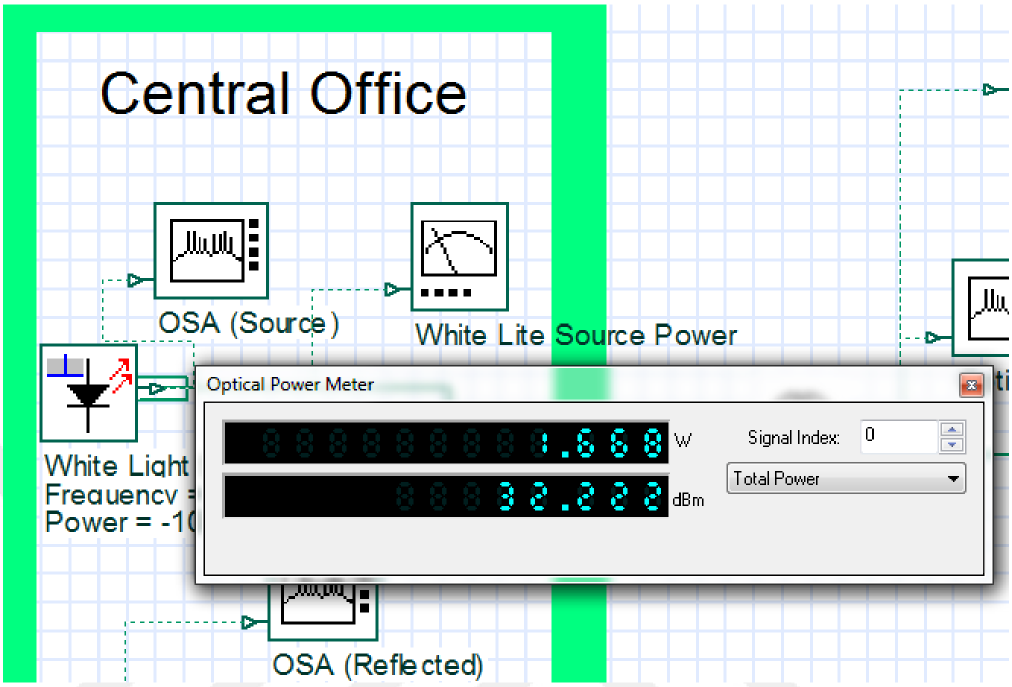


**Figure 4.3** White light source power meter measurement, showing that the output power is indeed 1.668W or 32.222 *dBm*

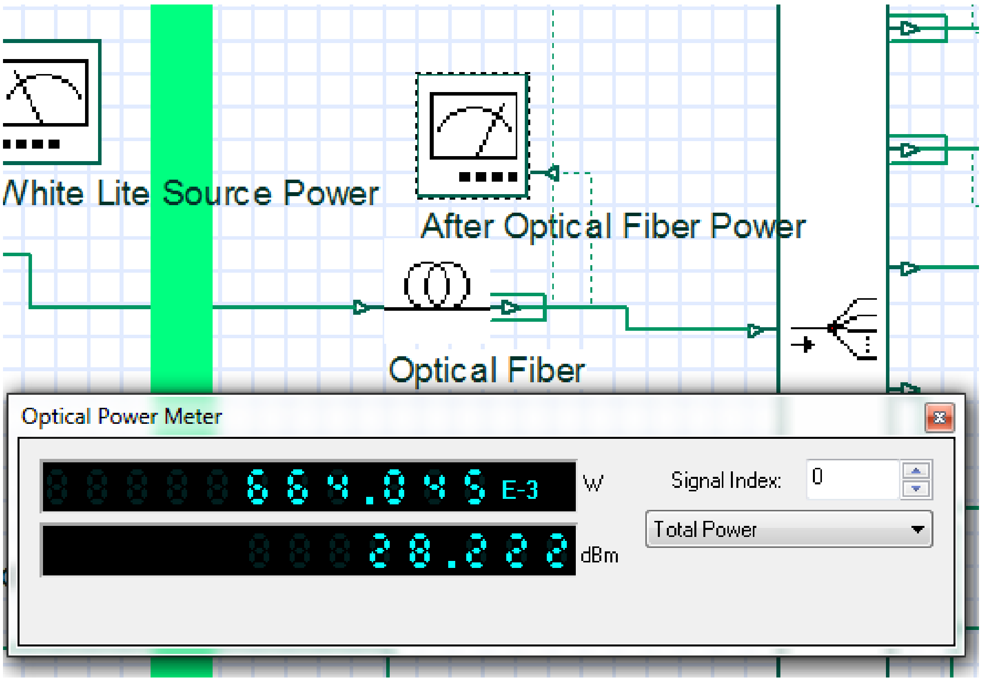


**Figure 4.4** Output power measurement of the optical fibre

That is, the output of the optical fibre transmission line will be passed to the first power splitter, which is the main power splitter (MPS) as shown in Figures 3.1, 3.13, and 3.12, where the MPS power ratio array is [1 1 1 1 1 1]. Hence, total output power of each output port of the MPS is divided by six. Therefore, each output port of the MPS produces total power of $110.667\times10^{-3}$ W, or 20.44 dBm, as shown in Figure 4.5, where the three optical power meters shown in Figure 4.5 are measuring the total output powers of the first, third, and fifth ports of the MPS, respectively.

Subsequently, each group combination received $110.667\times10^{-3}$ *W*, and this amount of power will be divided by eight after the output of the sub-PS-*i*, where $i$ = 1, 2, 3, 4, 5, and 6. Thus, each group, obtained total power of $13.813\times10^{-3}$ *W* (11.403 dBm) as depicted in Figure 4.6, which shows the total output power of the 1$^{st}$, 3$^{rd}$, and 5$^{th}$ ports. This power will be fed to the two FBGs combination of each group, then, each branch received around 11 dBm or power.

