Revista Ciencia e Ingeniería Neogranadina 2024 julio - diciembre Vol. 34(2) ISSN: 0124-8170 · e-ISSN: 1909-7735 ■ pp. 11-22

Editorial Neogranadina

DOI: https://doi.org/10.18359/rcin.7262

5G/GPON: A Convergent Architecture Wireless and Optical Sensor Networks in Bogotá City*

Cristian Camilo Quevedo Beltran[a] ■ Gustavo Adolfo Puerto Leguizamón[b]

Abstract: This paper presents a convergent optical transport architecture for wireless and photonic sensor networks, utilizing the optical access network deployed in Bogotá. The proposed approach is evaluated through the transmission of services using Subcarrier Multiplexing (SCM) to support the seamless transport of various standards, including WiFi, Bluetooth, zigBee, sigFox, and others. The design demonstrates the feasibility of leveraging the existing GPON network infrastructure, enabling the integration of both optical sensors based on Fibber Bragg Gratings (FBG) and wireless sensors in locations of significant historical, economic, cultural, and social importance. The system shows optimal signal quality performance based on Bit Error Rate (BER) and signal power across multi-coverage zones, evaluated using parameters such as SS-RSRP, SS-RSRQ, and throughput.

Keywords: 5G; Subcarrier Multiplexing (SCM); Fiber Bragg Grating (FBG); Radio over Fiber (ROF); Sensor Networks; Optical Access Network

Recibido: 14/03/2024 **Aceptado:** 03/09/2024 **Disponible en línea:** 29/10/2024

Cómo citar: Quevedo Beltran, C. C., & Puerto Leguizamon, G. A. (2024). 5G/GPON: Una Arquitectura convergente para redes de sensores inalámbricos y ópticos en la ciudad de Bogotá. *Ciencia E Ingeniería Neogranadina, 34*(2), 11–22. https://doi.org/10.18359/rcin.7262

* Research article.

a Electronic Engineer. IMT Atlantique Bretagne - Pays de la Loire École Mines - Télécom, School Plouzané, Francia. Email: cristian.quevedo-beltran@imt-atlantique.net; ORCID: https://orcid.org/0009-0003-2397-7287

b Doctor in Telecomunications, Telecomunications Engineer. Universidad Distrital Francisco José de Caldas, Bogotá, Colombia. Email: gapuerto@udistrital.edu.co; ORCID: https://orcid.org/0000-0002-6420-9693

5G/GPON: una arquitectura convergente para redes de sensores inalámbricas y ópticas en la ciudad de Bogotá

Resumen: En este artículo se presenta una arquitectura de transporte óptico convergente para redes de sensores fotónicos e inalámbricos basada en la red de acceso óptico implementada en la ciudad de Bogotá. Las prestaciones de la propuesta se comprueban mediante la transmisión de servicios en multiplexación de subportadora (SCM) para permitir el transporte fluido de diferentes estándares como WiFi, Bluetooth, Zigbee, SigFox, entre otros. El diseño presentado demuestra la viabilidad de la propuesta dada la distribución de la red (GPON) actualmente desplegada, permitiendo la incorporación tanto de sensores ópticos basados en FBG como de sensores inalámbricos en ubicaciones con mayor relevancia histórica, económica, cultural y social. La propuesta presenta un rendimiento óptimo de la calidad de la señal basado en la tasa de error de bits (BER) y la potencia de la señal en la zona de cobertura múltiple para varios parámetros como SS-RSRP, SS-RSRQ y Throughput.

