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Study of HFC Networks in Educational Contexts

(Estudio de Redes HFC en Contextos Educativos)

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Abstract: This paper presents the proposed design of a Hybrid Fiber-Coaxial (HFC) network for the optical communications laboratories of an academic institution. This infrastructure combines optical fiber and coaxial cable to ensure efficient and robust connectivity, especially adapted to the needs of academic and research laboratories. The design includes key stages such as backbone planning, optical distribution and power supply, prioritizing the use of optical fiber for data transmission, which ensures high performance and capacity suitable for large data volumes. This work provides a comprehensive view of HFC network design, highlighting how this technology improves internal connectivity and facilitates collaboration and data exchange between different academic and research areas.

Keywords: HFC network, academic research, backbone network, fiber optics, communication infrastructure.

Resumen: Este artículo presenta la propuesta de diseño de una red HFC (Fibra Híbrida-Coaxial) para los laboratorios de comunicaciones ópticas de una institución académica. Esta infraestructura combina fibra óptica y cable coaxial para garantizar una conectividad eficiente y robusta, especialmente adaptada a las necesidades de los laboratorios académicos y de investigación. El diseño incluye etapas clave como la planificación de la red troncal, la distribución óptica y la alimentación, priorizando el uso de fibra óptica para la transmisión de datos, garantizando un alto rendimiento y una capacidad adecuada para grandes volúmenes de datos. Este documento ofrece una visión completa del diseño de redes HFC, destacando cómo esta tecnología mejora la conectividad interna y facilita la colaboración y el intercambio de datos entre diferentes áreas académicas y de investigación.

Palabras clave: red HFC, investigación académica, red troncal, fibra óptica, infraestructura comunicación.

1. INTRODUCTION

HFC (Hybrid Fiber-Coaxial) networks have evolved over this time as a result of transformations in cable television distribution networks. This evolution was motivated by the significant increase in channel supply, which generated a growing demand for bandwidth. To address this challenge, cable networks evolved from the utilization of coaxial cables to the implementation of optical transmission technology. This transition allowed for substantial improvements in reliability and transmission capacity, giving rise to multi-service HFC networks [1].

Telecommunications encompass a variety of technologies and services, requiring networks that integrate various services with different capabilities and quality. HFC networks are emerging as an alternative to achieve this integration. While fiber-based architectures, such as FTTH (Fiber To The Home) and FTTC (Fiber To The Cabinet), are uneconomical due to the investment required, fiber optics offer advantages in terms of distance and transmission speed, being ideal for backbone and distribution links in metropolitan networks [2].

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HFC networks are divided into trunks, optical distribution and feeders, where coaxial is used to minimize costs. Typical configurations include star, bus, or tree connections. In these networks, the asymmetrical cable modem manages data access. In small municipalities, the infrastructure comprises the headend, splitters, and ONU (Optical Network Units), the latter being terminal nodes connected to the coax, with each ONU, covering about 500 subscribers. The challenge lies in balancing cost-effectiveness with network survival in these areas [3].

An HFC network is a network technology that combines fiber optic and coaxial cable components to provide communication services, such as cable television, high-speed Internet access, and telephony. The HFC infrastructure uses fiber optics for high-speed data transmission and coaxial cable for signal distribution to homes and businesses [4].

The CATV (Community Antenna Television) system or community television antenna is a system that allows the transmission of television signals by radio frequency through a guided medium such as coaxial cable or fiber optics. Originally, CATV networks were designed for the one-way transmission of television signals, but over time, the demand for broadband and two-way communication services, especially with the popularization of the Internet, led to the need to improve these networks [5].

The implementation of fiber optics as in HFC networks allows a greater bandwidth capacity, being able to cover many more services by the same medium and with much faster transmission speeds. The combination of fiber and coaxial cable provides a cost- and performance-efficient solution to deliver advanced multimedia and communication services to end users [6].

HFC networks have undergone a significant evolution, driven by changes in cable television distribution networks. This process was motivated by the increase in the supply of channels and the growing demand for higher bandwidth capacity. In response to this challenge, cable networks have replaced coaxial cables with optical transmission technology, which has led to significant improvements in reliability and transmission capacity, resulting in multiservice HFC networks. The combination of optical fiber and coaxial cable in these networks is presented as an efficient option for integrating various services in telecommunications.

Despite the advantages offered by fiber-based architectures, such as FTTH (Fiber To The Home) and FTTC (Fiber To The Cabinet), in terms of distance and transmission speed, their implementation in educational environments can be costly. Therefore, HFC networks are positioned as a more economical and practical solution in this context. This project aims to design an HFC network adapted to the needs of the optical communications laboratories of an educational institution, providing a robust and efficient connectivity infrastructure to support academic and research activities. The proposed design encompasses backbone planning, optical distribution and powering, prioritizing the use of fiber optics to ensure efficient transmission of large volumes of data, and improving internal connectivity to support collaboration and information exchange between different academic areas.

1.1. Optical Power Calculation in Fiber

The optical power in an optical fiber is determined by the formula: (P)

$$P = \frac{E}{t} \tag{1}$$

Where:

- P is the optical power (mW).
- E is the transmitted optical energy (mJ).
- T is the time during which the energy(s) was transmitted.

For example, to calculate the optical power when a light source emits 2 milli Jules of energy over a period of 5 seconds. The formula is applied as resulting in where:

$$P = \frac{2mj}{5\,s} \quad (2)$$

This result indicates that the optical power in the optical fiber is 0.4 milliwatts during the 5-second interval $P = 0.4\,mW$.

In experimental or industrial contexts, this calculation could be crucial for evaluating the performance of an optical transmission system [7].

1.2. Channel Traffic Calculation

The goal of the traffic model is to establish a probability distribution for the number of TV channels watched simultaneously, for a given content popularity and user demand. In other words, you have to find out how the simultaneous requests from users R more than N available TV channels are distributed.

Variables

Where

- Variables is channels that are not requested. $NX_n = 0$.
- If the channel is requested once. $X_n = 1$.
- When it's possible that a particular user is made for the channel to request, the corresponding odds for are: $q_{(n)} n X_n$.

$$\left.\begin{array}{r} \text{Prob } [X_n = 0] = (1 - \text{q(n)})^R = p1(n) \\ \text{Prob } [X_n = 1] = 1 - (1 - \text{q(n)})^R = 1 - p1(n) \end{array}\right\} \quad (3)$$

Where

- Prob is the possibility for all requests to be made for one of the other channels in addition to the channel and this opportunity is for each of the individuals (and independents). $[X_n = 0] N - 1n\left(1 - \text{q(n)}\right)R$.
- Defined as the ability to determine channels that are not requested: Pi

$$\left.\begin{array}{r} p_1(n) = \left(1 - q(n)\right)^R \\ p_2(j,k) = \left(1 - q(j) - q(k)\right)^R,\ j \neq k \end{array}\right\} \quad (4)$$

The goal is to find the probability distribution for the total number of TV channels watched simultaneously, i.e., channels requested by at least one user:

$$\Upsilon = \sum_{n=1}^{N} X_n \quad (5)$$

γ is the sum of a large number of statistically independent variables (N variables in total).

$$\text{P(y)} = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(y-\mu)^2}{2\sigma^2}} \quad (6)$$

1.3. Related Works

With the advancement of individual, intelligent and interactive broadcasting, comes the need for an ultra-high-speed converged network to deliver high-quality 3D multimedia services. Within this framework, a cable transmission technology has been developed that exceeds the frequency efficiency of conventional methods by more than 30 %. In North America, CableLabs has created the DOCSIS 3.1 standard, while Europe has developed the DVB-C2 standard. In addition, in 2012, IEEE 802.3 began developing EPoC (Ethernet Passive Optical Network over Coax)to support EPON (Ethernet Passive Optical Network) 1G/10G interfaces in hybrid fiber optic and coaxial cable networks[8], [9].

