# REVISIÓN DE TÉCNICAS AVANZADAS WDM PARA EFICIENCIA ESPECTRAL EN REDES DE COMUNICACIÓN ÓPTICAS. doi

## REVIEW OF ADVANCED WDM TECHNIQUES FOR SPECTRAL EFFICIENCY IN OPTICAL COMMUNICATION NETWORKS.

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## RESUMEN

Este trabajo presenta el análisis de la multiplexación por división de longitud de onda (WDM) en redes de fibra óptica (FTTH) con el objetivo de optimizar la calidad de servicio al cliente. Se diseñó y simuló una red FTTH con WDM utilizando el software OptiSystem. Posteriormente, la configuración se validó experimentalmente con equipos de una red GPON del laboratorio de comunicaciones ópticas. Se realizaron mediciones con diferentes longitudes de onda y potencias para evaluar la eficiencia de multiplexación.

Los resultados mostraron que la longitud de onda de 1490 nm con una potencia de -82,737 dB resultó ser la más eficiente, con una eficiencia del prototipo del 87,5%. La simulación en OptiSystem arrojó un valor de -76,471 dB, lo que indica que la simulación no refleja con exactitud los resultados de la técnica WDM en la práctica. Este trabajo valida la técnica WDM como solución viable para mejorar la calidad de servicio en redes FTTH. Se estableció un precedente para futuras investigaciones utilizando un modelo GPON y la técnica WDM en diferentes escenarios de telecomunicaciones.

**PALABRAS CLAVES:** WDM; FTTH; Calidad de servicio; Red GPON; Redes ópticas.

# ABSTRACT

This paper presents the analysis of wavelength division multiplexing (WDM) in fiber optic networks (FTTH) with the objective of optimizing the quality of service to the customer. An FTTH network with WDM was designed and simulated using OptiSystem software. Subsequently, the configuration was experimentally validated with equipment from a GPON network of the optical communications laboratory. Measurements were performed with different wavelengths and powers to evaluate the multiplexing efficiency.

The results showed that the 1490 nm wavelength with a power of -82.737 dB proved to be the most efficient, with a prototype efficiency of 87.5%. The simulation in OptiSystem yielded a value of -76.471 dB, indicating that the simulation does not accurately reflect the results of the WDM technique in practice. This work validates the WDM technique as a viable solution to improve the quality of service in FTTH networks. A precedent was established for future research using a GPON model and the WDM technique in different telecommunication scenarios.

**KEY WORDS:** WDM; FTTH; Quality of service; GPON Network; Optical Networking.

## INTRODUCCION

Wavelength multiplexing (WDM) are technologies for the transmission of several signals on the same fiber without too much or no interference, each of them represents an optical channel passing through the same fiber, where the main problem is the speed and one of the alternatives is to use the WDM technique that will economically improve the costs in the maintenance of the networks (Luan et al., n.d.), (Kuroda, 2022).

In this work, the effects on the signal of fiber optic networks are simulated using measurement equipment such as the frame controller and spectrum analyzer for active and hidden signals, with the objective of improving the quality of service in an FTTH network. The behavior of WDM modulation is analyzed to understand the characteristics of different modulation techniques and their impact on signal quality. Several measurement scenarios are compared to identify the key factors and environments that influence the achievement of optimal results in the WDM technique.

For the WDM wavelength measurement in optical systems, where we will use the equipment provided by the university to see the results in a better way with more accurate results we will use a launch coil as the waves will be represented with the OTDR (Zhao et al., 2022) and a 1x8 Splitters and will be observed on the screen the results obtained; where the losses and dBm in dead zones will be verified and all the information of the analysis will be saved directly for the test systems, as it will be presented in the laboratory and less pulses will be observed for the measured distances. We will use 144-wire fiber of 12 ADSS buffer and the patch cords will be presented in each wire of the wavelengths (Choyon & Chowdhury, 2022; Niu et al., 2020).

The evolution of communications and the increase of new applications of the internet of things (Santillán Carranza et al., 2024), leads providers to seek solutions for service efficiency, since with the saturation of the Internet to measure these problems in fiber optics, optical equipment will be used, where the biggest problem

is the speed and one of the alternatives is to use the WDM technique that will economically improve the costs in network maintenance (Rodriguez et al., 2017).

The equipment to be used are the spectrum analyzer Yokogawa model AQ6370D, Yokogawa Frame Controller model AQ2211 provided by the university in the laboratories of block E. In addition to the equipment mentioned above, we will use a transceiver (R. Wang et al., 2022).

The Optical Fiber will be of great help to us since, a fiber of 144 threads must be used where it will allow us to use the means of transmission to send data at a higher speed and a greater distance than other means of transmission. This is due to the material of which the optical fiber is made, which it can be glass or plastic, which has a low signal loss (S. Wang et al., 2022).

There are two kinds of fiber which are single mode and multimode, where there will be a difference in propagation by guided media. Where this type of fiber will transmit in one mode; where as opposed to single-mode fiber it will transmit in multiple modes (Keiser, 2021).

We implemented the use of an OLT where it will be responsible for receiving and sending signals through the optical fibers, analyzing the traffic flowing determining our node to obtain data in the different scenarios of analysis of the fiber optic network. Using the ODF distributing this service to the different distribution boxes (Ding et al., 2022), (Alipour et al., 2022).

The review of advanced WDM techniques for spectral efficiency in optical communication networks was carried out with the support of a launch coil, a crucial component in the experimental setup. This coil, used for calibration and signal control purposes, played a key role in obtaining accurate and reliable data. Its inclusion in the experimental process ensured the quality and integrity of the results, thus allowing a thorough evaluation of the WDM techniques analyzed and their impact on the spectral efficiency of optical communication networks (Krivosheev et al., 2022).

Furthermore, in the context of the review of advanced WDM techniques in optical communication networks, the experiment was carried out with the assistance of an optical router. This router played an essential role in the experimental setup, allowing the implementation and evaluation of various WDM techniques (Zhang et al., 2021).