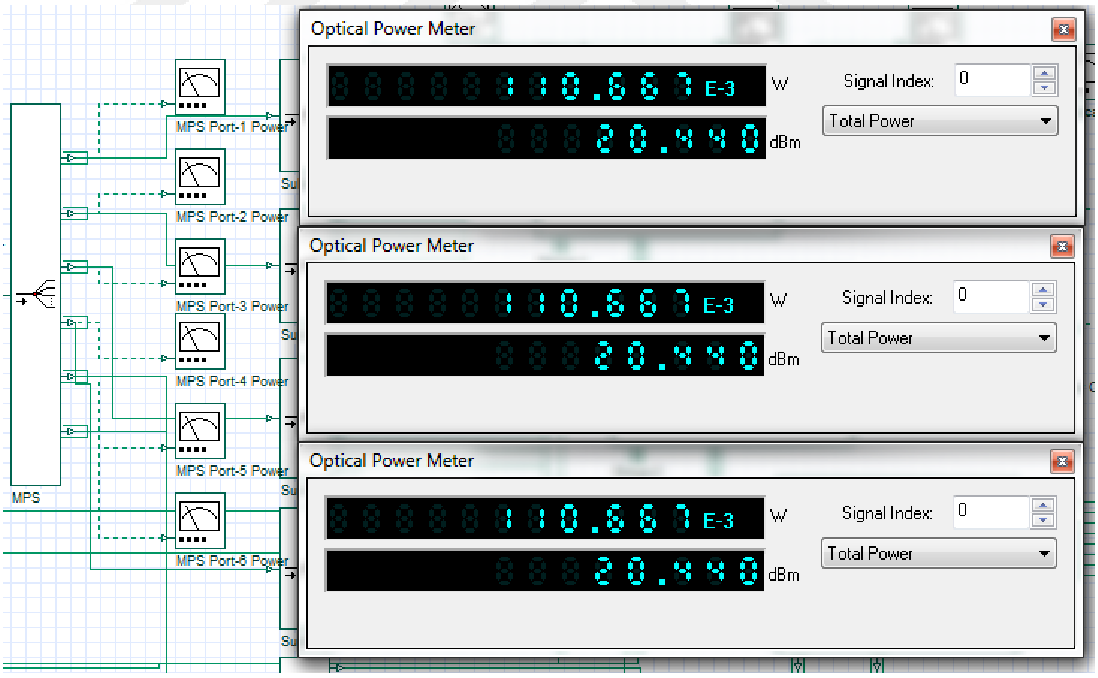


**Figure 4.5** Output power measurements of 1st, 3rd, and 5th ports of the MPS power splitter

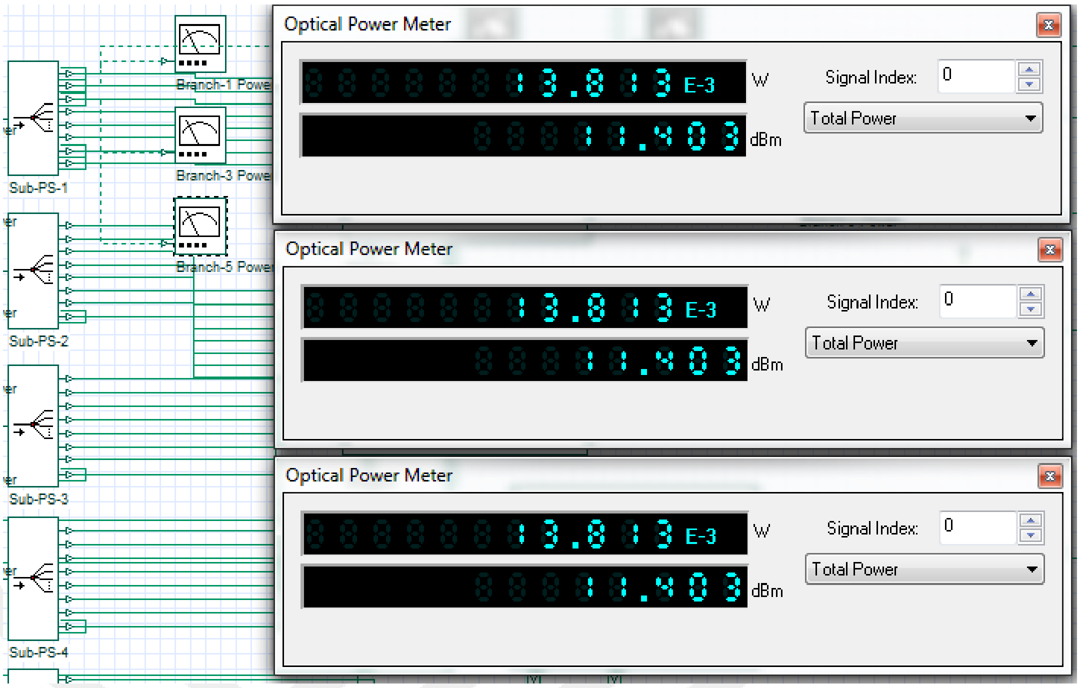


**Figure 4.6** Output power measurements of 1st, 3rd, and 5th ports of the sub-PS-1 power splitter

In the next section, the fault location investigation will be explained in details. There will be various positions in the investigation process, in order to validate the suggested network. Even when there is more than one fault location, the suggested phenomenon will help predict all fault locations at the same time coherently.

### 4.3.1 Faulty location investigation

In this section, fault locations will be tracked. In other words, fault location in the first group, second group, third group, fourth group, fifth group, and sixth group. Furthermore, fault locations in more than one group at the same time, as well as fault locations at the same group, will be tracked.

#### 4.3.1.1 Faulty location investigation: single line within a group

Nonetheless, to find out which branch is out of service, suppose that the first group has a fault line. Making fault line is achieved by feeding the required line to be dropped by an optical null as shown in Figure 4.7. That is, according to this procedure, Figure 4.7 shows a fault branch, seventh branch, in the first group.

Accordingly, it was found that the output power is dropped to 0.0 W. Thus, the connected units to this branch have lost the service completely. To discover this in the central office, the OSA (Reflected) in the central office should show that the missing line is the seventh one in the first group.

Hence, to configure out which branch has lost the service, it is necessary that the central office worker knows the plan of the received signals that are previously explained in Figure 4.1 or Figure 4.2. Therefore, by comparing the received signals, as shown in Figure 4.8, with any one of the two figures, Figure 4.1 or 4.2, it can be recognized clearly that the missing branch's signal is the seventh one of the first group.

However, since there is a spacing of 2 nm wavelength between each consecutive branches, it is possible to find out more than single faulty branch. As stated at the beginning of this subsection, more than one faulty branch can be tracked, as will be shown soon in this section.

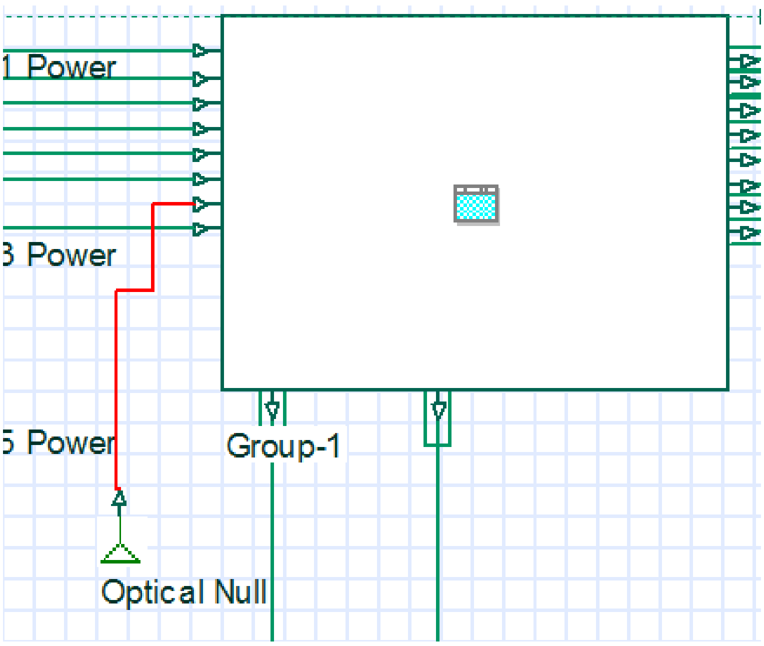


**Figure 4.7** Making a fault branch using optical null in the first group, seventh branch

Figure 4.9 shows that there is a fault location in the second group, first branch, made be the ON generator. The effect of this operation should be recognized in the CO-OSA as shown in Figure 4.10. That is, the recognized missing signal is the first branch directly after the second isolation wavelength, 1576 *nm*, which is 1578 *nm*, which is if compared to Figure 4.1 or Figure 4.2 (the optimal display at the central office), it is indeed the first branch of the second group has been lost and became out of service. Out of service, means that the branch has become providing no any type of service, which should be went back to the service by taking an action by the operator.

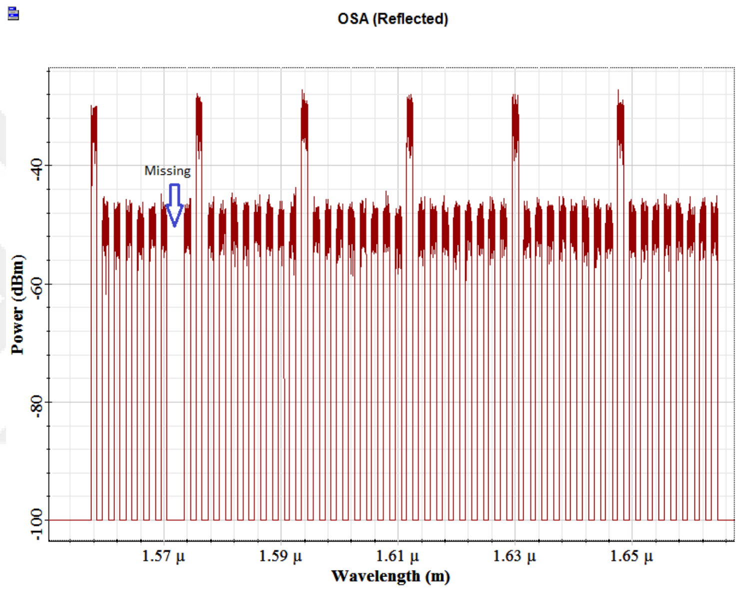


**Figure 4.8** Missing branch signal at the central office OSA, here the missing signal is related to the seventh branch of the first group