In response to growing data traffic, cable TV providers are upgrading their HFC networks and adopting mixed multicast and unicast models to meet the demand for high-quality video and improve the customer experience. Introducing a software-based bandwidth solution to enhance the HTTP Adaptive Streaming (HAS) experience on hybrid fiber and coax networks. The proposal optimizes the delivery of content to any device, addressing common problems, such as video instability and uneven quality distribution. The solution allows scaling to many concurrent sessions without significant overhead [10].

Modern HFC networks serve millions of users, making it crucial for operators to ensure high availability of network access [11]. This requirement becomes even more critical with the rise of remote work. Therefore, it is essential to detect and locate network faults as early as possible, a complex task due to the large number of devices present in typical HFC networks. However, the abundance of devices also allows operators to collect huge amounts of valuable data for multiple purposes. In this context, the use of big data technologies in HFC networks is being adopted to manage this data efficiently [12], [13].

Nowadays, internet providers must offer a high-quality service. Performance monitoring is essential for network maintenance and to meet customer expectations. However, network operators face numerous challenges in this area. The current goal of operators is to provide an overview of the challenges in monitoring the performance of HFC networks by using Big Data as a solution to address these challenges [14], [15].

For a long time, hybrid fiber and coax networks have faced significant challenges due to limitations in upstream data rates [16]. With the growing demand for cloud services and the need to offer symmetrical services for various applications, operators have focused on exploring system architectures and concepts that can overcome these asymmetric limitations. This approach prepares these networks to meet the growing demand for symmetrical services. The feasibility of achieving symmetrical speeds of 10 Gb/s has been demonstrated by means of a prototype full-duplex transmission system, which is compatible with existing HFC networks [17], [18].

Capacity requirements in fixed access networks are increasing towards multi-gigabit connections. In hybrid coaxial fiber (HFC) networks, speeds of up to 30 Gbit/s are achieved by expanding the DOCSIS spectrum to 3 GHz, with spectral efficiency of approximately 10 bit/s/Hz. Eliminating spectrum-limiting components, such as passive HFC network branches, is crucial to achieving these speeds, versus the cost of fiber-to-the-home (FTTH) deployment. Transmission amplifier distortion and attenuation dispersion between frequencies are challenges in the extended spectrum, requiring new optimization strategies [19], [20].

2. METHODOLOGY

For the development of the network, it begins with the simulation of data transmission services through fiber optics. Using the OptiSystem program, the data transmission is modeled and the wavelengths are multiplexed. The results obtained from these simulations will be compared with data collected from physical equipment in a laboratory environment. This approach allows validating the accuracy of the simulations and ensuring that the theoretical results are aligned with the actual performance of the system [21].

Next, the physical equipment is connected and configured. The signals are generated using a laptop and an antenna, which through a modulator produce a copper-modulated signal. This signal is then transferred to a 1550 nm signal generator and connected to a multiplexer. The multiplexer combines data and television signals, transmitting them through a single fiber optic strand to the final recipient. This process is illustrated in Figure 1, which details the devices and connection scheme used in the project.

The integration of simulation and practice is crucial to ensure the reliability and efficiency of the network. Comparing the theoretical results with the practical ones allows possible discrepancies to be identified and corrected, thus optimizing the design and operation of the fiber optic network.

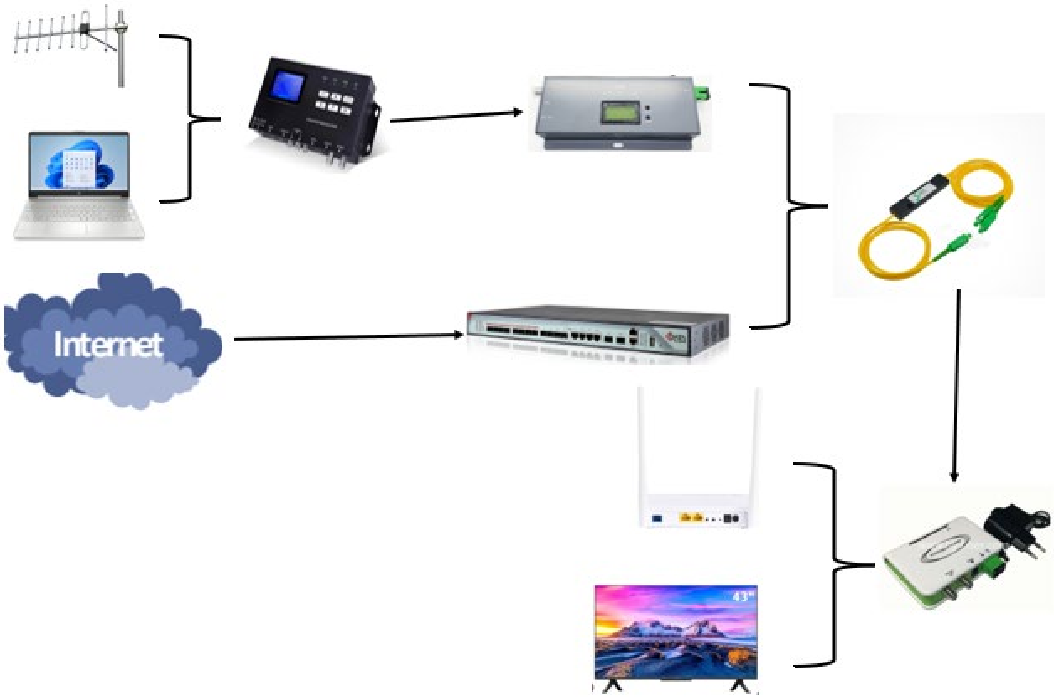

Figure 1. HFC Network Prototype.

To get started with the simulation, it is essential to set up an optical signal emitter in the three required wavelengths. This process involves several crucial components. First, you use a bit generator to create the sequence of data to transmit. A pulse generator then converts this data into optical pulses.

To generate the optical signals, lasers are used specifically for each of the desired wavelengths. These lasers are critical for defining the frequency and stability of transmitted signals. Once the optical signal is generated, it is modulated using a Mach-Zehnder modulator, which adjusts the phase of the optical signal to encode the information efficiently.