Also, within the framework of the review of WDM techniques for spectral efficiency in optical communication networks, an additional analysis was carried out using different optical connectors. These connectors were applied to investigate possible changes or variations in system performance. It is important to note that this study was carried out in the context of an FTTH network, which served as a measurement scheme to evaluate the feasibility and efficiency of the analyzed techniques (Fukai et al., 2020), (Maslo et al., 2020).

## 1.1. Related Work

The author of the topic Analysis of Wavelength Division Multiplexing (WDM) techniques and their simulation using OptiSystem software. He shows the different multiplexing methods that exist and evaluates each one with the OptiSystem software(Sánchez Herrera & Jimmy Francisco, 2020).

The researchers in this study examine the performance of a Gigabit Passive Optical Network (GPON) using Fiber-to-the-Home (FTTH) technology, show the analysis of triple play services over this GPON FTTH network, in order to ensure that every user has access to gigabit/s speeds for the upcoming 5G network and minimize the use of microwave communications whenever possible (Sadin et al., 2022).

This study focuses on the growing importance of high-speed data rate (HSDR) in applications such as live streaming, Internet video, and videoconferencing. It explores the design of an error-free gigabit point-to-multipoint communication network using the fiber Bragg grating (FBG) technique, which mitigates inter-symbol interference in point-to-point (P2P) communication and for HSDR. In the transmission section, it employs an optical meter to obtain the polarization at various lengths of the optical fiber (S. Verma et al., 2016).

The authors of this paper present innovative research that addresses the growing demand for high data rates by providing efficient and secure communication from the optical line terminal (OLT) to the optical network unit (ONU). The results have been validated by simulations in Opti-system optical simulation software, considering gain and power in wavelength-division multiplexing passive optical networks (WDM-PON) for extended ranges (D. K. Verma & Garg, 2023).

This article provides an overview of the transceiver technologies that will be employed in both current and future passive optical networks (PONs). Showing the increase of bit rates in PON networks in a cost-effective manner, to meet future bandwidth demands, which will generate the need for continuous improvements in PON transceiver technologies. In this paper, we discuss the necessary requirements and their impact on next-generation transceiver technologies, based on past and present PON transceiver designs (Houtsma et al., 2021).

This study presents a 25G passive optical network (PON) in C-band using an SOA and an EAM. The results show that the SOA in the ONU can eliminate the downlink signal and reuse the downlink wavelength. The gain of the SOA compensates for the loss of the EAM. Equalization algorithms for linear and nonlinear distortions are explored, and the robustness of the system to ASE and maximum transmission rate is evaluated. The system achieves a capacity of up to 25 Gbps, promising to be a technology for future PON WDM systems (Xu et al., 2022).

## 1.2.    Conceptual foundation

The following are the different frequencies allowed for a DWDM (Dense Wave Division Multiplexing), as shown in Equation 1 where the channel spacing can range from 12.5 Ghz to 100Ghz, in order to define them the following calculation will be required:

$$Fc = f + n * \Delta f \qquad\qquad (1)$$

Where:

$$Fc \rightarrow Central\ frequency\ (Ghz)$$

$$n \rightarrow Integer\ can\ be\ positive\ or\ negative\ (0; 1)$$

$$f \rightarrow Frequency\ (Ghz)$$

$$\Delta f \rightarrow Channel\ spacing\ (Ghz)$$

Wavelength refers to the distance between two identical points on a wave, such as the peak of a wave to another peak, we can also calculate velocity and frequency. Equation 2 is the general formula for calculating both velocity and frequency for wavelength (in meters) (CARLOS GUERRA ALTAMIRANO, 2021; Tomoyuki Kato et al., n.d.).

$$\lambda = \frac{c}{f} \qquad (2)$$

Where:

$$\lambda \rightarrow Wavelength\ (nm)$$

$$c \rightarrow Speed\ of\ light\ where\ c \approx 3\ x\ 10^8 \frac{m}{s}$$

$$f \rightarrow wave\ frequency\ (Hz)$$

The signal-to-noise ratio (SNR) refers to the ratio between the signal power and the noise power, where it is the ratio between the signal power of a service provided and the noise power within a valid bandwidth. Equation 3 will show in general terms the respective calculation for the signal-to-noise ratio in decibels (dB) (r Achyut K. Dutta et al., n.d.; Takahashi et al., 2021).

$$SN\ R_{dB} = 10 * log_{10}(SNR) \qquad (3)$$

Time Division Multiplexing (TDM) is a technique used in telecommunications to transmit multiple signals over a single communication channel. Instead of assigning a specific frequency for each signal, as in Frequency Division Multiplexing (FDM), in TDM time is divided into time slots and each signal occupies a specific time slot using Equation 4 (Kato et al., 2020; Smith & Jones, n.d.).

$$T = \frac{1}{f} \qquad (4)$$

Where:

$$T \rightarrow Frame\ time\ (\mu s)$$

$$f \rightarrow Frame\ frequency\ (\mu s)$$

## 2. MATERIALS AND METHODS

In the analysis of different wavelength division multiplexing techniques in optical communication systems, several methods are used to collect information on the status of a possible service. Measurements on the GPON network layout evaluate the status of different services such as sending frames with triple play service (internet, telephony, TV). Measurements in the outage can help identify the distance and the number of decibels of loss.

The structure of the WDM technique will be composed of the GPON network model plus the devices that are evaluated with the launching coil. As a next step, supported by the spectrum analyzer, simulations of the effects of the fiber and the frame controller are performed to verify the desired parameters and perform the correct analysis for the service offered is expected.