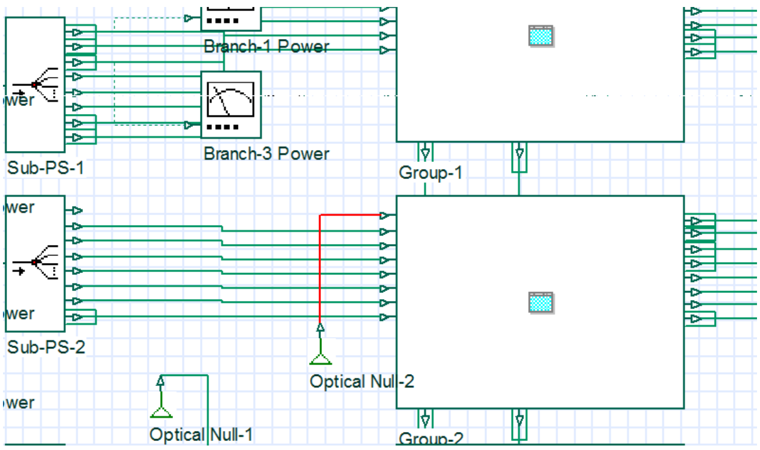


**Figure 4.9** Making a fault branch using optical null in the second group, first branch

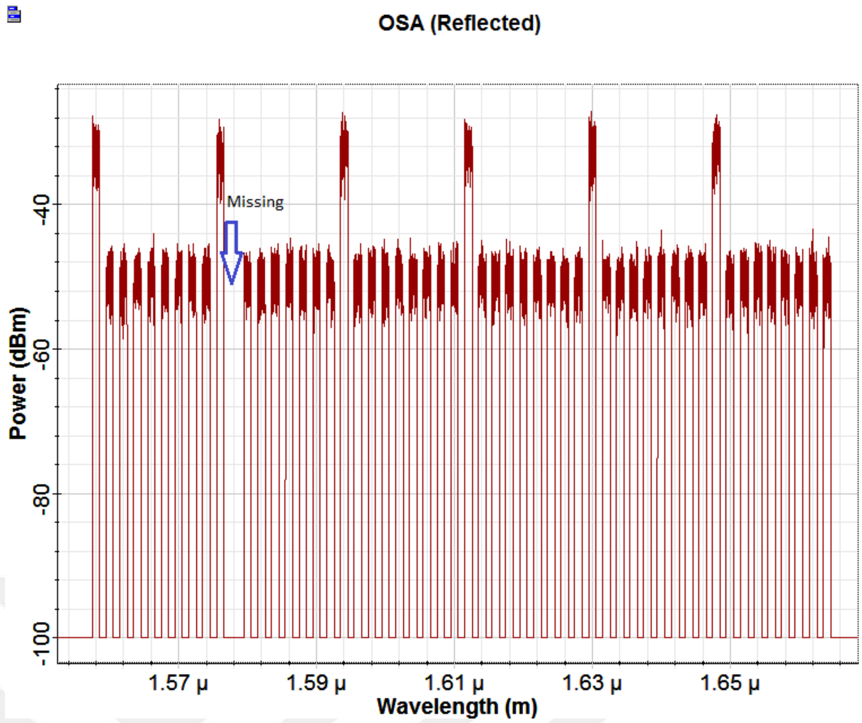


**Figure 4.10** Missing branch signal at the central office OSA, here the missing signal is related to the first branch of the second group

One different fault branch has been made in the third group, it can be seen in Figure 4.11 using the ON generator component, which feeds the branch by zero value signal (as described in chapter three). The missing signal, in the branch connected to the third group is; therefore, reflected to the OSA of the CO. Then, it can be seen in Figure 4.12 that the out of service branch is fifth one. That is, really easy investigation process can be followed up to recognize the fault location. No more processing for more investigation is required to detect the fault location. It is confirmed that the dropped or went out of service line is the signal with lowest power, as shown in Figure 4.12, when compared to the optimal configurations in Figures 4.1 and 4.2, respectively. Following the same procedure, it can be seen in Figure 4.13, that the fault branch is the eight one of the fourth group, which can be seen, as reflected, in the CO in Figure 4.14.