This modulated system ensures that signals are ready for transmission. Figure 2 illustrates this process in detail, showing the configuration of the equipment and the interconnection of the different components. In this figure, you can see how the bit and pulse generators, lasers, and the Mach-Zehnder modulator work together to produce the optical signals needed for the simulation.

It is important to consider the calibration and adjustment of each component to ensure the accuracy and reliability of the signals emitted. The modulation and transmission of optical signals must be carefully controlled to avoid distortion and data loss. This level of detail in the initial setup is crucial for accurate and comparable results during the later phases of the project.

This approach ensures that the emitted optical signals meet the required standards and are prepared to be multiplexed and sent over the fiber optic network, facilitating efficient and reliable data transmission.

It is essential to monitor the thermal stability of lasers and the Mach-Zehnder modulator, as temperature shifts can impact wavelength precision and modulator efficiency. Effective temperature control is integrated to maintain stable wavelength outputs, preventing interference and supporting clear signal separation. This stability improves signal fidelity, reduces cross-talk during multiplexing, and ensures the transmission equipment's reliability and longevity—key factors for the effective deployment and scalability of fiber optic networks.

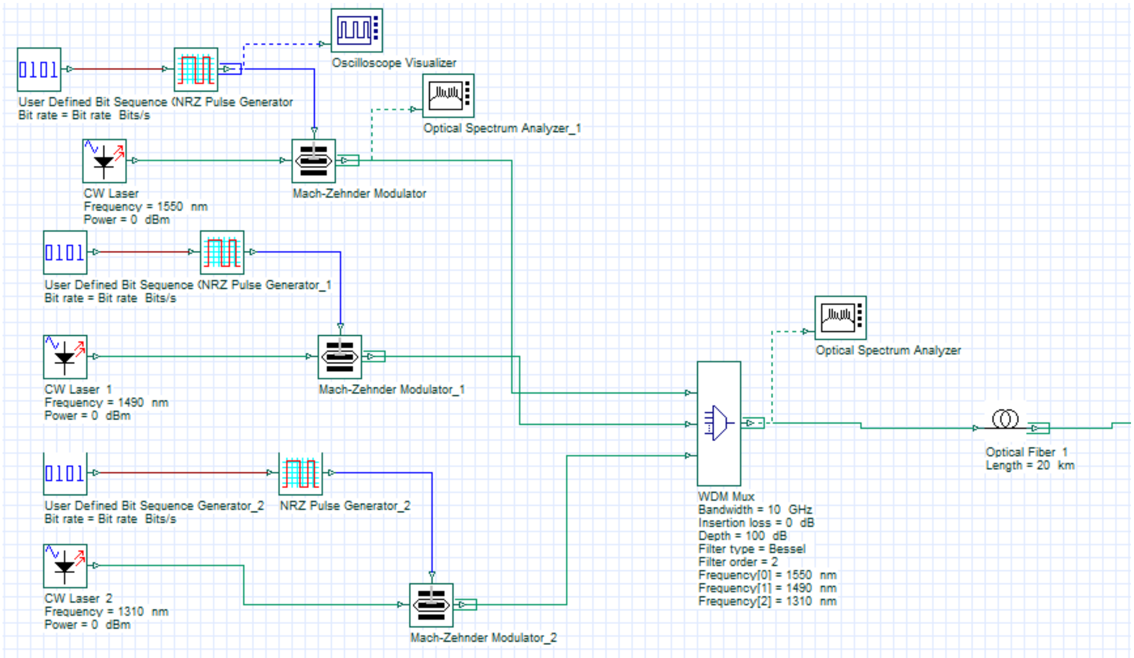

Figure 2. Simulation Topology.

It is worth mentioning that three wavelengths are needed, 1310 nm and 1490 nm necessary for the internet, one upstream and the other downstream respectively, and another signal for 1550 nm video. A WDM (Wavelength Division Multiplexing) multiplexer is added and then the number of input ports is changed, then the channels that the multiplexer will receive and then send over the fiber wire are configured. To analyze the wavelengths, a photodetector must be placed at the end of each port of the demultiplexer, with the BER (Bit error rate) analyzer you can see the eye diagram of the fiber.

Figure 3 shows the components necessary to analyze the wavelengths by means of simulation in Optisystems where a photodetector must be placed at the end of each port of the demultiplexer, with the BER analyzer you can observe the results of the simulation of the wavelengths being directed by the optical fiber. It is also possible to compare the data sent before passing through the multiplexer and at the end of the transmission.

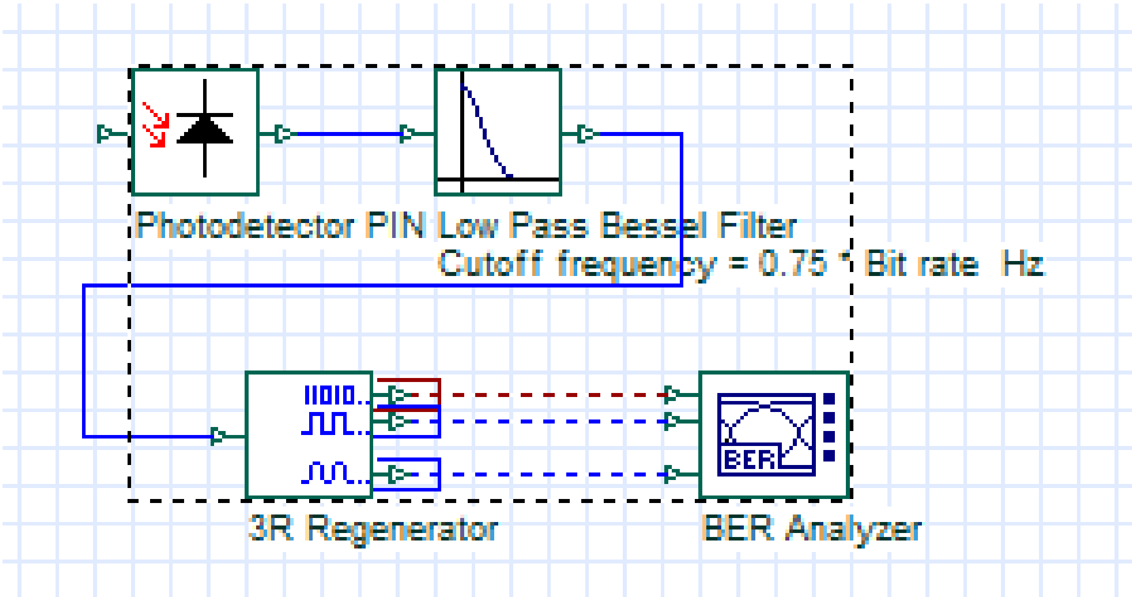

Figure 3. Reception Elements for Analysis.

The following is the diagram of measuring the signal after being multiplexed, demultiplexed, and converted back into an electrical signal, as illustrated in Figure 4. The resulting graphs will be analyzed and compared with the initial measurements.