To carry out the development of the work, the scheme described in Figure 1 will be followed. At point A, the internet input is located in the optical router, from where it is directed to the OLT (B). It is then connected to the ODF (C), which is linked to a 4-output splitter and connected to the spectrum analyzer (D) to perform the corresponding measurement from the OLT. The OLT is connected to the frame controller (E), which will simulate an internet connection, displaying two plots on the spectrum analyzer: one from the GPON network and one from the frame controller.
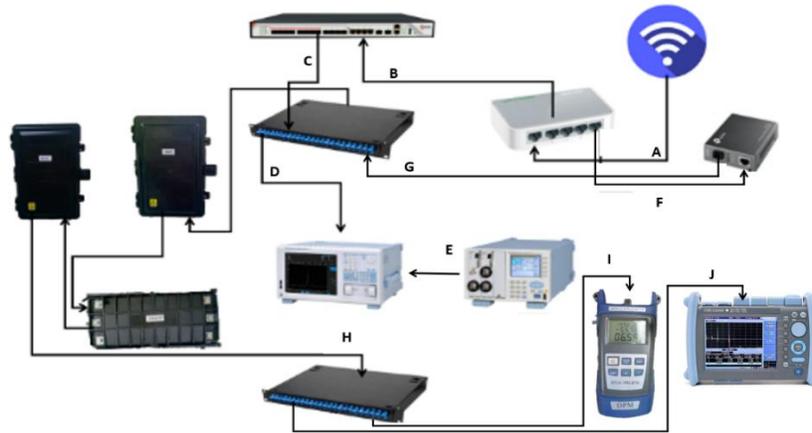
**Figure 1.** Schematic of the test prototype

Figure 1 shows the following connections and equipment according to each legend.

A: internet connection via the optical router

B: connection of the optical router to the OLT

C: connection from the OLT to the ODF 1

D: connection of the ODF 1 to the spectrum analyzer

E: connection of the frame controller to the spectrum analyzer

F: Connection of the optical router to the transceiver

G: connection of transceiver to ODF 1

H: connection of the junction box to the ODF 2

I: connection of ODF 2 to OPM

J: connection of ODF 2 to OTDR

Then an optical router is connected to a transceiver (F), where the transceiver is connected through the optical port to ODF 1 (G), a link is made between ODF 1 to ODF 2 (H); then a Splitter is connected to a port of ODF 2 and after that a direct

optical cable to connect and perform the power measurement by regulating the wavelength at which the OPM works (I).

Finally, it is going to measure the sections and splices that may have a damage at a certain distance. Through an OTDR (J).

Figure 2 shows the results obtained from the path from ODF 1 to ODF 2 using a transceiver as a booster of our network and an OPM as a power meter adding span with a 20 km launching coil.
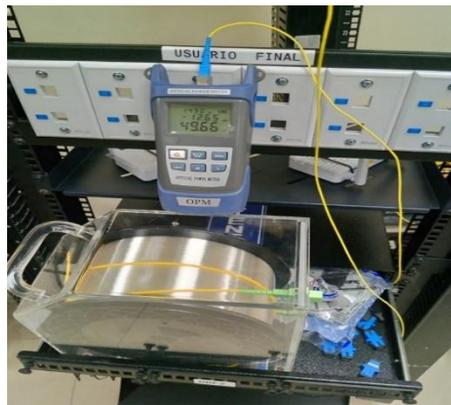


**Figure 2.** Power testing through an OLT using an OFM

Figure 3 presents the results of the simulation performed using a frame controller to measure the multiplexing between a frame controller, an OLT, and a transceiver.
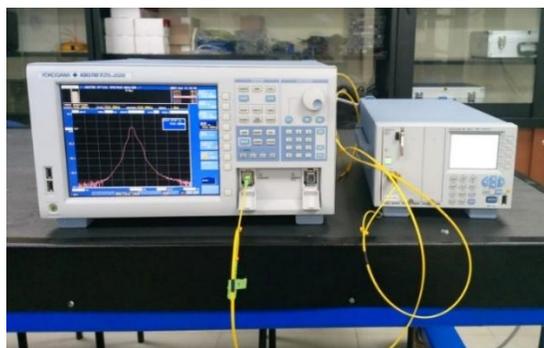


**Figure 3.** Results of network parameter measurements

Figure 4 shows the results obtained from the measurement performed by a VFL connected in ODF 1 to an OTDR connected in a port of ODF 2 where dead sections are searched in the change of the new fiber.
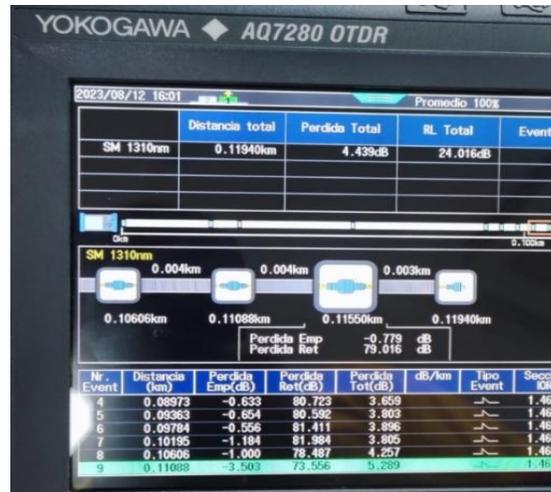
**Figure 4.** Data obtained from the measurement of the GPON network

## 3. ANALYSIS OF RESULTS

### 3.1. Prototype Results

The analysis produced the results presented in Table 1, which are generated by the OTDR and show the locations and characteristics of possible damage in the spans and splices at certain distances. Another set of results is found in Table 2, obtained through the optical spectrum analyzer, which indicates the analysis of the multiplexing performed on the GPON network mockup by the spectrum analyzer.