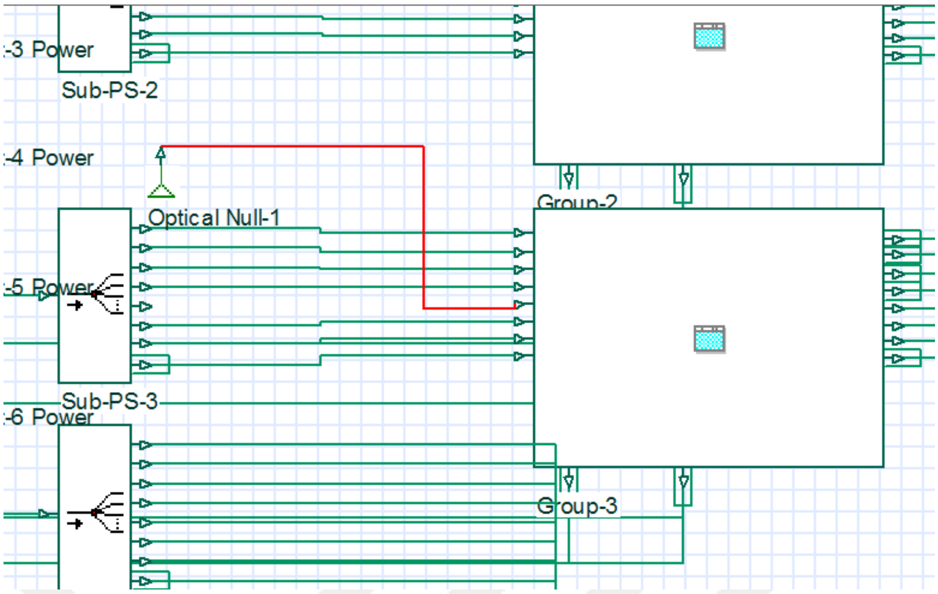


**Figure 4.11** Making a fault branch using optical null in the third group, fifth branch

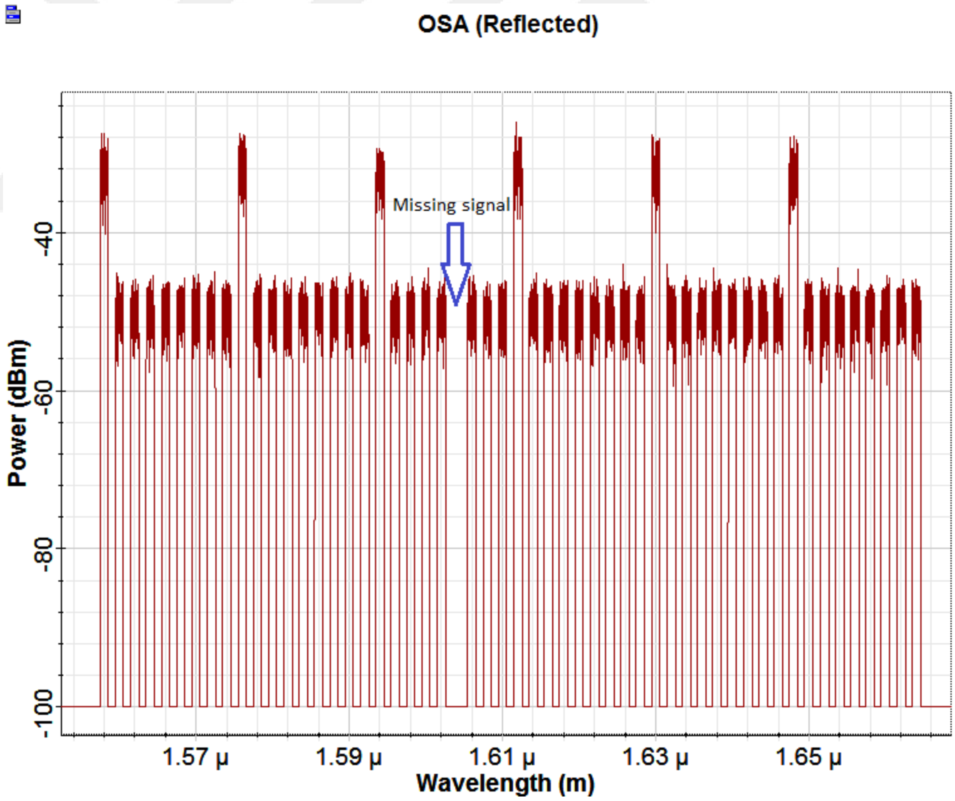


**Figure 4.12** Central office OSA, missing signal at fifth branch of the third group

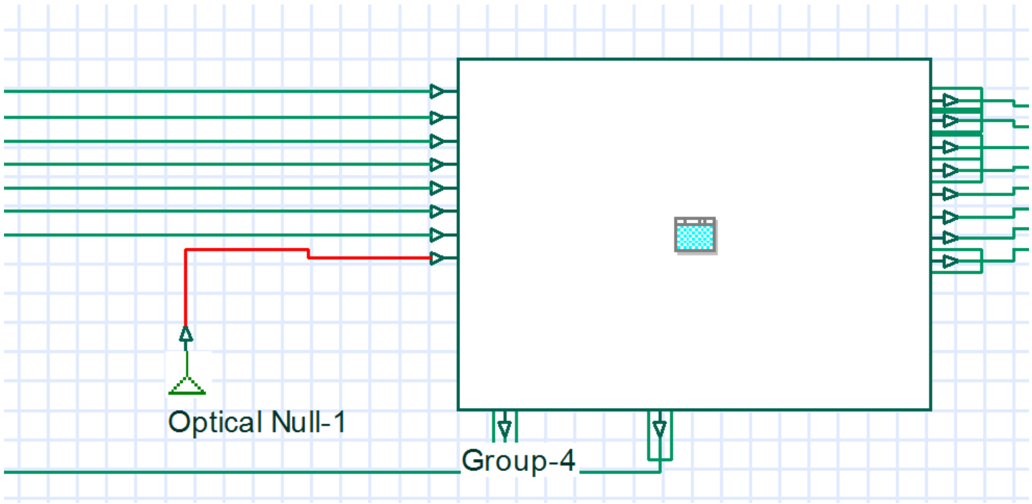


**Figure 4.13** Making a fault branch using optical null in the fourth group, eighth branch

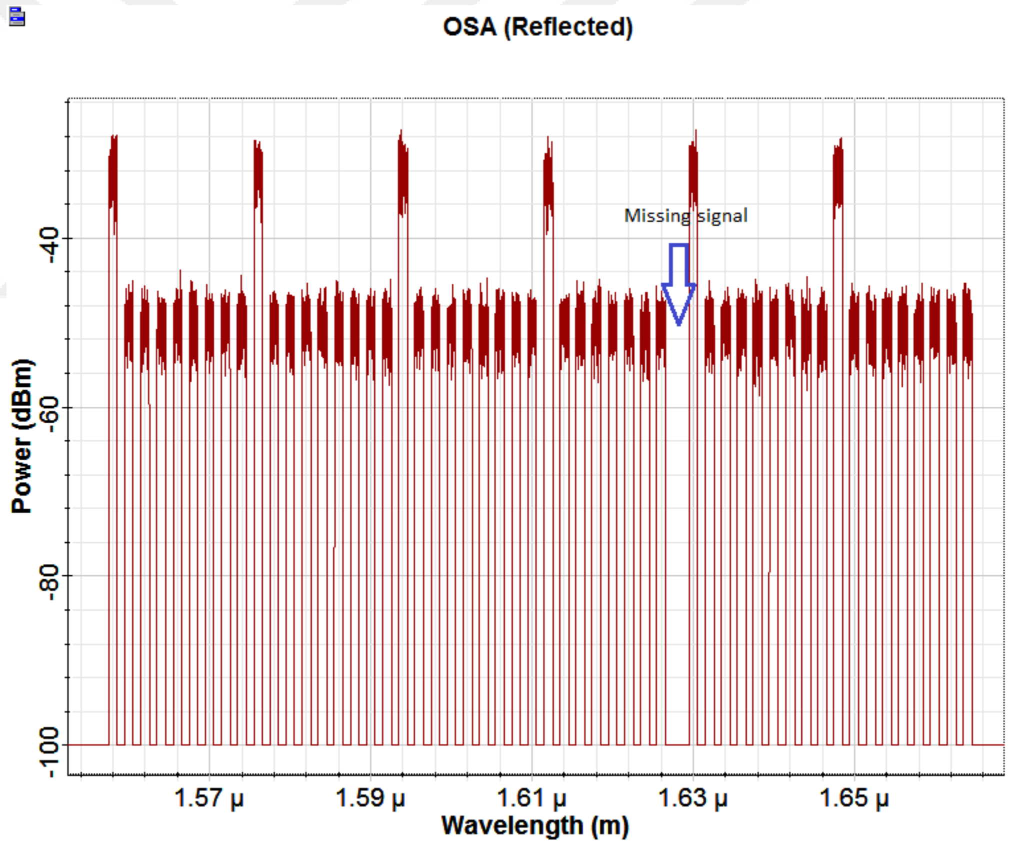


**Figure 4.14** Central office OSA, missing signal at eighth branch of the fourth group

Figure 4.15 draws the explanation of the fault branch generation in the fifth group, it is clear that the fault branch number is six. This is obviously reflected to the central office as shown in Figure 4.16.

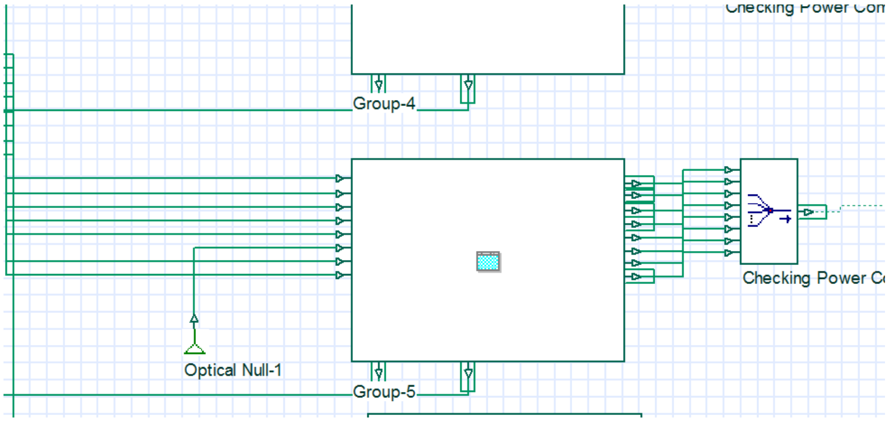


**Figure 4.15** Making a fault branch using optical null in the fifth group, sixth branch

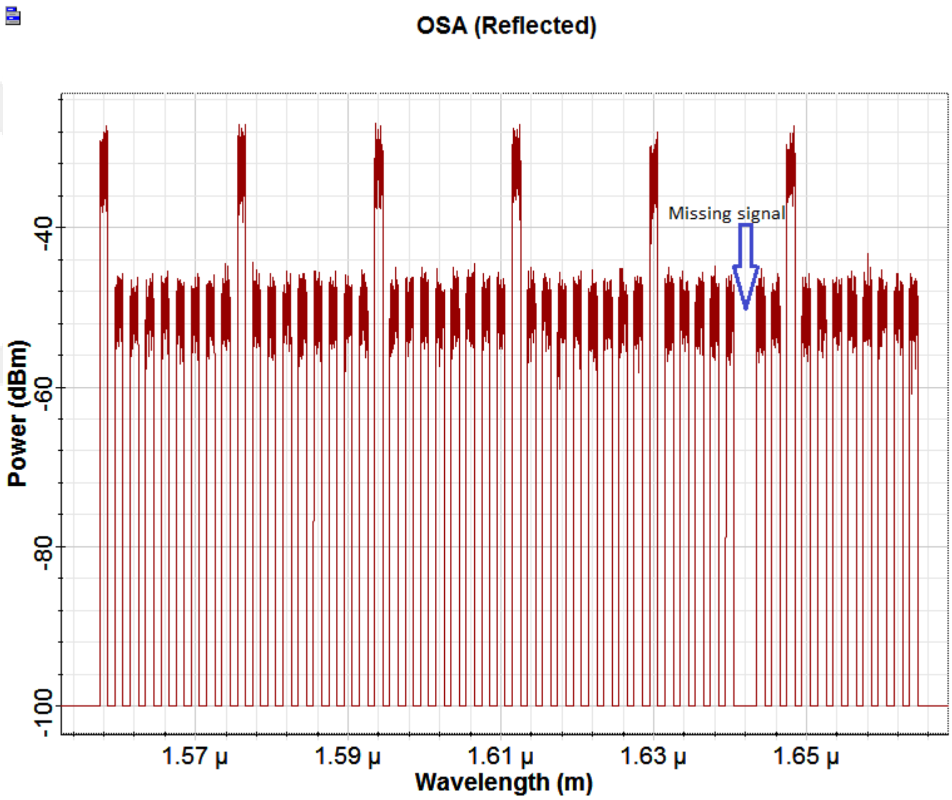


**Figure 4.16** Central office OSA, missing signal at sixth branch of the fifth group

Last but not least, Figures 4.17 and 4.18 show the making up seventh branch as a fault in the eight group, using the same scenario of the previous groups