Palabras clave: 5G, multiplexación de subportadoras (SCM); red de difracción de Bragg (FBG); radio sobre fibra (ROF); red de sensores; red de acceso óptico

5G/GPON: Uma Arquitetura Convergente para Redes de Sensores Sem Fio e Ópticos na Cidade de Bogotá

Resumo: Neste artigo, apresenta-se uma arquitetura de transporte óptico convergente para redes de sensores fotônicos e sem fio baseada na rede de acesso óptico implementada na cidade de Bogotá. As características da proposta são verificadas por meio da transmissão de serviços em multiplexação por subportadora (SCM) para permitir o transporte fluido de diferentes padrões como WiFi, Bluetooth, Zigbee, SigFox, entre outros. O design apresentado demonstra a viabilidade da proposta, dada a distribuição da rede (gpon) atualmente implantada, permitindo a incorporação tanto de sensores ópticos baseados em FBG quanto de sensores sem fio em locais de maior relevância histórica, econômica, cultural e social. A proposta apresenta um desempenho ótimo da qualidade do sinal baseado na taxa de erro de bits (BER) e na potência do sinal na área de cobertura múltipla para vários parâmetros como ss-rsrp, ss-rsrq e Throughput.

Palavras-chave: 5G, Multiplexação por subportadoras (SCM); Rede de difração de Bragg (FBG); Rádio sobre fibra (ROF); rede de sensores; rede de acesso óptico

Introduction

Since ancient times, humans have relied on their senses to gather information about their environment. However, the advent of sensors has enabled more precise and reliable measurement and quantification of this information. The versatility offered by sensors is now applied to a wide range of human development scenarios, including industrial process control, automation, environmental monitoring, security, social protection, healthcare, and overall social well-being.

Consequently, industrial processes have continuously demanded the development of technologies capable of providing real-time data for critical variables that must be controlled with significant precision. The technological advancements in mechanical, electronic, optical, and wireless sensors have contributed to improvements in diverse fields such as medicine, industry, agriculture, transportation, and smart homes.

At the same time, telecommunications networks have evolved continuously, from the second, third, and fourth generation of mobile communications to the current fifth-generation mobile network, also known as 5G New Radio (NR). This evolution has enabled the introduction of enhanced Mobile BroadBand (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and massive Machine-Type Communications (mMTC) [1], fostering the development of new services, applications, and the massive adoption of Internet of Things (IoT).

Designing telecommunications networks is a critical process for ensuring effective and reliable connectivity. Although conventional transport networks are still favored for their simplicity and cost-effectiveness compared to more advanced options [2], the growing demand for bandwidth has led to the development of Gigabit-capable Passive Optical Networks (GPON) and Subcarrier Multiplexing (SCM) access networks for data transport in 5G technologies [3-6]. Furthermore, wireless sensor networks using Low Power Wide Area Network (LPWAN) technology have been proposed [7], [8], along with multi-channel systems for Radio-over-Fiber (RoF) transport [9], [10] and cost-effective Digital SubCarrier Multiplexing (DSCM) for Point to Multi Point signal transmission and distribution [11], [12]. However, it is worth noting that no architectures have been proposed to date that integrate subcarrier multiplexing for wireless communication with optical sensor technologies.

This paper presents the conceptualization and development, using Optisystem and Xirio Online software, of a convergent wireless and optical sensor network deployed across five key areas in Bogotá, Colombia, chosen for their high sociocultural and economic significance. The proposed approach leverages the existing GPON infrastructure in these areas to transport signals from both optical and wireless sensor networks. This represents the paper's theoretical and methodological contributions to the telecommunications field. Specifically, while the interrogation band of optical sensors based on Fiber Bragg Gratings (FBG) [13] operates between 1515 nm and 1540 nm, Subcarrier Multiplexing (SCM) is used to enable the convergent transport of wireless sensors data signals, carried on wavelengths between 1570 nm and 1594 nm. To the best of our knowledge, this is the first time proposal for an architecture that multiplexes data from both optical and wireless sensors operating in this manner.