Finally, the results of the measurement performed with the OPM are presented and shown in Table 3. This measurement is carried out to evaluate the performance of the data link transmitted over a transceiver in the GPON network. After replacement of the damaged 24-strand fiber with a new 144-strand fiber, a comprehensive analysis was performed using the Yokogawa AQ1200A OTDR to detect possible faults along the entire fiber path in the GPON network. The results show minimal losses, as detailed in Table 1.

| Events Overview | Distance (Km) | Splice Loss (dB) | Loss return (dB) | Loss Total (dB) |
|---|---|---|---|---|
| 1 | 0.08973 | -0.633 | 80.723 | 3.659 |
| 2 | 0.09363 | -0.654 | 80.592 | 3.803 |

| | | | | |
|---|---|---|---|---|
| 3 | 0.09784 | -0.556 | 81.411 | 3.896 |
| 4 | 0.10195 | -1.184 | 81.984 | 3.805 |
| 5 | 0.10606 | -1.000 | 78.487 | 4.257 |
| 6 | 0.11088 | -3.503 | 73.556 | 5.289 |

**TABLE 1.** GPON model condition analysis results

Once the state of the GPON network is verified, we proceed with the analysis of the WDM multiplexing technique using equipment such as the transceiver, the frame controller, the OPM and the OLT. It is observed that the use of the frame controller presents higher noise levels compared to other analyses performed, as detailed in Table 2.

| Events Overview | Multiplexing (nm) | Power (dBm) | Central Frequency (nm) | Central frequency power (dB) | Noise (dBm) | Signal-to-noise ratio (dB) |
|---|---|---|---|---|---|---|
| 1 | 1491.8426 | -82.196 | -0.9000 | -2.945 | -76.165 | 15.874 |
| 2 | 1491.8556 | -82.992 | -0.8914 | -3.742 | -96.337 | 13.345 |
| 3 | 1491.8756 | -80.992 | -0.8716 | -1.742 | -92.690 | 11.698 |
| 4 | 1491.8834 | -79.127 | -0.8636 | 0.123 | -219.209 | 140.092 |
| 5 | 1491.8962 | -81.224 | -0.8500 | -1.974 | -96.247 | 15.023 |
| 6 | 1491.9152 | -82.737 | -0.8318 | -3.487 | -92.323 | 9.587 |

**TABLE 2**. Results of multiplexing analysis with the spectrum analyzer

In addition, this study verified the state of the GPON network when switching to the new optical fiber using an OPM. The power arriving from ODF 1 to ODF 2 at the same wavelength was also measured to detect possible variations, which is summarized in Table 3.

| Type | Wavelength | Power (dB) | Power (nw) |
|---|---|---|---|
| splittter | 1490 | -68.49 | 0.141 |
| straight wire | 1490 | -65.30 | 0.295 |

**TABLE 3**. Results of the analysis to be performed with the OPM on the GPON model

Multiple measurements were performed in the optical communications laboratory using the GPON mockup. Measurements were carried out from the ODF 1 and ODF 2 ports through the OLT using two transceivers and a splitter to observe multiplexing using the Yokogawa AQ6370D spectrum analyzer. The results obtained are presented in Figure 5.
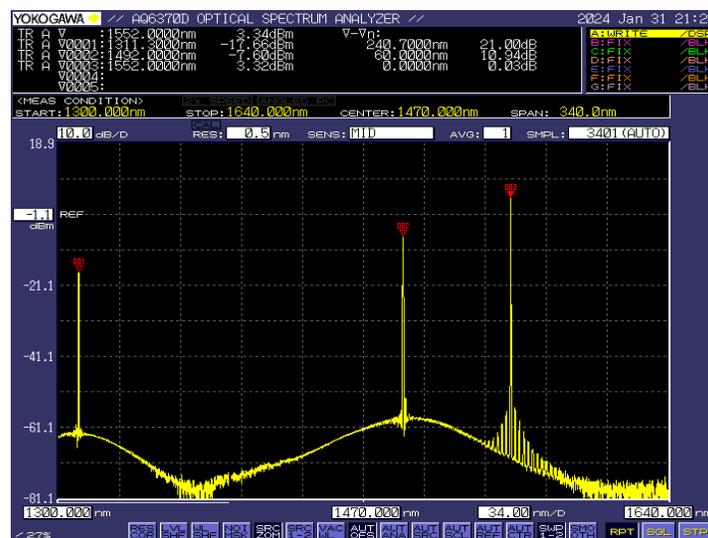


**Figure 5**. Spectrum of the multiplexed signal from 1311nm, 1492nm y 1552nm

The results depicted in Figure 6 were obtained by connecting a 1x4 splitter, dividing the outputs as follows: the first output was connected to a transceiver, the second output was linked to box 1, establishing a connection between OLT and ODF 1, and the third output was connected to the frame controller.
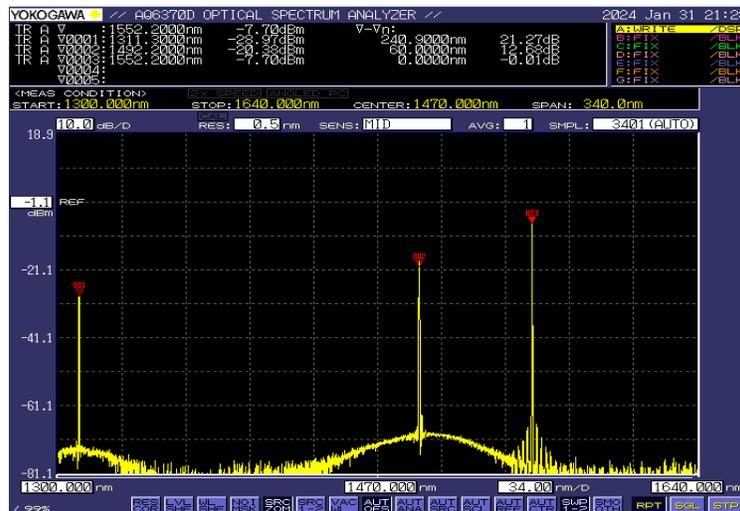
**Figure 6**. Results from blue wire in ODF 1 to ODF 2 via transceiver and OLT