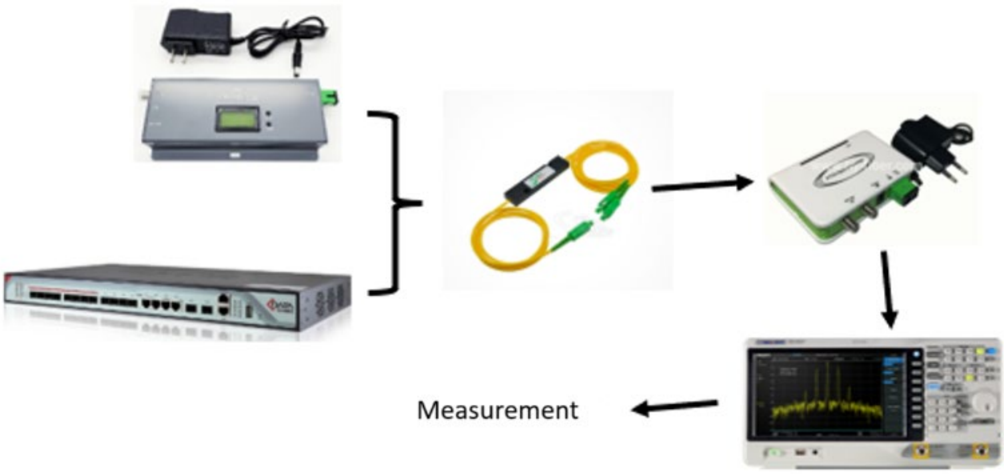

Figure 4. Measurement at CATV receiver output.

3. ANALYSIS OF RESULTS

Using the Siglent spectrum analyzer, data will be captured at the output of the modulator to study the spectrum of the ISDB-T (Integrated Services Digital Broadcasting - Terrestrial) signal to be transmitted. Initially, the modulation frequency and output power will be observed, as shown in Figure 5. Then, the signals will be measured after being multiplexed, demultiplexed and converted back to electrical signals. These measurements will be carried out both at the point of transmission and at the point of reception, ensuring a comprehensive evaluation of the process.

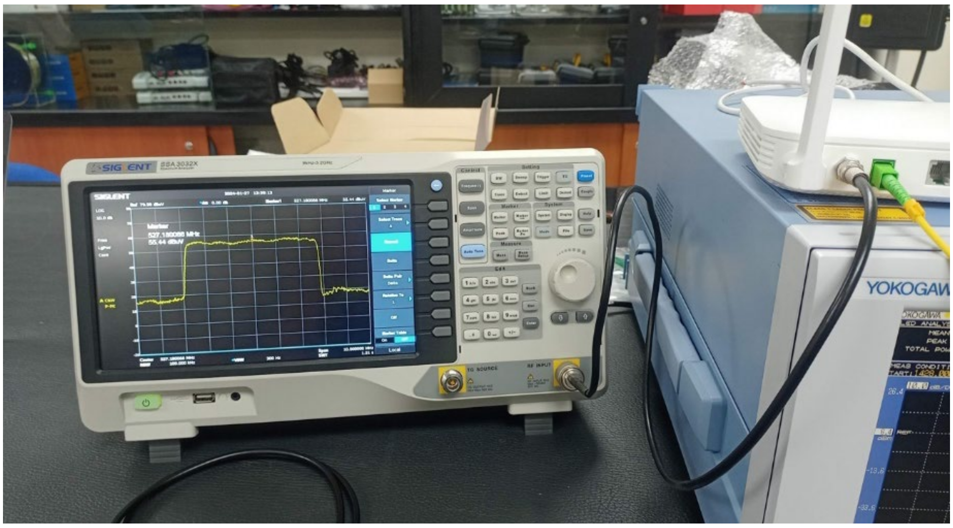

Figure 5. Spectrum Analyzer on the output of the ISDB-T modulator.

The graphs obtained at each stage will be carefully analyzed and compared with the initial measurements to evaluate the integrity of the signal and the efficiency of the transmission process. In particular, attention shall be paid to any distortion or loss of quality that may occur during multiplexing and demultiplexing. The collection of data at the end of the transmission, at the receiver's input for CATV, makes it possible to verify that the received signal maintains the characteristics necessary for a high-quality transmission. This systematic approach ensures the reliability and accuracy of the results.

Then, data will be collected at the output of the multiplexer to demonstrate how the different wavelengths pass through the optical fiber, complying with the principles of WDM multiplexing. In this process, both the power of the signals and the graphics generated will be analyzed. As illustrated in Figure 6, the Yokogawa optical spectrum analyzer will be used to identify the peaks of the wavelengths that transit the optical fiber, as well as the power with which they are transmitted.

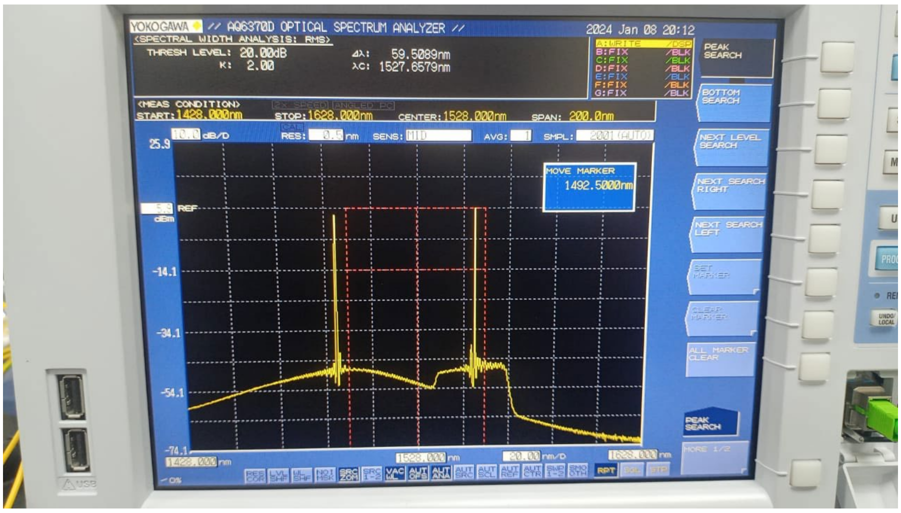

Figure 6. peaks of transmitted wavelengths and power.

In addition, measurements are presented before and after the signal passes through a 4-port splitter, simulating FTTH transmission. This evaluation allows comparing losses at different points in the transmission process, providing a detailed understanding of the efficiency and quality of the implemented system. By analyzing these measurements, it will be possible to identify and mitigate potential loss points and optimize the performance of the prototype in real conditions.

To visualize the spectrum of the generated signal, it is essential to connect the modulator output to the spectrum analyzer, as detailed in Figure 7. This procedure is essential to examine and study the various wavelengths that propagate through optical fiber, thus simulating FTTH transmission. This configuration makes it easy to evaluate the effectiveness of WDM multiplexing and verify the power of the transmitted signals, ensuring the optimal quality and performance of the implemented system.