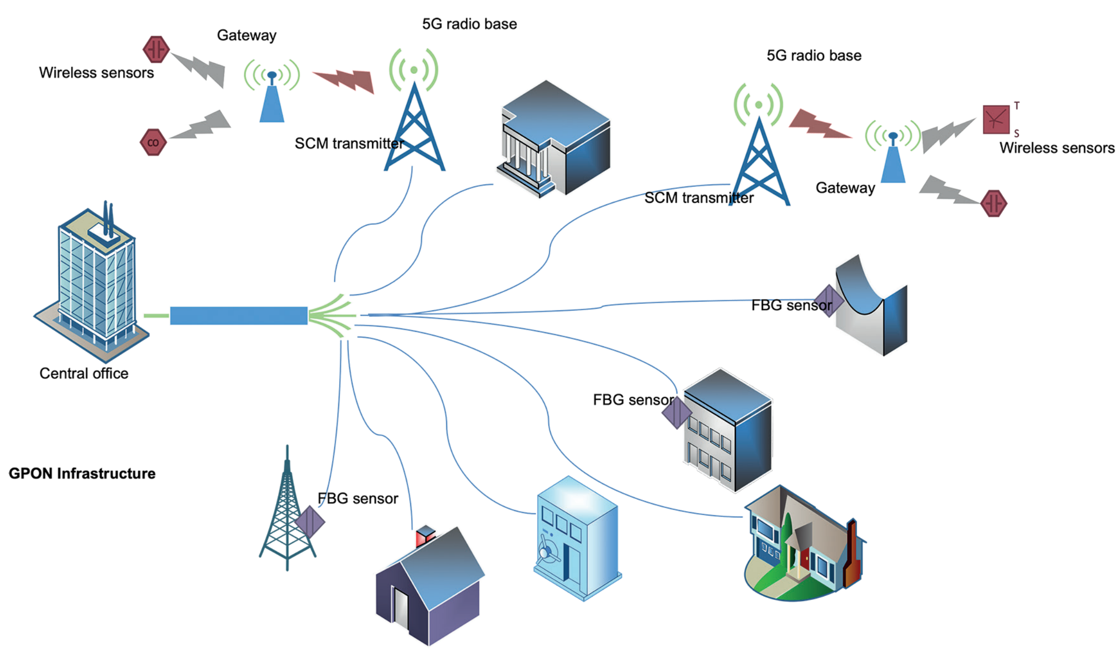
1. Methodology

Figure 1 illustrates the envisioned environment of the city, where the existing fiber infrastructure is utilized as a platform to provide transport for fixed end users, optical sensors, and wireless sensor radios deployed in various localities. The end users include residential, commercial, governmental, healthcare, and educational institutions. Optical sensors based on (FBG) are used for monitoring the deformation of civil structures such as bridges, buildings, and electricity distribution towers, among others. Wireless sensor radios include technologies such as ZigBee, LoRa, WiFi, operating in the 915 MHz, 2.4 GHz or 5.8 GHz frecuency bands. In this context, the SCM transmitter facilitates the transport of wireless sensor radios from the 5G-radio base station to the central office.

The first part of the architecture was developed using Xirio Online. To conceptualize and design the system, it was necessary to understand the GPON architecture in Bogotá to select appropriate locations for each antenna that would serve the wireless sensors. The configuration for the frequency band of the 5G network, FR 1 NR n77, operating between 3.5 GHz and 3.6 GHz for the upper range, and between 3.6 GHz and 3.7 GHz for the upper range, with a carrier separation of 20 MHz [14]. Recently, Colombia's Ministry of Information and Communications Technologies (MinTIC) auctioned the 3.5 GHz band, and at the time of writing this article, several operators were already offering 5G connectivity in the localities defined for this study [15].

Following the frequency band setup, the power levels for 5G signals were defined, categorized into four levels: excellent (between -70 dBm and -80 dBm), good (between -81 dBm and -90 dBm), fair (between -91 dBm and -100 dBm), and poor (between -101 dBm and -110 dBm). The radiation pattern of the reference antenna, the AM-3G18-120 2x2 MIMO Base Station Sector Antenna from Ubiquiti Networks [16], was configured with a power output of 15 Watts. This antenna has a gain of 17.3 to 18.2 dBi in a frequency range of 3.3 to 3.8 GHz, along with beamwidth of 118°@ 6dB horizontally and 121°@6dB vertically. Finally, the location's height and sector for each of the 24 antennas were determined for deployment.

Figure 1. Converged Access Network scheme



Source: The authors.