In Figure 7, a scenario was implemented where the second output of the splitter was connected to box 2 through ODF 2. A difference of 1000 nm and 10 dB was achieved, observing a lower loss in the graph when analyzing the multiplexing, with a maximum loss of -18 dB at the 1311 nm wavelength.
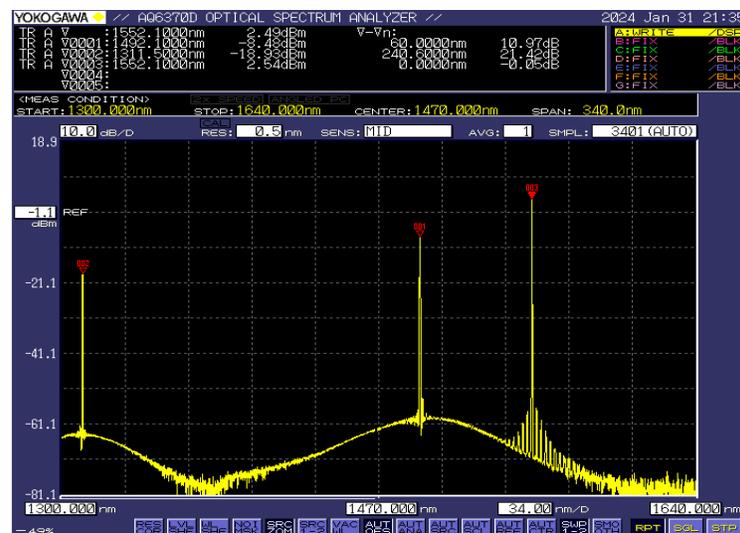


**Figure 7**. Results on the measurement of the blue wire from ODF 2 to ODF 1 by transceiver and OLT

Figure 8 shows that the wavelengths are at 1309 nm, which were measured at the outputs of the 1x4 splitter, where two transceivers and an ONT were connected. As

a result, the ONTs were lossless, allowing them to link with a loss of -18 dB and maintain uninterrupted services.
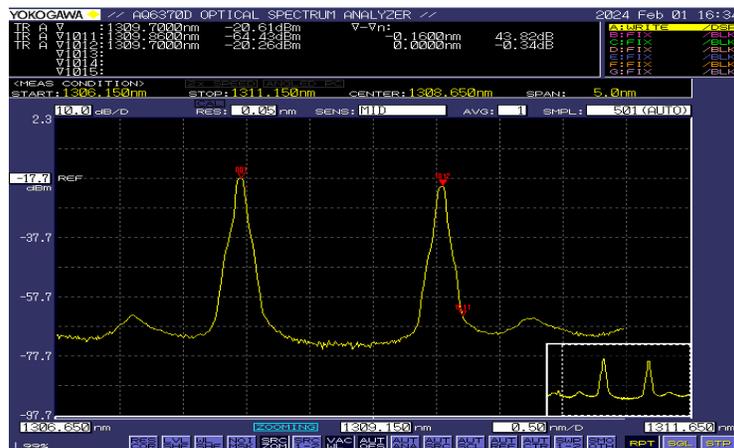


**Figure 8**. Multiplexed signal spectrum of 1309nm

## 3.2.     Scenario Simulation Results

OptiSystem software was used to simulate the analysis of wavelength division multiplexing (WDM) techniques and improve spectral efficiency in optical communication networks. This software facilitates the design and simulation of optical systems, including analysis in a GPON network. To carry out the simulation and compare the results with the measurements obtained, specific test scenarios were configured, which are detailed in this section.

The diagram is divided into three parts. The first corresponds to the transmission, represented by the OLT or transceivers. In the simulation, a 16-output WDM transmitter connected to our ideal multiplexer is used, where all signals are sent on the same channel and combined until the next process, as illustrated in Figure 9.
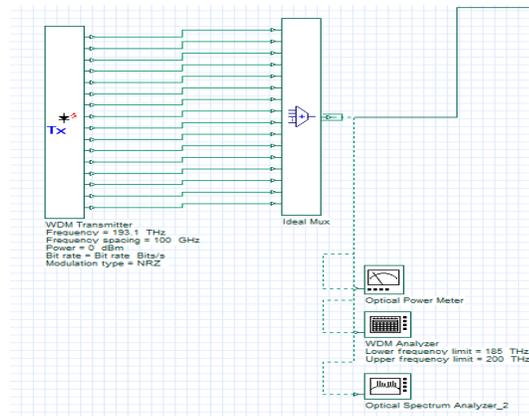
**Figure 9**. WDM Transmitter Module with respective WDM multiplexer

Figure 10 shows the second part of the multiplexing simulation diagram. This part is composed of two optical amplifiers with a gain of 20 dB and fibers with a distance of 40 km each. In addition, the respective OPMs are included to analyze the power passing through each amplifier and verify the state of both.
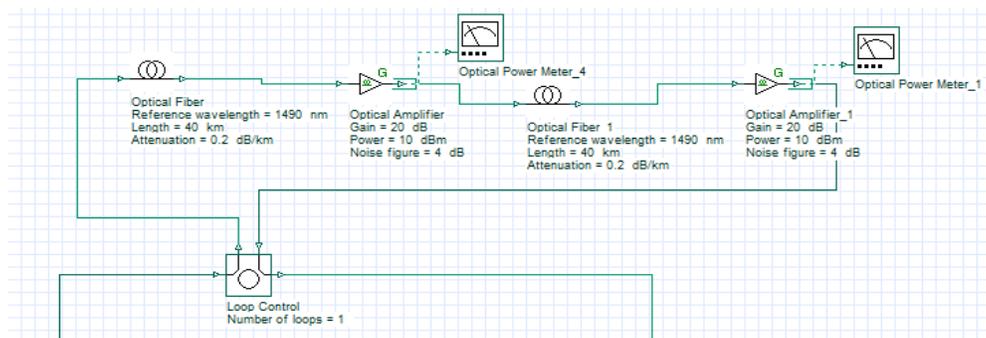