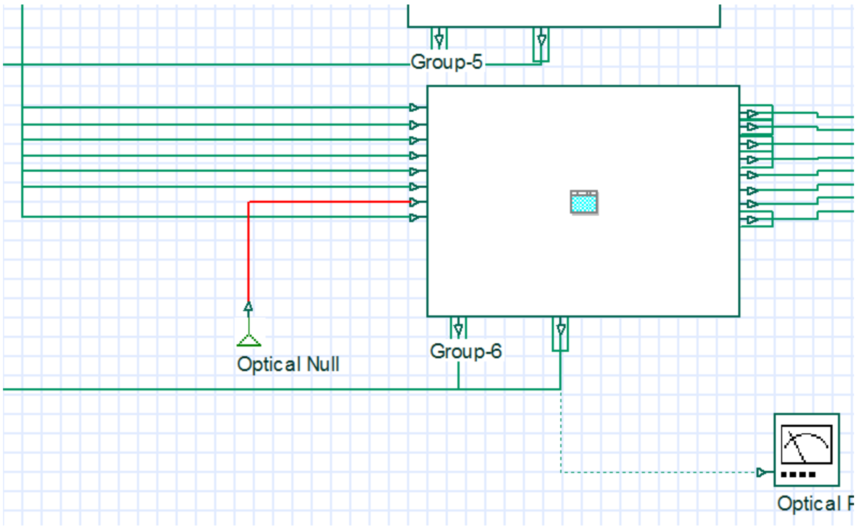


**Figure 4.17** Making a fault branch using optical null in the sixth group, seventh branch

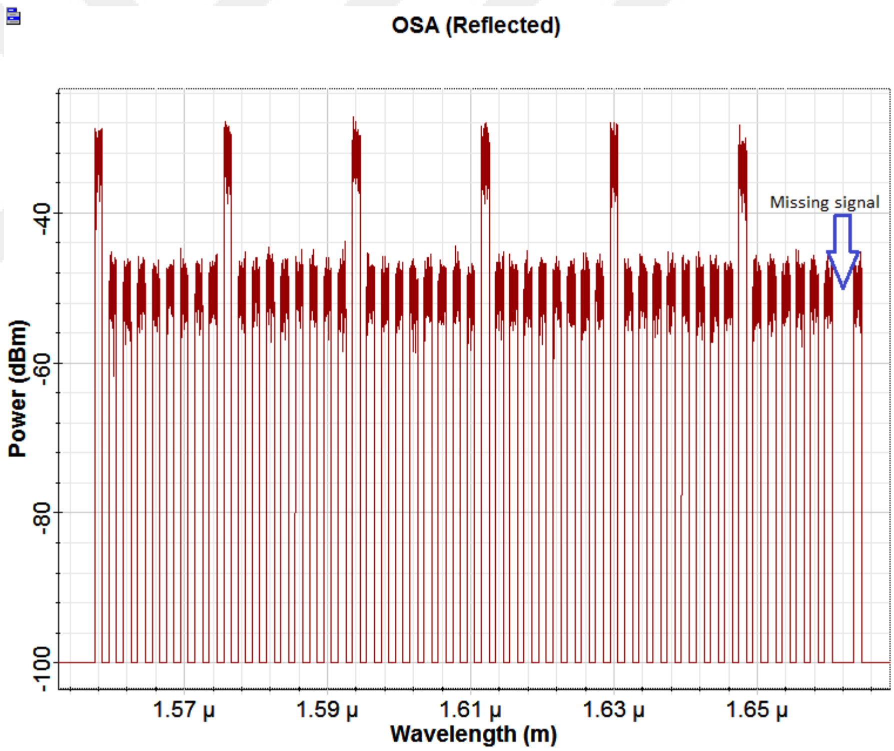


**Figure 4.18** Central office OSA, missing signal at sixth branch of the fifth group

#### 4.3.1.2 Faulty location investigation: multi line within a group

In the last subsection, section 4.3.1.1, it was shown how to locate the single faulty branch inside the same group. In this subsection, more than one fault location within the same group will be localized.

For example, if the sixth and seventh branches are lost in the first group, as shown in Figure 4.19, then, the sixth and seventh signals of the first group should be missed in the central office as shown in Figure 4.20. Suppose that the worker of the central office could not recognize that there are two consecutive branches are missing, it is also possible to count out the number of available signals between the two isolation wavelengths of the first group and the second group. That is, in Figure 4.20, it is clear that there are six reflected wavelengths out of eight, therefore, it is easily to say that there are two branches are missing from the first group, which they are the sixth and seventh wavelengths, corresponding to the sixth and seventh branches, respectively.