Regarding the 5G parameters, a configuration of 44 slots (D:6/U:2/X:6) was used in stand-alone mode, with an aggregation threshold of -5 dB and numerology 0. For the downlink parameters, a traffic load of 70% and 2x2 MIMO were chosen, while for the uplink, 2x2 MIMO was also applied. Other parameters, such as noise increment, noise factor, and MIMO gain, were kept at default values. For the calculation method, the New York University model, incorporating the Alpha-Beta-Gamma model and Close-In Free Space Reference Frequency Dependent, was used [17]. It is important to note that traditional calculation methods, such as Okumura-Hata, lose relevance when operating outside the range of 150 MHz and 2 GHz.

For the coverage study of individual antennas, the area was defined based on adjacent antennas. A total of 24 coverage studies were conducted, each with sectorization tailored to the specific area, sometimes prioritzing directionality towards key locations. This involved calculating interference parameters by combining the results of the 24 individual coverage studies.

The second part of the architecture was developed in the Optisystem software. Understanding Bogotá's GPON architecture was crucial in determining the dimensions; specifically the length of the entire system. Based on this, potential locations were selected for each of the 26 FBGs, and a complete architectural structure was created, factoring in the positions of the 24 antennas and the 26 FBGs. Five simulations were then conducted, one for each locality, as the complexity of the final architecture made simulating all localities simultaneously a challenge in terms of software resources.

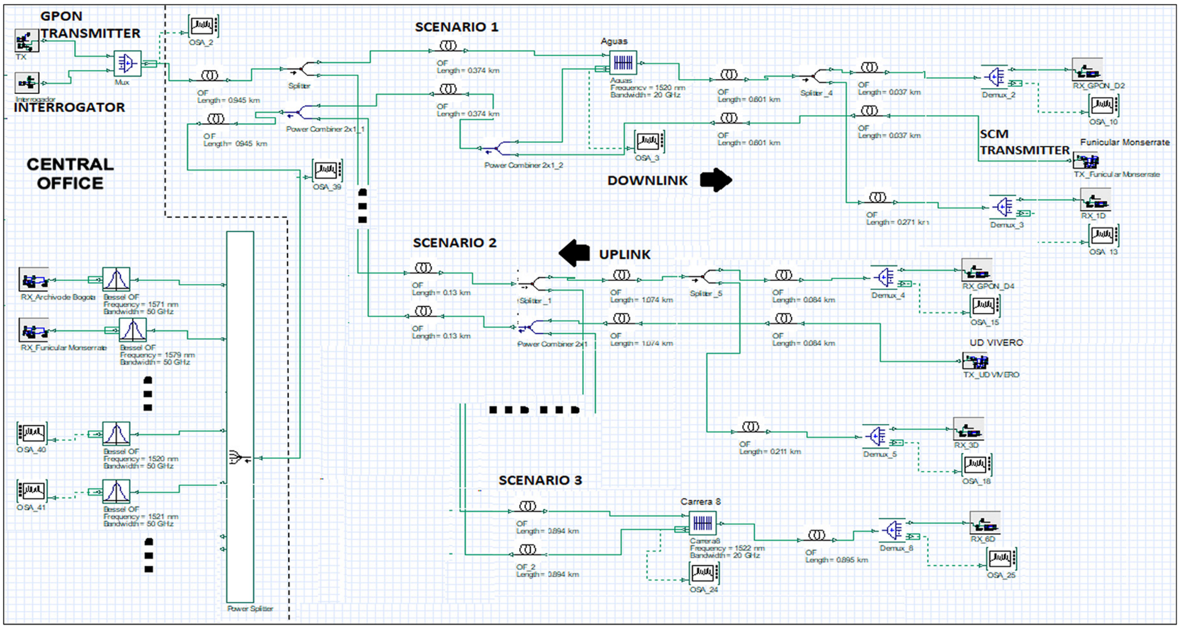
For each simulation considered, the downlink configuration including the GPON transmitter and the wideband spectrum interrogator, which passed through each FBG. A GPON receiver was placed at the end of each link. For the uplink, antenna locations included an SCM transmitter that multiplexed the data from the wireless sensor radios and the reflections from each interrogated FBG. These components, once multiplexed, returned to the physical point where the interrogator was located and were then separated for further processing. The global simulation parameters were set at 5 Gb/s, with a sequence length of 8 bits and 32.768 samples per bit, fixing both the time window and the sample rate.