**Figure 10**. Feedback loop from transmitter to receiver

Figure 11 shows the third part of the diagram corresponding to the multiplexing simulation. This section includes a modulator, two optical receivers and the respective meters to obtain the relevant measurements. In addition, two optical amplifiers with a gain of 20 dB and 40 km long fibers are integrated in this segment of the diagram.
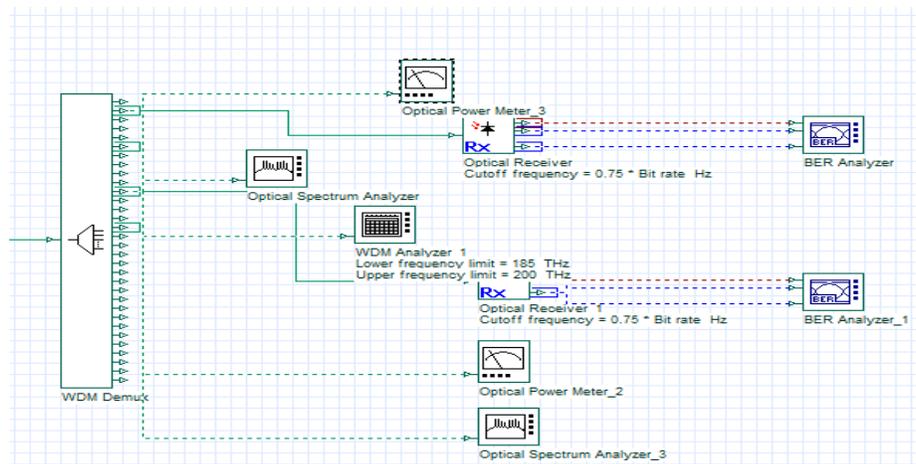
**Figure 11**. 32-output demodulator and optical receivers

The multiplexing simulation part of the diagram is shown, including the optical spectrum analyzer, WDM analyzer, OPM, and BER analyzer, as illustrated in Figure 12. In addition, the eye diagram of the analyzed optical network is presented.
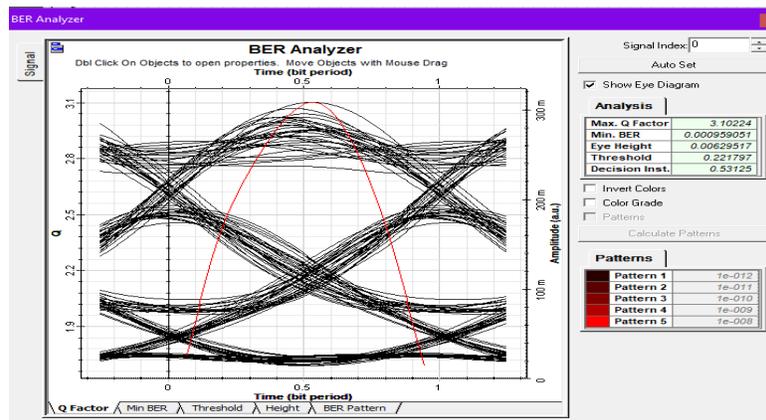


**Figure 12**. BER Analyzer Results

The results obtained in the simulation through OptiSystem will determine the efficiency of a simulated equipment as a possible result to be obtained in the field. The results, as shown in Figure 13, were obtained in the simulation of multiplexing techniques using OptiSystem, with the following parameters of channel speed, spacing and distance.
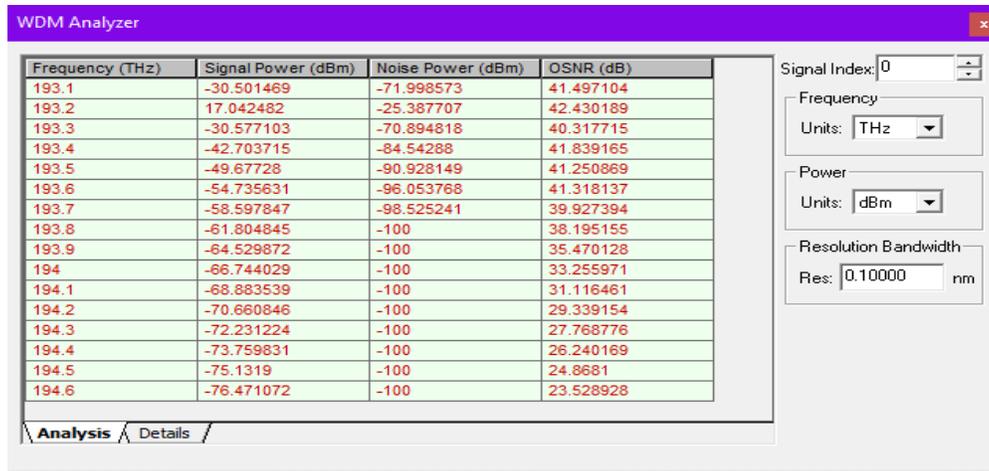
**Figure 13**. Results of the WDM Analyzer

Figure 14 of the spectrum analyzer in the software used is presented, where it can be seen that all signals are continuous. This contrasts with an analysis using real equipment, where different wavelengths will generate several peaks, as described in the previous scenarios in this section.
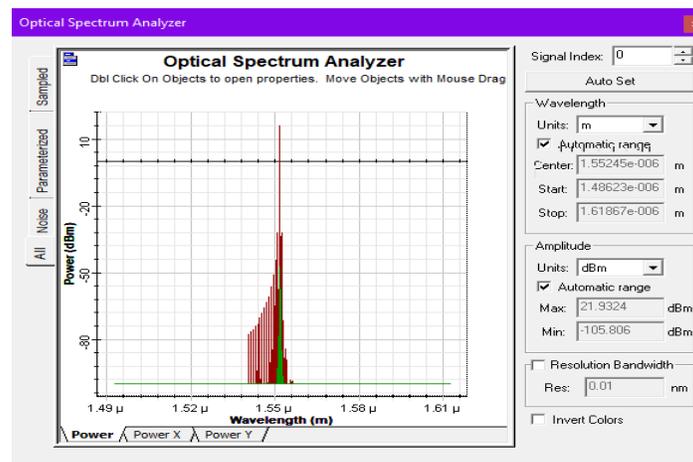


**Figure 14**. Spectrum analyzer results

## 4. DISCUSSION

The author provides a table of nominal wavelengths with which he performs the respective simulations and tests in OptiSystem for DWDM modulation, using wavelength 1530nm, which would be the frequency conversion of 195.93 GHz (Sánchez Herrera & Jimmy Francisco, 2020).