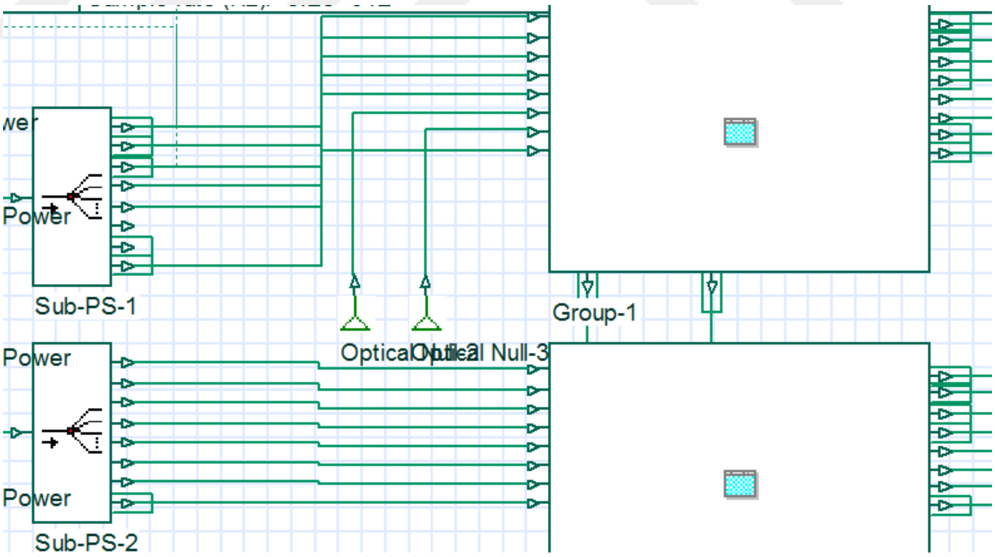


**Figure 4.19** Making a fault branches using optical nulls in the first group, sixth and seventh branches

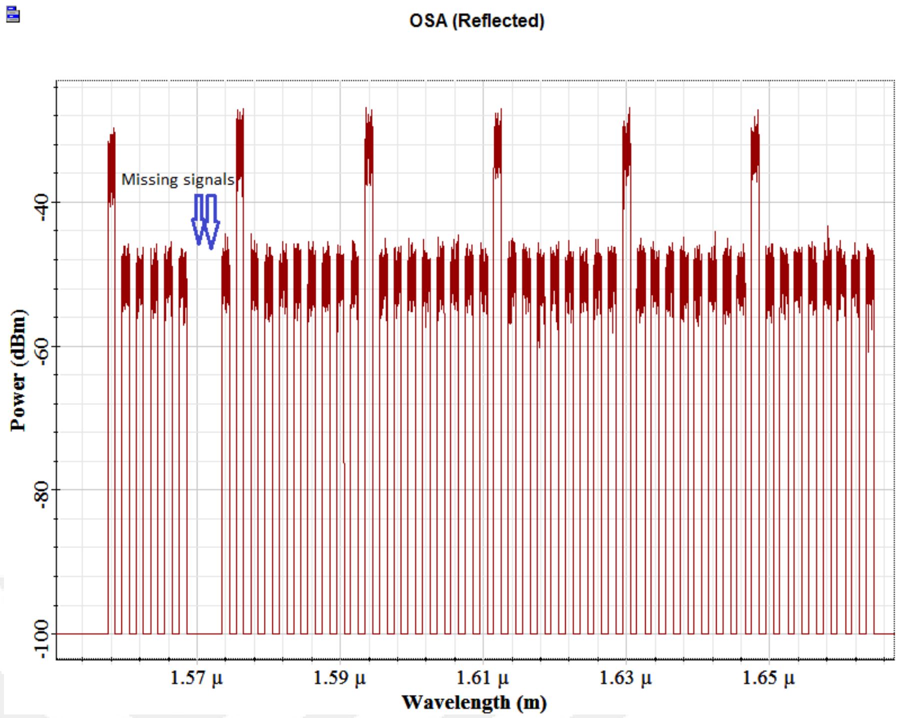


**Figure 4.20** Two missing branch signals at the central office OSA from the first group (G1)

Furthermore, lets involve fault locations in this scenario, fault locations in the same group. Thus, the fault locations will be made in the fifth group, third and eighth branches. This can be seen in Figure 4.21 using two optical null generators. Thus, the missing signals can be accepted in the central office as the missing signal in the third and eighth locations of the fifth group, as shown in Figure 4.22.

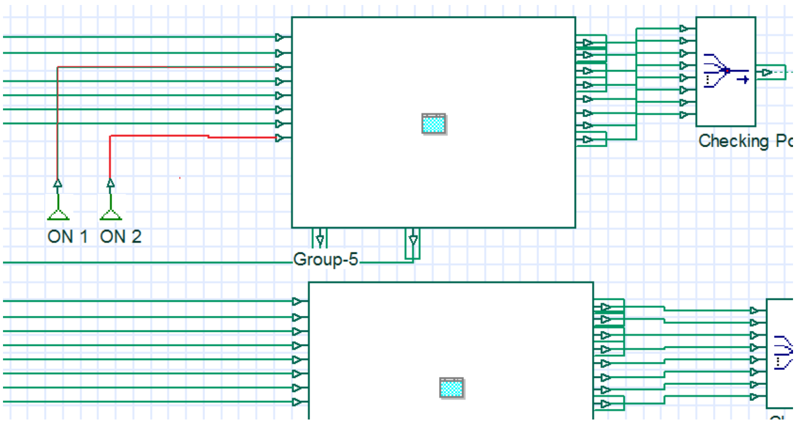


**Figure 4.21** Making fault branches in the G5, 3rd and 7th branches

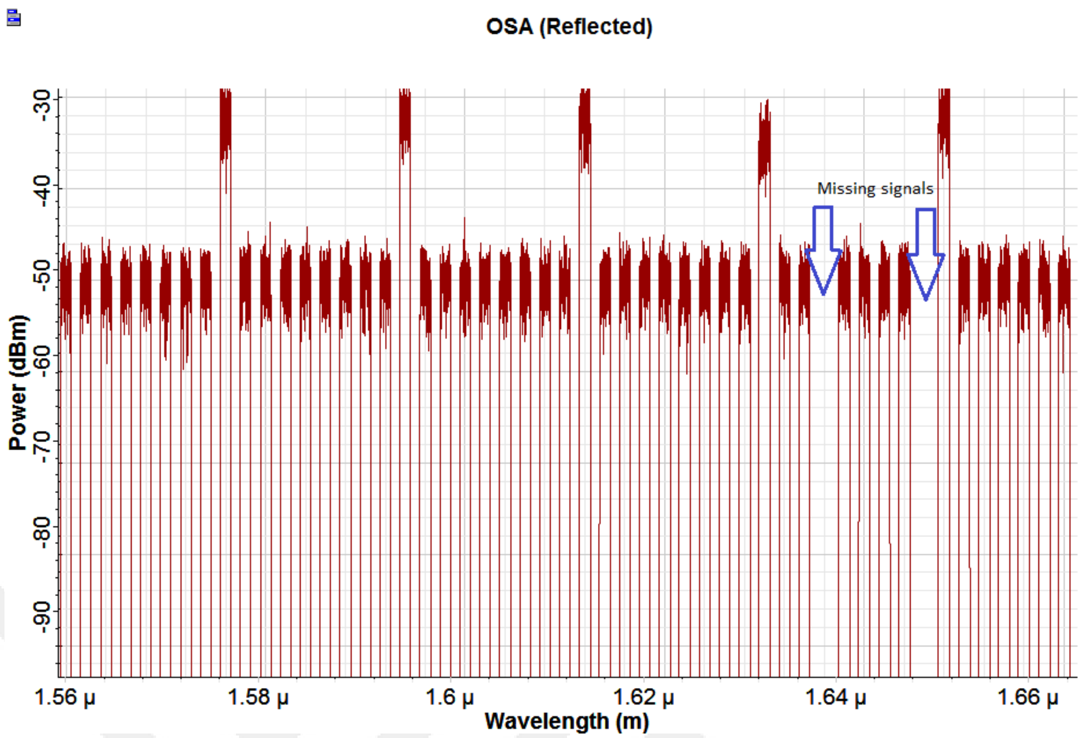


**Figure 4.22** Two missing branch signals at the central office OSA from the fifth group (G5)

#### 4.3.1.3 Faulty location investigation: multi line within different groups

In this subsection, fault locations in different groups, will be tracked as the third scenario of the results. Assume that there are two more missing/fault branches but are in different group combinations. Thus, suppose that the first two missing/fault branches are belonging to the second and third groups. That is, by connecting optical nulls to their feeding points as shown in Figure 4.23, where four optical nulls, Optical Null-1, Optical Null-2, Optical Null-3, and Optical Null-4, are connected to make drops/faulty lines in the first and fifth branches of the second group and first and last branches of the third group, as shown in Figure 4.23, respectively. Then, at the central office OSA (Reflected), there should be four missing signals. After carefully watching/study the screen of the OSA, it should be easily recognizing which branch signals are missing

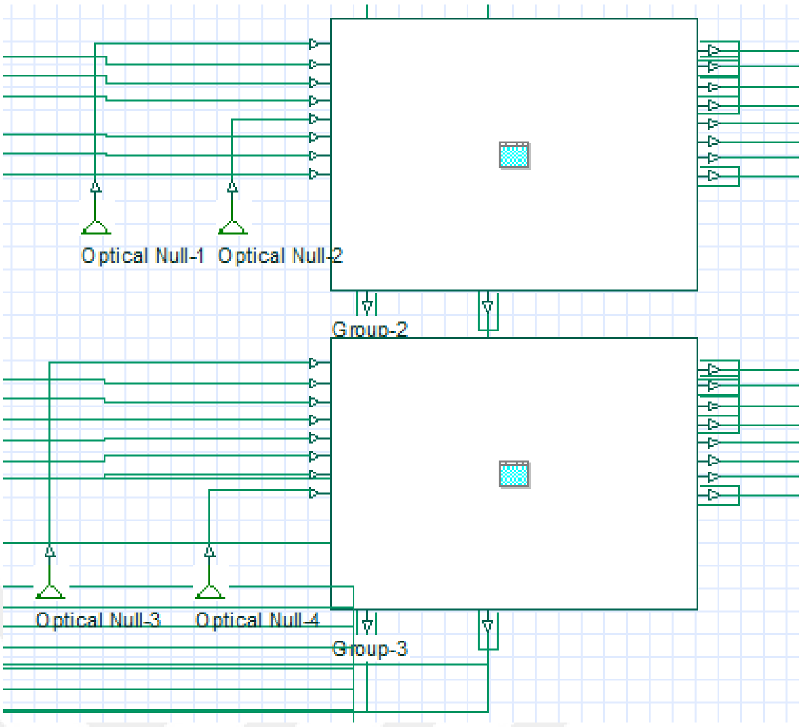


**Figure 4.23** Four missing branch signals creation using four optical nulls to the second and third groups

Accordingly, Figure 4.24 shows that there are actually four missing not-reflected signals. That is, the first missing/faulty branch signal is belongs to the second group, which is the first wavelength in the group. Hence, the first branch of the second group is down. Consequently, the second missing wavelength is the fifth one in the same group, third group, this corresponding to the fifth branch of the third group is down also. Additionally, the third missing wavelength is belonging to the third group, which is in fact the first wavelength directly after the third isolation-edge wavelength of the third group.