Figure 7. Connecting equipment with coaxial cable.

As can be seen in Figure 8 and in the results obtained with the BER analyzer in the output of the multiplexer, the three wavelengths that cross the optical fiber are identified. This finding highlights the ability to effectively use transmission windows for data transfer. This means that it is feasible to use a single single-mode fiber strand to carry out simultaneous transmission at three different wavelengths, thus optimizing spectrum usage and improving the efficiency of the transmission system.

The eye diagram is a graphical representation that visualizes both the noise that can impact our signal and the level of quality that is achieved in the output, offering a clear view of the potential quality of the transmitted signal. This diagram shows two intersecting sinusoidal lines; The sharpness of these intersections is crucial, as it indicates the quality and efficiency of the service transmission. In addition, two horizontal and vertical lines can be distinguished in the diagram that represent the level of noise generated by the system. Figure 9 shows two horizontal lines that do not disturb the sinusoidal lines, confirming that the noise is not adversely affecting the quality of the service transmitted.

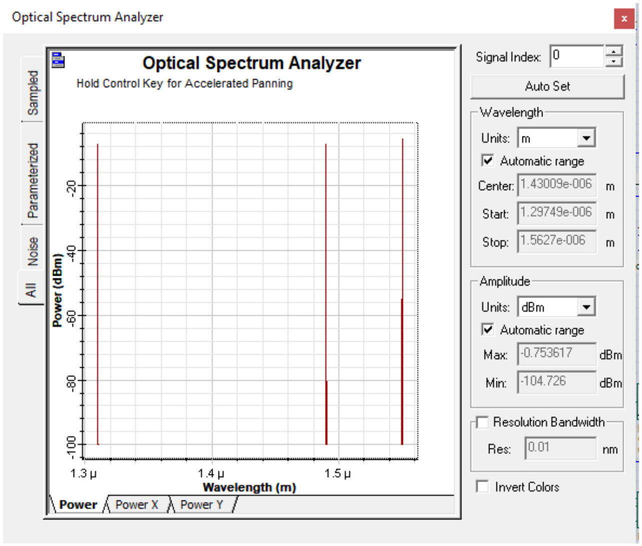

Figure 8. Optical spectrum analyzer result at Optisystems.

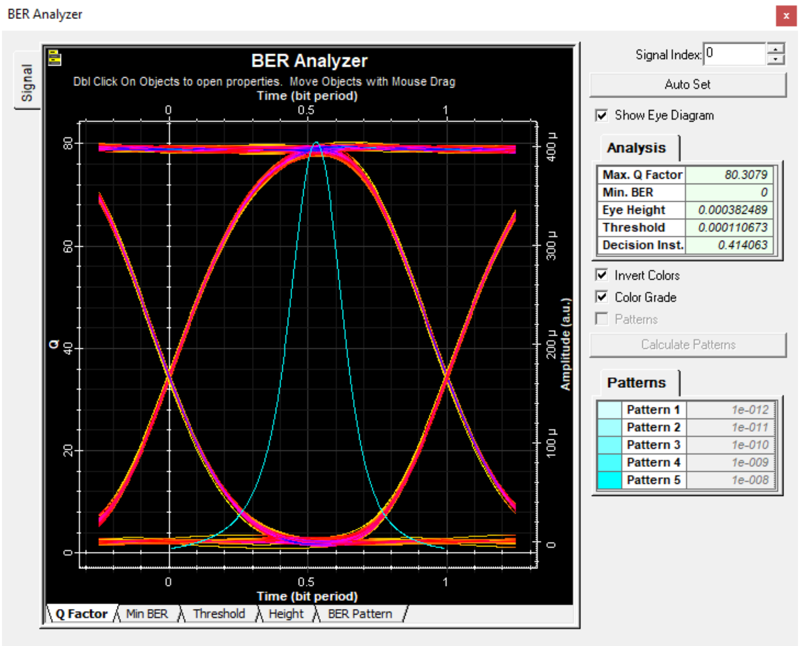

Figure 9. Diagram of eye to optical signal output.

The above result analyzes the comparison between the data sent and received before and after the multiplexing process. Figure 10 shows that the transmitted bits, visualized as pulses to the left, closely match the data captured in the output of the transmission system. This finding indicates that the simulated data is not lost during the multiplexing process, despite having been combined with different wavelengths.

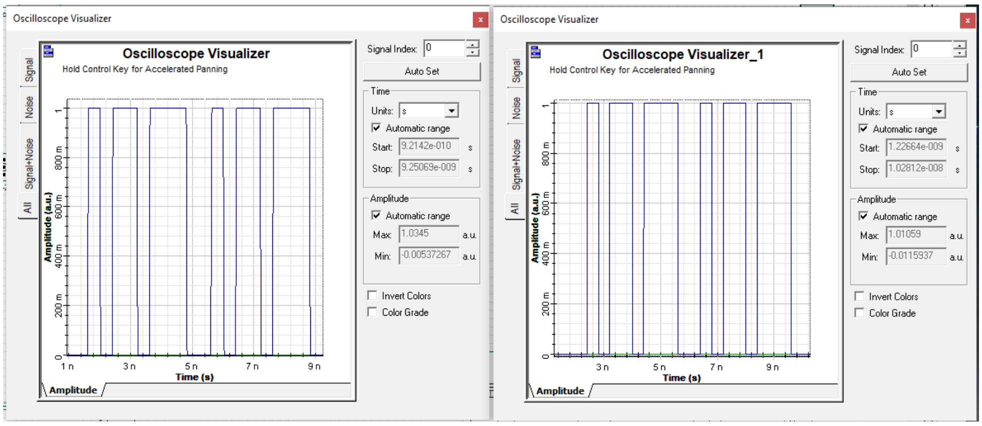

Figure 10. Oscilloscope bits at the start and end of transmission.

Figures 11 and 12 provide a detailed visualization of the electrical signal spectrum at two key points in the system. Figure 11 shows the spectrum of the electrical signal at the output of the ISDB-T modulator, where the information is transmitted at 527 MHz with an initial power of 75.93 dBuV. This initial stage shows the signal in its electrical form before being converted for optical transmission.