The results obtained from the spectrum analyzer, as shown in Table 3, and the results obtained by the author in the simulation provide a reference point on how they are attenuated by approximately 3 dBm. These variations in the measurements can be attributed to various factors, such as cable condition and signal-to-noise factor, among others (Sánchez Herrera & Jimmy Francisco, 2020).

The results obtained from all the simulated measurements, including the eye diagram, show a Q factor $Q = 3.1022$ and a BER rate $BER = 95.9\ x10^{-3}$,which represents the superposition of different binary combinations in a specific time range or number of bits, as mentioned by the author (Chen et al., 2018). These results were obtained through simulations in OptiSystem for a DWDM modulation scenario with a distance of 80 km at 100 GHz.

Furthermore, it was found that the 1490 nm wavelength, with a power of -82.737 dB, showed the highest efficiency, reaching a prototype performance of 87.5%. However, the simulation in OptiSystem yielded a value of -76.471 dB. This suggests that the simulation may not accurately reflect the results of the WDM technique in practice, possibly due to various factors intrinsic and extrinsic to the optical fiber, such as splice and connector losses, which also influence these measurements(Sánchez Herrera & Jimmy Francisco, 2020).

The results obtained by the author reveal a much cleaner eye diagram compared to the results obtained in this study. In this investigation, several input signals were evaluated at different wavelengths, including a video signal, with gains of 17 dBm (D. K. Verma & Garg, 2023).

The authors highlight the evolution of the various transceivers in PON networks, referring to the high migration rates ranging from 25 Gb/s to 50 Gb/s. This reflects how the analysis in GPON networks is evolving with the introduction of different transceivers, as shown in the results of the present study for the 1311 nm, 1492 nm, and 1552 nm multiplexed signal spectrum (Houtsma et al., 2021).

## 5. CONCLUSIONS

WDM multiplexing has emerged as an efficient and economical solution to increase transmission capacity in communication networks, achieving an optimum efficiency of 87.5%, in contrast to possible analyses in OptiSystem that could show a simulated efficiency between 5.5% and 10% lower than the actual efficiency of the analysis. By enabling the simultaneous transmission of multiple signals, WDM optimizes the utilization of existing infrastructures, resulting in higher efficiency and lower costs compared to other transmission techniques. However, WDM also poses certain considerations and challenges, such as signal amplification, especially over long distances where the signal can be weakened. Therefore, it is necessary to employ optical amplifiers in the network to maintain signal quality and compensate for losses, especially over 40 km in some cases.

This study has helped to clarify the complex processes involved in fiber optic switching, OLT and ONU configuration, power measurements, and signal quality improvement. The detailed exploration covers various components and equipment used in these systems, such as splitters, transceivers, optical spectrum analyzers, and routers. In addition, methods and techniques for data collection and network performance analysis are discussed.

# REFERENCIAS

Alipour, H., Fazaeli, M. H., & Keramat, M. M. (2022). Using the smart tags technology in power system substation automation. *Proceedings of the 16th International Conference on Protection and Automation of Power Systems, IPAPS 2022*. https://doi.org/10.1109/IPAPS55380.2022.9763148

CARLOS GUERRA ALTAMIRANO. (2021). *PARAMETRIZACIÓN DE SISTEMAS MULTIPLEXADOS EN LONGITUD DE ONDA MEDIANTE HERRAMIENTAS DE SIMULACIÓN: DESARROLLO DE PRÁCTICAS DE LABORATORIO NO-PRESENCIALES*. oai:oa.upm.es:67560

Chen, X., Macho, A., & Horche, P. R. (2018). Performance evaluation of 100 and 200-Gb/s WDM PM-QPSK transmission systems: tolerance analysis to the optical link impairments according to the optical carrier shape. *Optical Review*, *25*(6), 663–677. https://doi.org/10.1007/s10043-018-0463-y

Choyon, A. S. J., & Chowdhury, R. (2022). Multifunctional chalcogenide (As2S3, As2Se3) dual-core photonic crystal fiber with elliptical air-hole for mid-IR optical communications: Design and analysis. *Optik*, *258*. https://doi.org/10.1016/j.ijleo.2022.168857

Ding, H., Wu, Z., Mao, Y., Wang, X., Wu, Q., Cheng, Y., Li, Y., Chang, T., & Ji, R. (2022). Combo-PON OLT Transceiver Using Photonic Integration Technology. *IEEE Photonics Journal*, *14*(5). https://doi.org/10.1109/JPHOT.2022.3205783

Fukai, C., Abe, Y., Takaya, M., Koyama, R., & Katayama, K. (2020). Investigation into the Influence of High-Power Optical Transmission on Fiber Withdrawal from Optical Connector. *Journal of Lightwave Technology*, *38*(18), 5128–5135. https://doi.org/10.1109/JLT.2020.2998133

Houtsma, V., Mahadevan, A., Kaneda, N., & Van Veen, D. (2021). Transceiver technologies for passive optical networks: Past, present, and future [Invited Tutorial]. *Journal of Optical Communications and Networking*, *13*(1), A44–A55. https://doi.org/10.1364/JOCN.403500

Kato, T., Watanabe, S., Yamauchi, T., Nakagawa, G., Muranaka, H., Tanaka, Y., Akiyama, Y., & Hoshida, T. (2020). Multi-Band WDM Transmission Technology Exceeding Transceiver Wavelength Band. *2020 Opto-Electronics and Communications Conference (OECC)*, 1–3. https://doi.org/10.1109/OECC48412.2020.9273578

Keiser, G. (2021). Fiber Optic Communications. In *Fiber Optic Communications*. Springer Singapore. https://doi.org/10.1007/978-981-33-4665-9

Krivosheev, A. I., Barkov, F. L., Konstantinov, Y. A., & Belokrylov, M. E. (2022). State-of-the-Art Methods for Determining the Frequency Shift of Brillouin Scattering in

Fiber-Optic Metrology and Sensing (Review). *Instruments and Experimental Techniques*, *65*(5), 687–710. https://doi.org/10.1134/S0020441222050268

Kuroda, K. (2022). Wavelength-Division Multiplexed Interrogation of FBGs Using a Distributed-Feedback Laser Array. *IEEE Photonics Technology Letters*, *34*(10), 509–512. https://doi.org/10.1109/LPT.2022.3168853

Luan, J., Wang, Y., Zhang, Z., Zhang, Y., & Tsang, H. K. (n.d.). *Multimode Wavelength Division Demultiplexing Based on an Angled Multimode Interference Coupler*.