Figure 2 presents an illustrative example of this architecture through three potential scenarios in the locality of "La Candelaria". In the first scenario, once the GPON wavelength channel at 1490 nm and the interrogation band signal are launched in the downlink, an FBG sensor located at "Aguas" reflects one of the available wavelength channels from the interrogation band. The GPON receiver is situated at the "Funicular Monserrate" site, which coexists with a site providing wireless sensor services, namely the radio base where the SCM transmitter is located. When the wireless sensor signal is received at the radio base, SCM is applied, and the signal is transmitted in the uplink using a wavelength between 1570 nm and 1594 nm. As the SCM signal passes through the FBG in the uplink, it multiplexes with the spectrum reflected by the FBG, allowing both the optical and wireless sensor signals to travel together.

In the second scenario, the principle is similar, except there is no FBG between the transmitter and receiver in the downlink to affect the spectral component of the interrogator. Here, only GPON is transmitted in the downlink, while SCM is used in the uplink.

In the third scenario, the first case is replicated, but without an SCM transmitter in the uplink. Therefore, the only spectral component reaching the receiver in this direction comes from the FBG.

Figure 2. Simplified example of the 5G/SCM architecture for "La Candelaria" locality



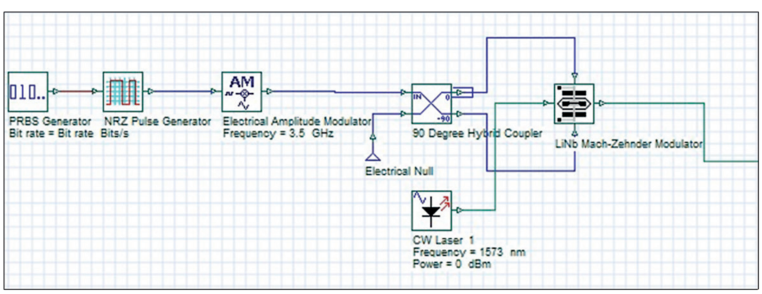
Source: The authors.

The integration of the two parts, -the multi coverage study design in Xirio Online and the fiber optic architecture design in Optisystem - was made possible by the SCM technique, which directly modulates the RF signal onto an optical carrier. Figure 3 illustrates an SCM transmitter for a single -sideband optical modulation. The optically intensity-modulated signal is transmitted through the optical fiber link and multiplexed with the reflected signal from the FBG in the uplink.

Regarding the wireless sensor radio, the proposed architecture is transparent to the wireless standard used in the sensor network. In this context, technologies such as Bluetooth, WI-FI, ZIGBee, SIGFOX, and LORa, which operate in the ISM bands at 915 MHZ, 2.4 GHZ, and 5.8 GHZ, can be seamlessly transported within this architecture.

This requires a gateway that, on one side, collects signals from the corresponding standard and, one the other side, connects with the 5G-radio base, as depicted in Figure 1.

Figure 3. ROF Transmitter Scheme with SSB



Source: The authors.

2. Results

Several parameters are proposed to assess the performance of the architecture in terms of capacity, integration with the existing GPON network, and the quality of the transported signals.

In designing the transport network architecture, multiple scenarios were considered. First, areas without sites or antennas were evaluated to understand the network's behavior in terms of bit error rate in downstream links. This assessment was based on the length and splitting factor of the network, as well as potential locations of GPON service users. Second, areas with existing sites, such as antennas, were analyzed.

These sites are crucial for studying the degradation of the GPON signal in the downstream links and the SCM signal from the antenna to the central office in the upstream links. Additionally, radiation patterns were studied by evaluating parameters such as the transmission data rate between the base station and mobile user, as well as power levels. Finally, the points where the GPON network integrated optical sensors, specifically FBG, were analyzed. This analysis involved measuring the reflected and transmitted spectral components and their degradation upon reaching the central office.