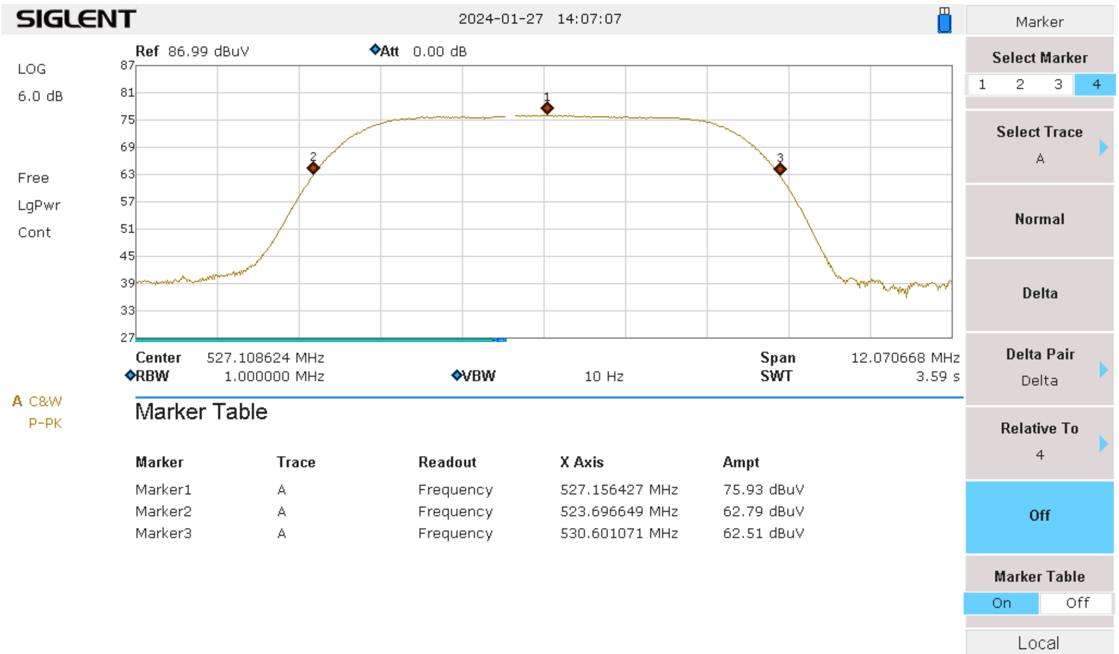

Figure 11. Spectrum of the signal to the output of the ISDB-T modulator in Spectrum Analyzer.

Subsequently, in Figure 12, the spectrum of the signal is presented after having gone through the complete process of transmission and reception. This signal, now transformed into optical, multiplexed, demultiplexed and finally reverted to its electrical form, shows that the transmission frequency has remained intact. However, a reduction in transmission power is observed, now measured at 66.02 dBuV. This phenomenon underscores the effectiveness of the system in preserving the integrity of the transmission frequency through the various stages of the process.

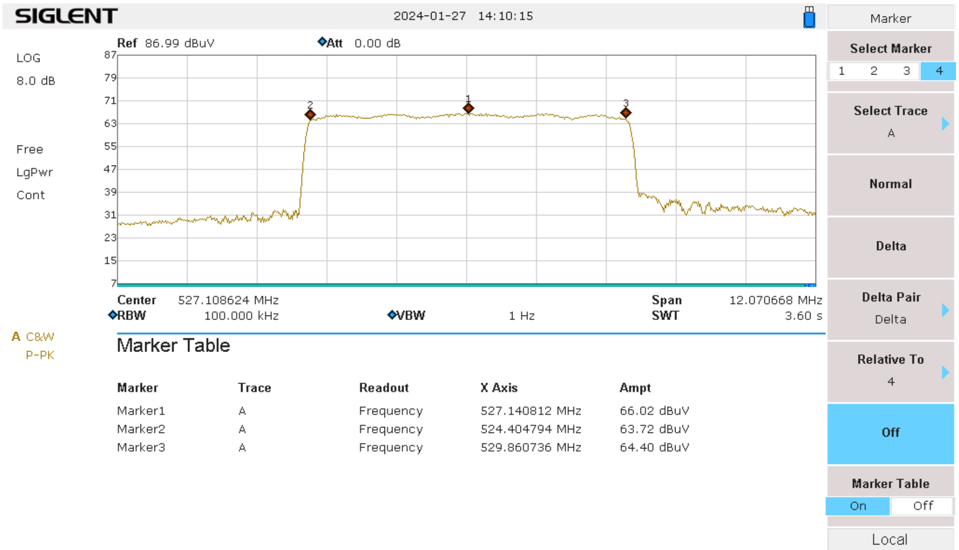

Figure 12. Signal spectrum to CATV receiver output.

The comparison between Figures 11 and 12 underscores the importance of each step in the transmission process. While Figure 11 shows the signal in its initial form before optical conversion, Figure 12 illustrates how the signal behaves after it has passed through the complete optical transmission infrastructure. This detailed analysis reveals that although the signal strength is slightly reduced, the transmission frequency remains stable, thus validating the efficiency of the system for effective data transfer through different technological stages. This means that it was possible to transform the information from an electrical signal to an optical signal using a wavelength to be transmitted.

Figures 13, 14 and 15 provide a detailed visualization of the optical spectrum comprising the three wavelengths critical to data transmission: 1492 nm, 1310 nm and 1552 nm, respectively. Each of these graphical representations not only illustrates the distribution of transmit power in specific nanometers, but also highlights how these frequencies are employed in hybrid coaxial fiber (HFC) networks, which are the main focus of our current project.

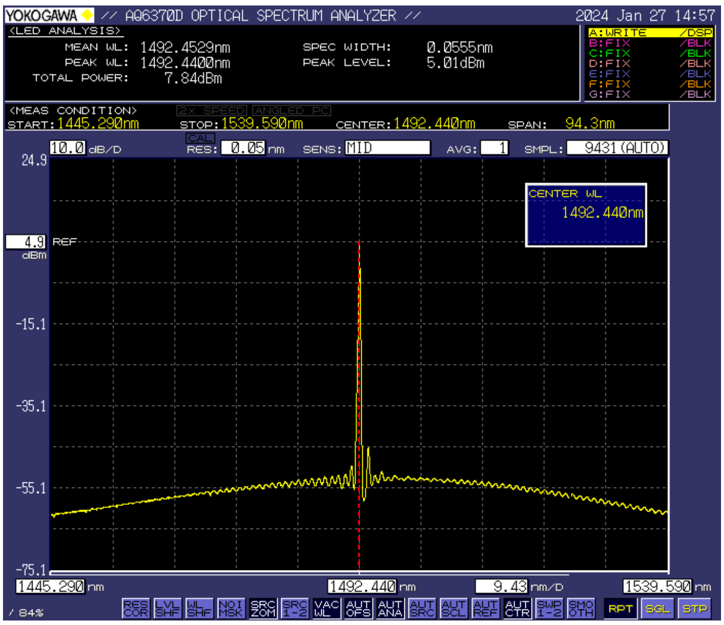

Figure 13. Wavelength spectrum of 1492 nm.

These visual representations play a crucial role in providing insights into how optical signals are distributed across various wavelengths within the HFC infrastructure. Each wavelength is carefully calibrated to ensure efficient and effective data transmission, taking into account the unique characteristics of each segment of the optical spectrum.