Thus, the recognized faulty branch, in this way, is the first branch of the third group, which is actually made in Figure 4.23 using Optical Null-3. So, it is successfully possible to distinguish the fault branch in central office. Last but not least, the fourth missing wavelength in Figure 4.23 is the last one of the third group, however, this is really being made in Figure 4.23 by employing the Optical Null-4. That is the eighth branch of the third group was lost, or this branch is providing no service any more.

Hence, it was possible to find out the lost branch service as simple as possible using the suggested passive optical network.

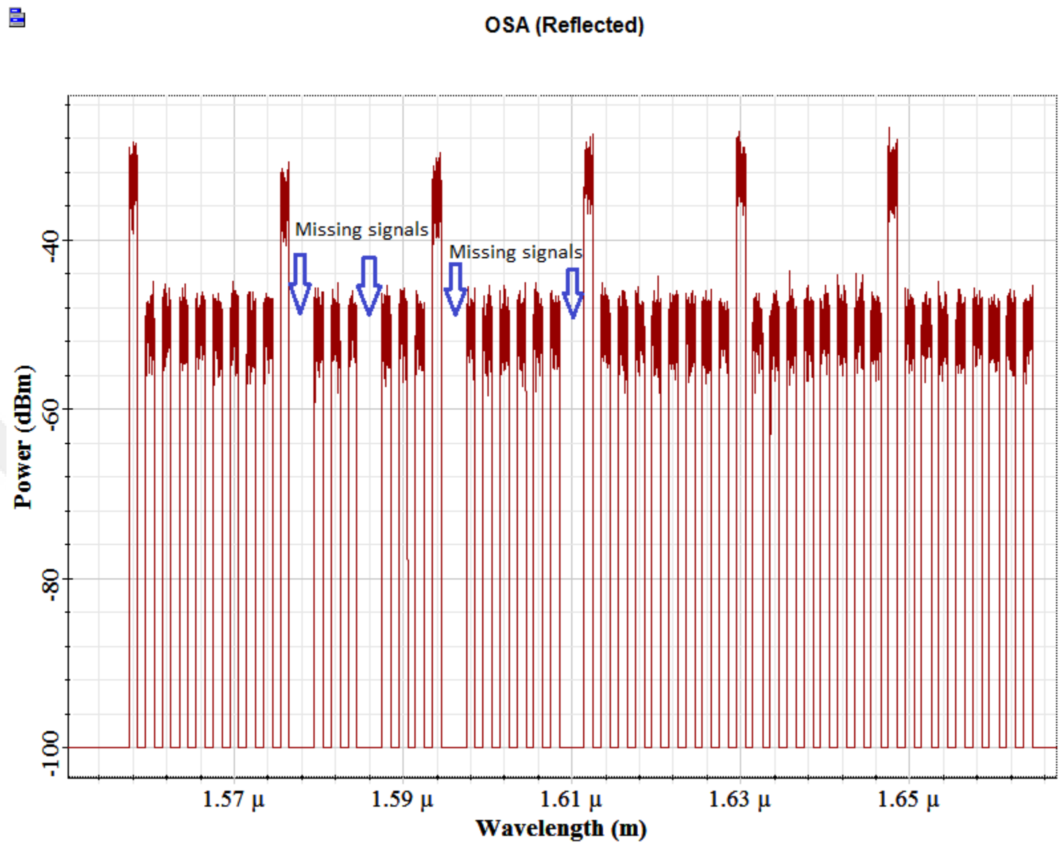


**Figure 4.24** Four missing branch signals at the central office OSA from the second and third groups

On the other hand, what will be seen in the central office OSA (Reflected) if a complete group is out of service? Furthermore, it will be assumed that the previous four missing wavelengths are also involved in this scenario.

The missing wavelengths, see Figure 4.24, will still be recognizable besides another missing signals, Figure 4.25 shows the implementation of making the fifth group behaves as missing, by connecting to its feeding point, which is the input to the sub-PS-5, an optical null (Optical Null-5). Hence, the fifth group should be out of service due to this operation. Therefore, in Figure 4.26, the mirror of Figure 4.25 should be observed. It is successfully significant in Figure 4.26 that there are four missing wavelengths, that are belong to the second and third groups as stated in the last paragraph, as well as the full group missing, which is the fifth one.