To evaluate the architecture's coverage, interference parameters were analyzed, which are critical in the context of 5G networks. These parameters provide insights into signal quality, network management, resource optimization, and the delivery of high-quality services, as illustrated in Figure 4.

Figure 4(a) shows the Synchronization Signal-Reference Signal Received Power (SS-RSRP), defined as the average power of all resource contributions carrying the reference signal over the specified bandwidth.

Figure 4(b) displays the Received Signal Strength Indicator (RSSI), which measures the average received power over some OFDM symbols in the configured bandwidth. This includes thermal noise, adjacent channel interference, and co-channel interference power.

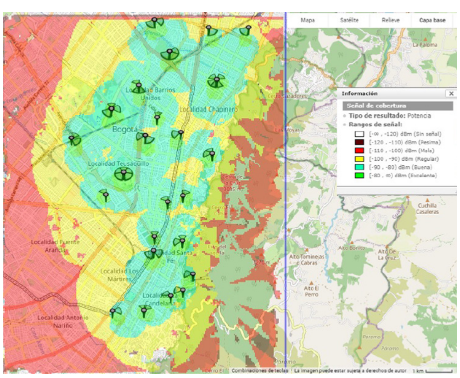
Figure 4(c) presents the Secondary Synchronization Signal-Reference Signal Received Quality (SS-RSRQ), which helps determine the relationship between the received signal power and the interference in the spectrum used.

Finally, Figure 4(d) shows the 5G network throughput based on signal ranges.

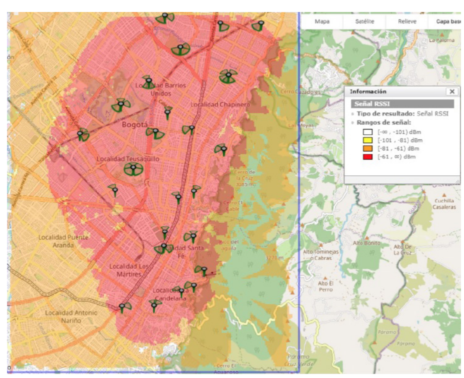
These parameters offer a comprehensive view of network quality and capacity across different locations, enabling a thorough performance evaluation.

Figure 4. Performance measurements. (a) SS-RSRP. (b) RSSI. (c) SS-RSRQ. (d) Throughput

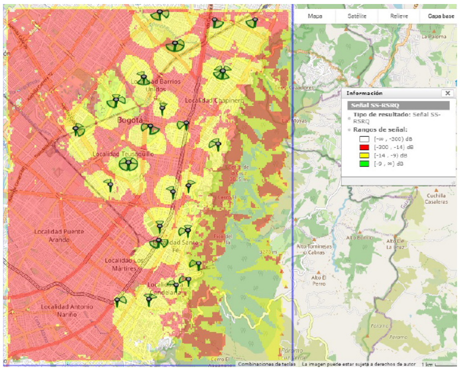
(a)



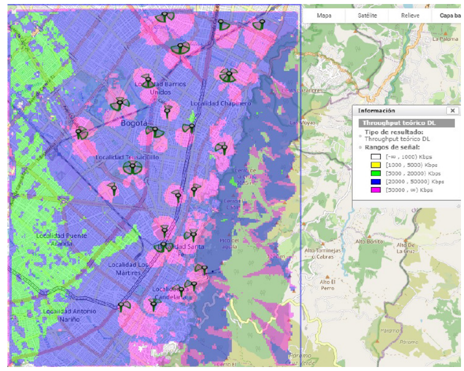
(b)



(c)



(d)



Source: The authors.

From these results, it can be inferred that the coverage area, i.e., the radiated zone, will maintain at least -100 dBm of power. Given that the sensitivity of an average receiver is around -110 dBm, this ensures effective communication in the downlink direction. Regarding the RSSI, the study shows that the localities analyzed have a power level exceeding -61 dBm, indicating a good signal strength. In the range between -40 dBm and -60 dBm, a connection efficiency of about 80% is achieved.