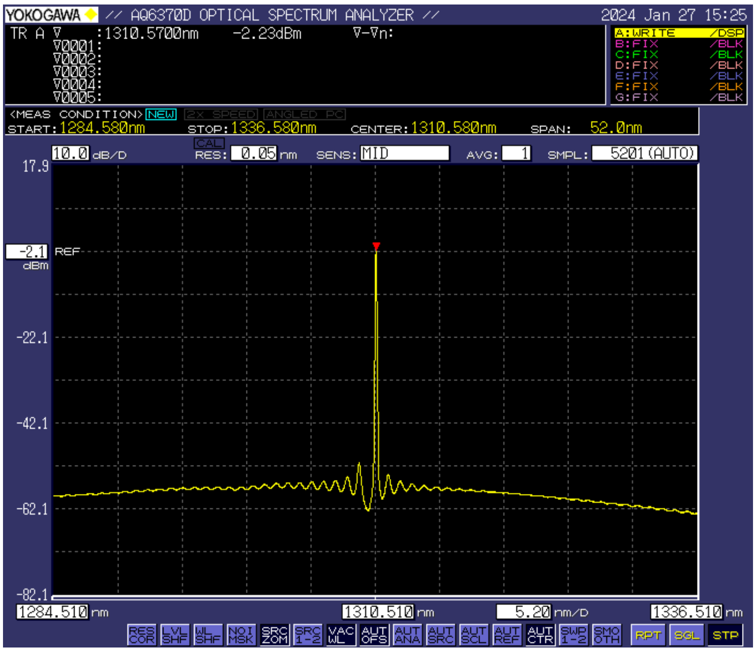

Figure 14. 1310 nm wavelength spectrum.

In the context of our project, these figures are essential as they offer a clear demonstration of how multiplexing and demultiplexing techniques allow the combination and separation of signals at multiple wavelengths. This not only optimizes the network's ability to handle increasingly large and diverse data loads, but also ensures optimal performance in terms of efficiency and transmission quality.

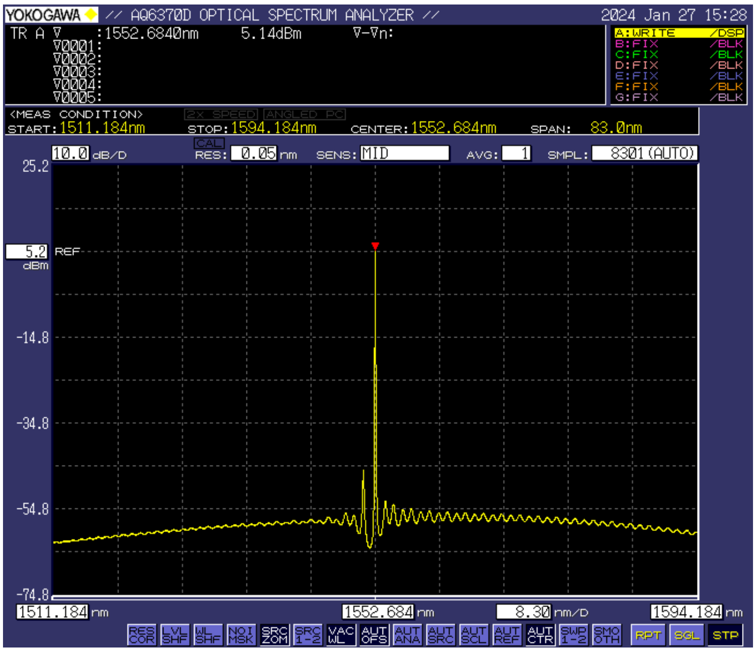

Figure 15. 1552 nm wavelength spectrum.

As evidenced in Figures 16 and 17, when combining the wavelengths of 1320 nm and 1552 nm by multiplexing, a decrease in transmit power of about 3 dB is observed. In contrast, multiplexing the 1492 nm and 1552 nm wavelengths results in a much lower loss, approximately 1 dB.

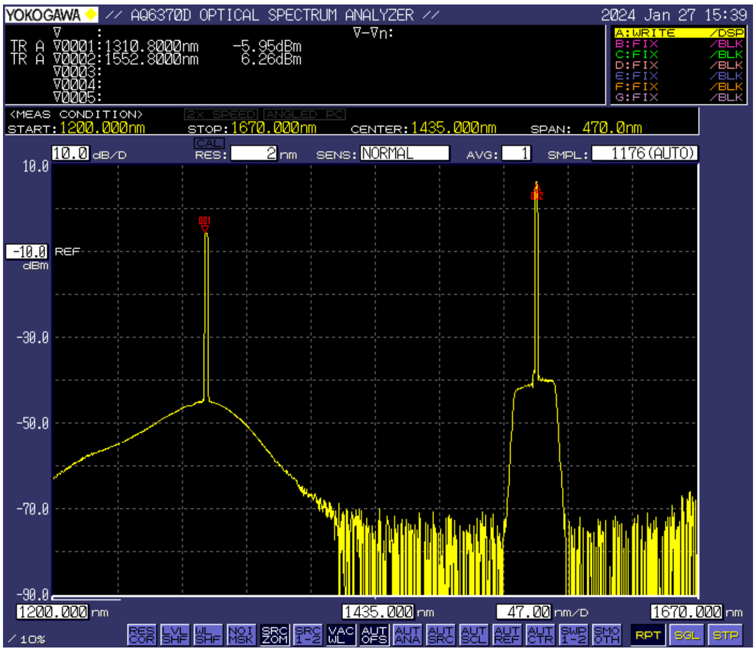

Figure 16. Multiplexed signal spectrum of 1310nm and 1552nm.

Despite these losses, their impact is not significant because ONT (Optical Network Terminal) equipment is designed to operate with a power link margin of approximately -18 dB. This capability ensures that services can be kept up without major interruptions due to the aforementioned losses.

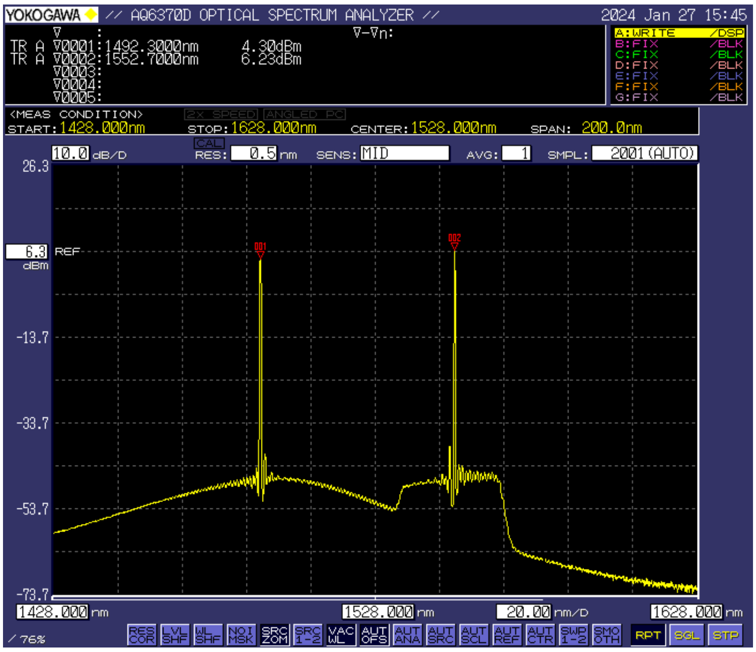

Figure 17. 1492nm and 1552nm multiplexed signal spectrum.