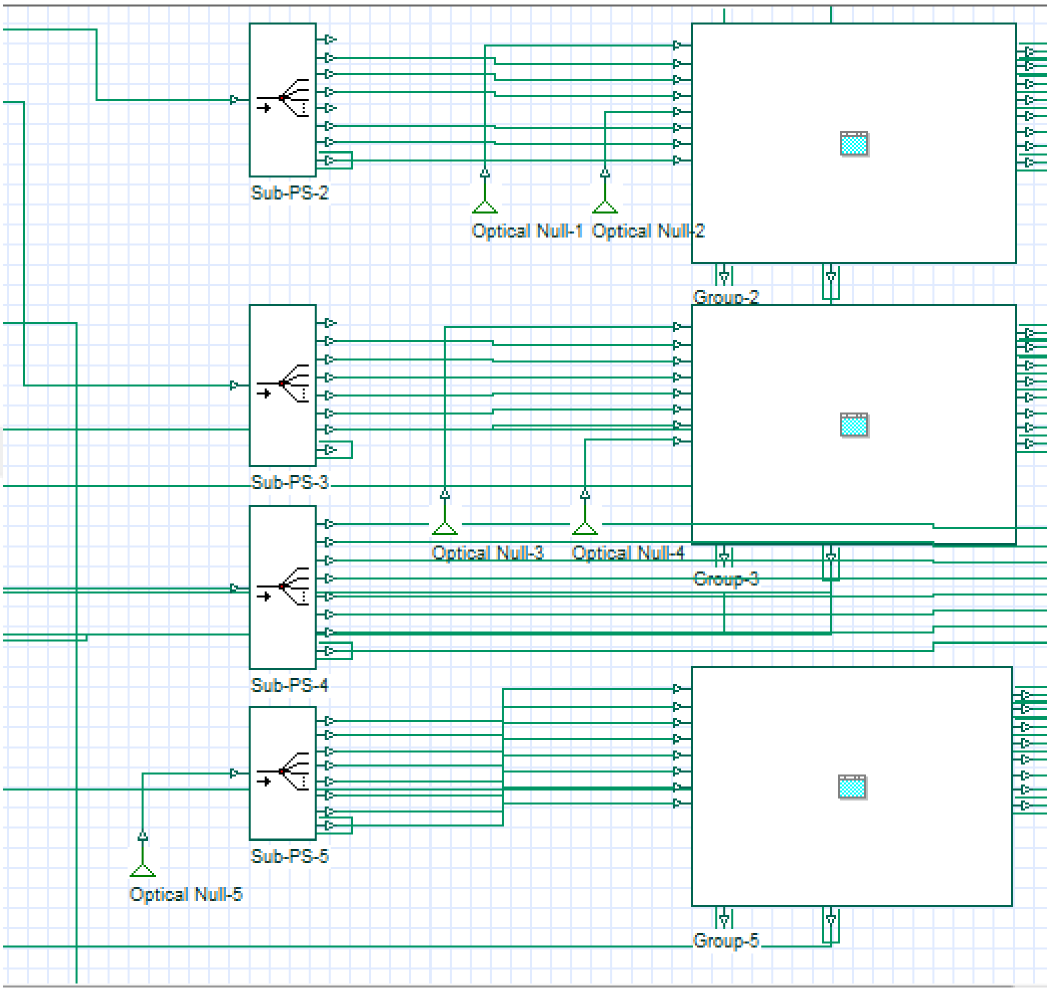


**Figure 4.25** Connecting Optical Null-5 to the input of the sub-PS-5 to make it behaves as missing group

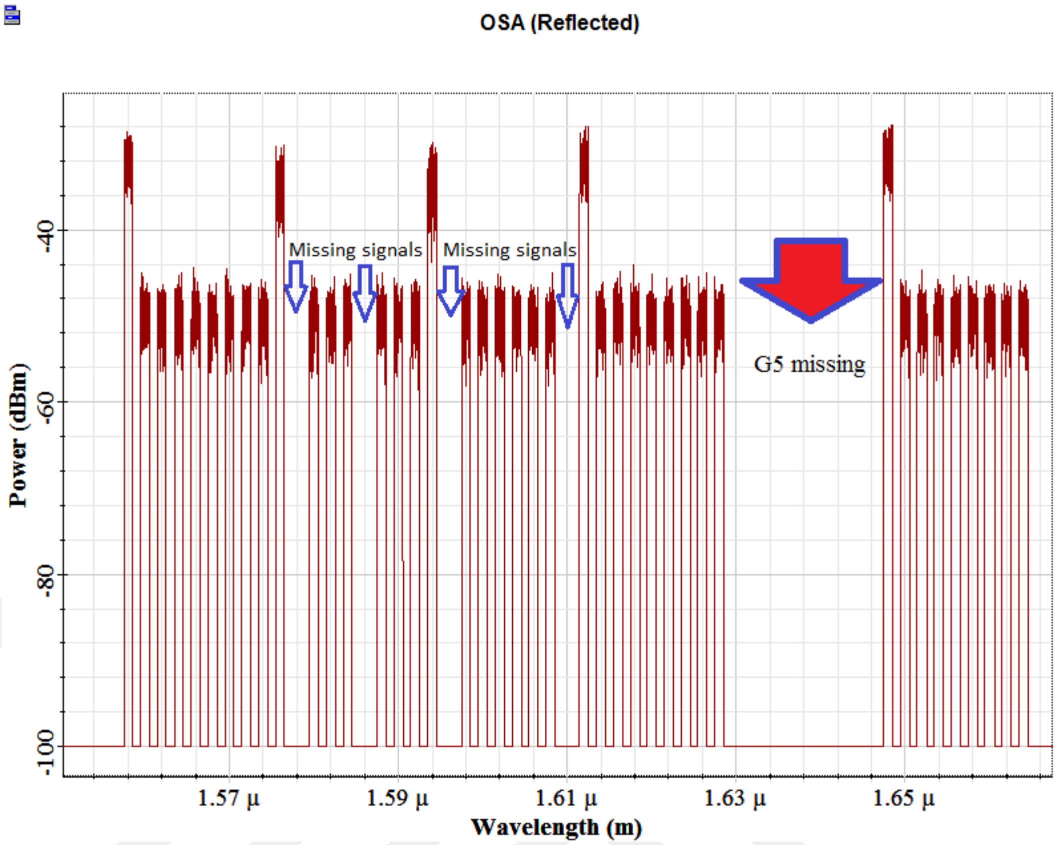


**Figure 4.26** Four missing branch signals as well as the missing of all of the fifth group as captured in the central office

One may think that there may be another missing wavelength in the screen view of the central office OSA (Reflected). Nevertheless, by counting the number of available wavelengths after the fourth isolation-edge wavelength, then, since there are eight successfully reflected wavelengths, therefore, it can be concluded that the fourth group is working properly and provides the service that it was assigned to it. While the sixth group is, really, starts with its isolation-edge wavelength and its eight reflected wavelengths are captured without problems. Hence, the missing is the complete group number five. Hence, it is simply and possible to discover any lost branch or even a full group, which consisting of eight branches, in the central office. Thus, one optical spectrum analyser can realize the full configuration of the suggested passive optical network productively

## [redacted]Conclusions

The projected configuration of the PON system has been designed in the previous chapter. However, in this chapter, the system has been investigated and validated using the various OptiSystem tools and components. It was shown that fault location in any group can be determined in no extreme complication. Simply, the fault can be found if it was within the same group, as stated in the results and discussion section. However, not only one fault branch was investigated, it was also more than two fault locations even in different groups. One more investigation, which can be considered as an important one, is the full group problem. If complete group was out of service besides another faulty location, the investigation of the suggested system does not add more complexity to the operator, as it was stated in this chapter.

Furthermore, the whole system fault locations can be followed up as follows: based on Figure 4.1, if the first wavelength is missing, 1560nm, the signal for the first user in the first group is out of service. When the second wavelength is missing, 1562nm, is lost, this corresponds to the second user in the first group being out of service and so on until the last signal. For instance, in the lsat group, G6, when the first wavelength of G6 is missing, 1650nm, it refers to the first user of G6 being lost. That is the method to discover any lost line in the suggested system in this thesis.

# 5 CONCLUDING REMARKS AND RECOMMENDATIONS FOR FUTURE WORKS

## [redacted] Introduction

In this chapter, concluding remarks for the projected PON system will be given. On the other hand, recommendation for future work will also be stated in this chapter for further investigation to develop the suggested system. Readers and researchers can configure out from this work that it is not difficult to add more characteristics to the current system to reach an optimal system design.

## [redacted] Conclusions

Passive Optical Network is one of the useful approaches to locate fault locations in the optical networks. However, PON network is simple, cost effective and with less construction components. All of these components are passive, such as power splitters, power combiners, fibre bragg gratings, and the feeder/fibre itself. There are no amplifiers used in this network. However, the deep investigation of this network shows that it is conceivable to determine the fault location without complexity.

As a conclusion to this chapter, it can be said that the suggested passive optical network could efficiently discover the faulty or the missing branch of group. In other words, by employing one optical spectrum analyser, the whole network can be monitored in the central office.

The network consists of six-groups. Each group provides eight-branches. There are eight reflected wavelengths from each group to realize the faulty branch, besides that, there is another eight reflections of the same wavelength from each group combination, which will be used to make the isolation-edge.

This isolation-edge wavelength has highest power, because it is a coherent/constructive addition of eight reflected signals of the same wavelength. Accordingly, there are six isolation-edges to distinguish the groups. Between each two consecutive isolation-edges, there are eight distinct reflected wavelengths (in the typical situation when there is not a fault branch), to be used to discover the fault/missing or out of service branch.

It has been demonstrated that the location of faults in any group may be determined without the need of severe intricacy. Simply said, if the error occurred within the same group, as indicated in the results and discussion section, the issue can be identified. However, not only was there more than one fault branch explored, but there were also more than two problem locations investigated, even in distinct groups. This problem might be deemed a significant investigation because it involves the entire group of participants.

As previously indicated in this chapter, if the entire group was out of service in addition to another defective location, the inspection of the suggested system does not add any further complexity to the operator's workload.

## [redacted]Future Works

Investigations for further future work and developments can be summarized as follows:

• It is possible to extend the network by simply adding another power splitter to each branch, thus, the branch will behave as a subgroup, then, from each branch, there will be another sub passive optical network of further branches. Then, for each sub passive optical network, there will be its specified optical spectrum analyser.

• The network of this research used even magnitudes of wavelengths. Therefore, it will be effectively building another passive optical network co-operates with the old-one. For instance, the old network used wavelengths of 1558 nm, to 1574 nm, the co-operated network could be built by using 1559 nm, 1561 nm, and so on. But in this way, there must be another OSA (Reflected) in the central office in order to not mix all the spectrum together.

- On the other hand, there are different parameters that affect the PON network, therefore, it is recommended to extend the work as follows:

- Deep investigation in the attenuation problems. Attenuation has different sources, such as fibre/feeder break, connectors, splicers, etc. that is, including the attenuation during constructing this network will increase the reliability of the design.

- The temperature also has significant effect on the passive network, therefore, more in depth investigation can be considered in the future work for such PON.

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# APPENDICES

## APPENDIX 1. Specifications of the FBG

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**Specifications**

**Product name FBG (Fiber Bragg Grating)**

| | |
|---|---|
| Central Wavelength (CW), nm | 530 - 2300 |
| Wavelength Tolerance, nm | < 0.1 |
| Reflectivity, % | 0.1 ... 99.9 |
| Bandwidth (FWHM), nm | 0.03 - 3 |
| Sidelobe Suppression Ratio (SLSR), dB | > 20 |
| FBG Length, mm | 0.1 - 50 |
| Coating | Acrylate; Polyimide; No coating |
| Temperature range (acrylate), °C | -20 ... +85 |
| Temperature range (polyimide), °C | -200 ... +350 |
| Connectors | FC/PC; FC/APC; any other |

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### Education

| | | |
|---|---|---|
| MSc | Çankırı Karatekin University<br>Faculty of Engineering<br>Electrical and Electronics Engineering | 2019-Present |
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