Maslo, A., Goran, N., Hodzic, M., Skaljo, E., & Mujcic, A. (2020, November 24). A practical analysis of attenuation in segment of home installation of FTTH networks. *2020 28th Telecommunications Forum, TELFOR 2020 - Proceedings*. https://doi.org/10.1109/TELFOR51502.2020.9306628

Niu, C., Liu, Z., Li, X., Liu, X., Wan, F., Zheng, J., Cheng, B., Xue, C., & Zuo, Y. (2020). High Extinction Ratio Polarization Beam Splitter Realized by Separately Coupling. *IEEE Photonics Technology Letters*, *32*(18), 1183–1186. https://doi.org/10.1109/LPT.2020.3016028

r Achyut K. Dutta, Niloy K. Dutta, & Masahiko Fujiwara. (n.d.). *WDM Technologies: Passive Optical Components, Volumen 2*. Retrieved January 26, 2024, from https://www.sciencedirect.com/book/9780122252624/wdm-technologies

Rodriguez, A. B., Ramirez, L. J., & Basile, F. R. M. (2017). Solución metaheurística para el problema de enrutamiento (RWA) en redes de ópticas de multiplexación por división de longitud de onda (WDM). *Informacion Tecnologica*, *28*(6), 133–146. https://doi.org/10.4067/S0718-07642017000600015

Sadin, S. I., Billah, A. B., Ahad, M. A., Fahim, K. S., Mitra, P., Shawon, D. S., & Shorna, R. T. (2022). Design and Performance Evaluation of a Gigabit Passive Optical Network (GPON) Through Fiber-To-The-Home (FTTH) Technology. *International Conference on Recent Progresses in Science, Engineering and Technology, ICRPSET 2022*. https://doi.org/10.1109/ICRPSET57982.2022.10188562

Sánchez Herrera & Jimmy Francisco. (2020). *Análisis de las técnicas de Multiplexación por división de longitud de onda (WDM) y su simulación mediante el software OptiSystem*. http://repositorio.ucsg.edu.ec/handle/3317/14188

Santillán Carranza, H. J., Wong Wong, P., Romero Alvarado, K. E., & Huayamave Cordero, M. J. (2024). Implementación de un Sistema Meteorológico Educativo Usando IoT y Rasperry PI. *INGENIO*, *7*(2), 4–17. https://doi.org/10.29166/ingenio.v7i2.5265

Smith, J., & Jones, A. (n.d.). *Avances en la multiplexación por longitud de onda en redes ópticas. Revista de Comunicaciones Ópticas*. https://doi.org/10.1234/rco.2020.012345

Takahashi, K., Roberts, R., Jiang, Z., & Memarzadeh, B. (2021). Statistical Evaluation of Signal-to-Noise Ratio and Timing Jitter in Equivalent-Time Sampling Signals. *IEEE Transactions on Instrumentation and Measurement*, *70*. https://doi.org/10.1109/TIM.2021.3078003

Tomoyuki Kato, Shigeki Watanabe, Goji Nakagawa, Hidenobu Muranak, Yu Tanaka, & Takeshi Hoshida. (n.d.). *Multi-Band WDM Transmission Technology Exceeding Transceiver Wavelength Band*. https://doi.org/https://doi.org/10.1109/OECC48412.2020.9273578

Verma, D. K., & Garg, A. K. (2023). Analysis with gain and power for better coverage of FTTH network using WDM-PON architecture. *Journal of Optics (India)*, *52*(4), 1903–1911. https://doi.org/10.1007/s12596-023-01098-w

Verma, S., Kakati, A., Luckysaurabh, & Bhulania, P. (2016). Performance analysis of Q-factor and polarization for GPON network using optisystem. *2016 International Conference on Information Technology (InCITe) - The Next Generation IT Summit on the Theme - Internet of Things: Connect Your Worlds*, 138–141. https://doi.org/10.1109/INCITE.2016.7857605

Wang, R., Chen, L., Yang, N., Du, Y., Zhang, C., & Zhang, X. (2022). Performance Improvement of Frequency-Domain Light Intensity Spectrum Analyzer (f-LISA). *Journal of Lightwave Technology*, *40*(14), 4663–4673. https://doi.org/10.1109/JLT.2022.3168055

Wang, S., Yang, H., Qin, Y., Peng, D., & Fu, S. (2022). Power-Over-Fiber in Support of 5G NR Fronthaul: Space Division Multiplexing Versus Wavelength Division Multiplexing. *Journal of Lightwave Technology*, *40*(13), 4169–4177. https://doi.org/10.1109/JLT.2022.3159540

Xu, W., Huang, L., Xu, Y., Jiang, W., Hu, W., Ke, G., & Yi, L. (2022). SOA Assisted Wavelength Reusing for 25G Colorless PON with Low-Cost 10G EAM. *IEEE Photonics Journal*, *14*(3). https://doi.org/10.1109/JPHOT.2022.3172118

Zhang, J., Wu, N., Ge, F., Zhou, F., & Xu, W. (2021). Design of WDM-Based Optical Networks-on-Chip Router for Low Insertion Loss and Crosstalk. *2021 IEEE 4th International Conference on Electronics Technology, ICET 2021*, 1068–1072. https://doi.org/10.1109/ICET51757.2021.9451093

Zhao, Z., Zhang, Z., Shi, H., Jia, Y., Li, Y., Zhao, Y., & Feng, Z. (2022). Field Trail of Shared Risk Optical Fiber Links Detection Based on OTDR and AI Algorithm. *Asia Communications and Photonics Conference, ACP*, *2022-November*, 1942–1945. https://doi.org/10.1109/ACP55869.2022.10088875