These findings underscore the robustness of the network design and the ability of its components to effectively manage variations in transmit power. This is crucial to ensure the continuity and reliability of the services offered to end users, even under conditions where minor losses occur during optical signal multiplexing.

4. DISCUSION

The data obtained using the Siglent spectrum analyzer and the Yokogawa optical spectrum analyzer provide a detailed view of the signal transmission and reception process within a HFC network infrastructure. In Figure 5, the spectrum of the ISDB-T signal can be initially observed directly from the modulator, allowing accurate evaluation of the modulation frequency and output power. This initial analysis is crucial to establish a clear reference of the initial state of the signal before going through various stages of processing and transmission.

Subsequently, in Figure 6, attention is focused on the signals after they have been multiplexed, demultiplexed, and converted back to electrical signals. The Yokogawa optical spectrum analyzer plays a critical role in identifying peaks in wavelengths passing through the optical fiber, ensuring that the power of the transmitted signals remains within optimal parameters. This analysis is essential to verify the effectiveness of WDM multiplexing and to ensure that the signals retain their integrity throughout the transmission process.

The detailed comparison between Figures 11 and 12 provides a clear perspective of how the signal evolves from its initial electrical form to its final optical form after passing through all stages of the infrastructure. Although a slight decrease in transmit power is observed in Figure 12, the modulation frequency remains stable, indicating the efficiency of the system in preserving signal integrity through different conversion technologies.

Figures 13, 14 and 15 highlight the key wavelengths used for data transmission in the HFC network, each meticulously tuned to maximize efficiency and effectiveness in data transmission, meeting the specific standards of the HFC infrastructure.

Multiplexing these wavelengths, as evidenced in Figures 16 and 17, introduces minimal power losses that are within the power link range of ONT equipment. These results indicate that the losses are negligible and do not adversely affect the system's ability to maintain high-quality, active services.

The eye diagram, shown in Figure 9, provides a visual assessment of the noise and the quality of the transmitted signal. The clarity of the sinusoidal intersections in the eye diagram confirms that noise does not have a negative impact on the quality of service, thus validating the effectiveness of the network design to mitigate interference.

Together, these results underscore the robustness and efficiency of the implemented HFC network, demonstrating its ability to effectively manage signals through different stages of transmission and reception. These findings not only support the technical feasibility of the system, but also confirm its ability to meet current and future requirements for data transmission and multimedia services, ensuring a reliable and optimal user experience. This section explains the required formatting for lists, numbered and unnumbered, tables, figures, and equations.

In the discussion of the results obtained, it can be seen how HFC networks, despite their robustness and capacity to maintain signal integrity throughout the transmission process, face challenges in the face of the evolution of new network technologies. Networks such as GPON (Gigabit Passive Optical Network), FTTX (Fiber to the x) and MPLS (Multiprotocol Label Switching) are gaining ground due to their lower deployment and operating costs, while offering advantages in terms of symmetrical bandwidth, stability and coverage. The comparison between newer technologies and HFCs highlights where HFCs may be at a disadvantage in today's telecommunications market.

Despite these challenges, the results obtained with Siglent and Yokogawa spectrum analyzers validate the effectiveness of HFC networks in transmitting data and multimedia services, especially in environments where they are already deployed and where their active infrastructure can provide stable and reliable service. This makes them a viable alternative for educational contexts that require a proven and stable infrastructure in terms of signal transmission and reception quality.

However, considering current trends, it is essential that telecommunications students not only understand how HFC networks work, but also acquire a practical and theoretical knowledge of new technologies. This will allow a critical vision that includes not only the implementation of existing networks, but also the comparison with emerging technologies that are emerging as the future of telecommunications networks.

Table 1 helps to visualize the pros and cons of HFC networks compared to modern alternatives, providing a baseline for decision-making on telecommunications infrastructure in different contexts.

Table 1. Comparison of Network Technologies.

Feature	**HFC**	**GPON**	**FTTX**	**MPLS**
Implementation Cost	High	Middle	Low	Middle
Cost of Operation	High	Low	Low	Middle
Bandwidth	Asymmetric	Symmetrical	Symmetrical	Variable (depending on QoS)
Stability	High over short distances	Very high	Very high	Loud
Coverage	Limited	Wide	Wide	Wide
Maintenance	Frequent (active teams)	Low	Low	Middle
Ideal Application	Multimedia and cable TV	High-speed internet	Residential Access Network	Backbone and enterprise networks
Fit for the Future	Limited	Loud	Loud	Loud

Academic training, then, should address both HFC networks and modern alternatives, allowing students to acquire versatile and up-to-date skills. This study provides a comprehensive basis for understanding technological evolution and applying the knowledge acquired in real scenarios of network infrastructure implementation and analysis.

5. CONCLUSIONS

HFC networks have become a cornerstone in modern communications infrastructure by integrating fiber optic and coaxial cable, significantly improving transmission capacity and reliability in the delivery of multimedia services.

Comprehensive analysis using spectrum analyzers has validated the efficiency of HFC networks in transmitting and receiving signals. From the initial evaluation of the ISDB-T signal spectrum to the integrity check of multiplexed and demultiplexed signals, these systems have been proven to maintain signal integrity through various conversion technologies.

The application of WDM multiplexing has optimized the use of key wavelengths, thus maximizing the efficiency and effectiveness of data transmission in accordance with HFC infrastructure standards.

The results of the eye diagram analysis corroborate that the design of the HFC network is effective in mitigating interference and ensuring a high quality of service, underlining its robustness and efficiency in signal management.

The implementation of the HFC network for educational environments not only meets the current requirements of data transmission and multimedia services, but is also prepared to meet future demands, ensuring a reliable and optimal experience for future research and for academic teaching, highlighting the strategic importance of HFC networks in the current telecommunications context.

The analysis of HFC networks versus emerging technologies such as GPON, FTTx and MPLS highlights the strengths and limitations of each type of infrastructure. While HFC networks have proven to be reliable in the transport of multimedia services, networks such as GPON and FTTx offer advantages in terms of deployment and operating costs, greater stability, symmetrical bandwidth and optimized coverage. These alternatives present a promising outlook in terms of efficiency and cost-effectiveness, presenting new opportunities for the expansion and modernization of telecommunications infrastructures.

This article stands out for offering an academic and practical study, which facilitates learning and understanding in telecommunications students on how these technologies are deployed and operate in practice. Through this approach, students can understand the key processes and components of HFC networks, while becoming familiar with state-of-the-art technologies.

In addition, the article underscores the relevance of HFC networks in educational environments, not only for their current ability to support data transmission demands, but also for their formative role in preparing future professionals for the adoption of advanced technologies. This theoretical and practical integration in education reinforces academic preparation in the field of telecommunications and contributes significantly to the strengthening of applied knowledge.

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