As for the SS-RSRQ signal, which represents the ratio between SS-RSRP and RSSI, areas within the multi coverage zone are identified where potential connectivity issues may arise due to resource limitations. However, this does not entirely eliminate the possibility of establishing communication. Finally, in terms of transmission capacity for both the downlink and uplink, theoretical values exceeding 20 Mbps for the downlink and 50 Mbps for the uplink are estimated near the antennas, determined by the radiation patterns of the SS-RSRP signal.

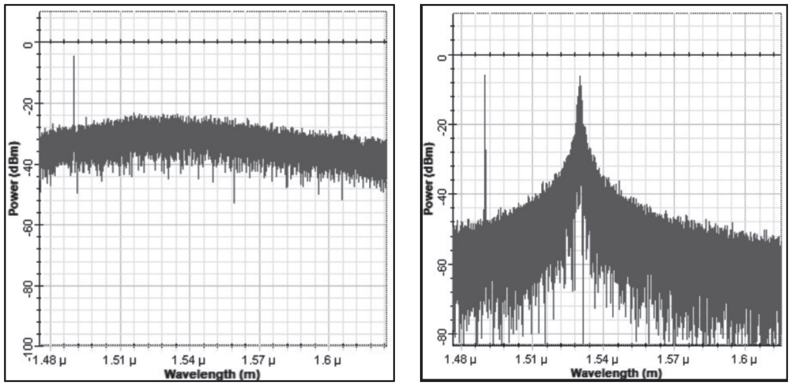
Next, to evaluate the architecture's capacity, tests were conducted using both a wideband interrogator with a spectral width of 10 THz centered at 1530 nm and a narrowband interrogator with a spectral width of 100 GHz, also centered at 1530 nm, as illustrated in Figure 5. Specifically, Figure 5(a) shows the wideband interrogation signal multiplexed with the GPON carrier at 1490 nm, and Figure 5(b) shows the narrowband interrogation signal similarly multiplexed with the GPON carrier. The objective was to analyze the over-dimensioning of the interrogation system, particularly in the wideband case, and compare how this affects the Bit Error Rate (BER), which indirectly reflects the communication channel's efficiency.

The Bit Error Rate (BER) results measured across the five localities are shown in Figure 6. Comparing Figure 6(a), which presents the BER measurements of the GPON and SCM signals with the wideband interrogator, and Figure 6(b), which displays the BER performance of the same signals with the narrowband interrogator, reveals that the interrogator's spectrum minimally affects both the GPON and SCM signals. In all the cases, the BER results indicate a good performance.

However, slight differences in signal quality at various wavelengths are observed, primarily due to cumulative attenuation in specific channels, which varies depending on the propagation distance of the GPON and SCM links across the five localities.

Figure 5. Multiplexing of GPON Carrier with (a) Wideband Interrogator. (b) Narrow-band Interrogator.

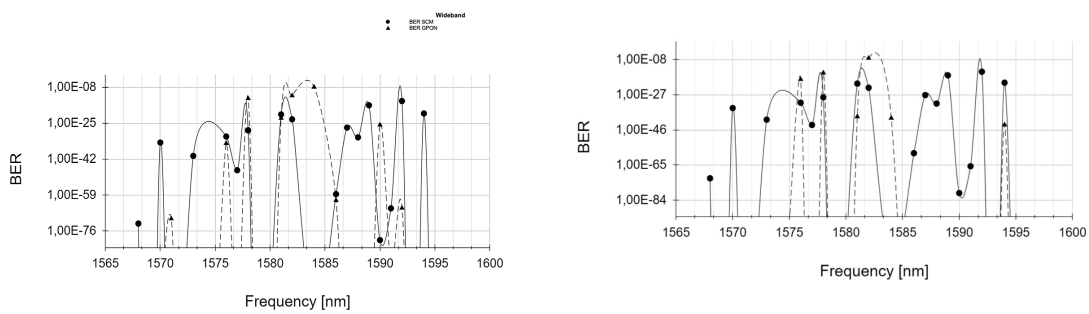
(a) (b)



Source: The authors.

Figure 6. BER as a function of the wavelength for GPON and SCM signals: (a) Wideband interrogator. (b) Narrow-band Interrogator

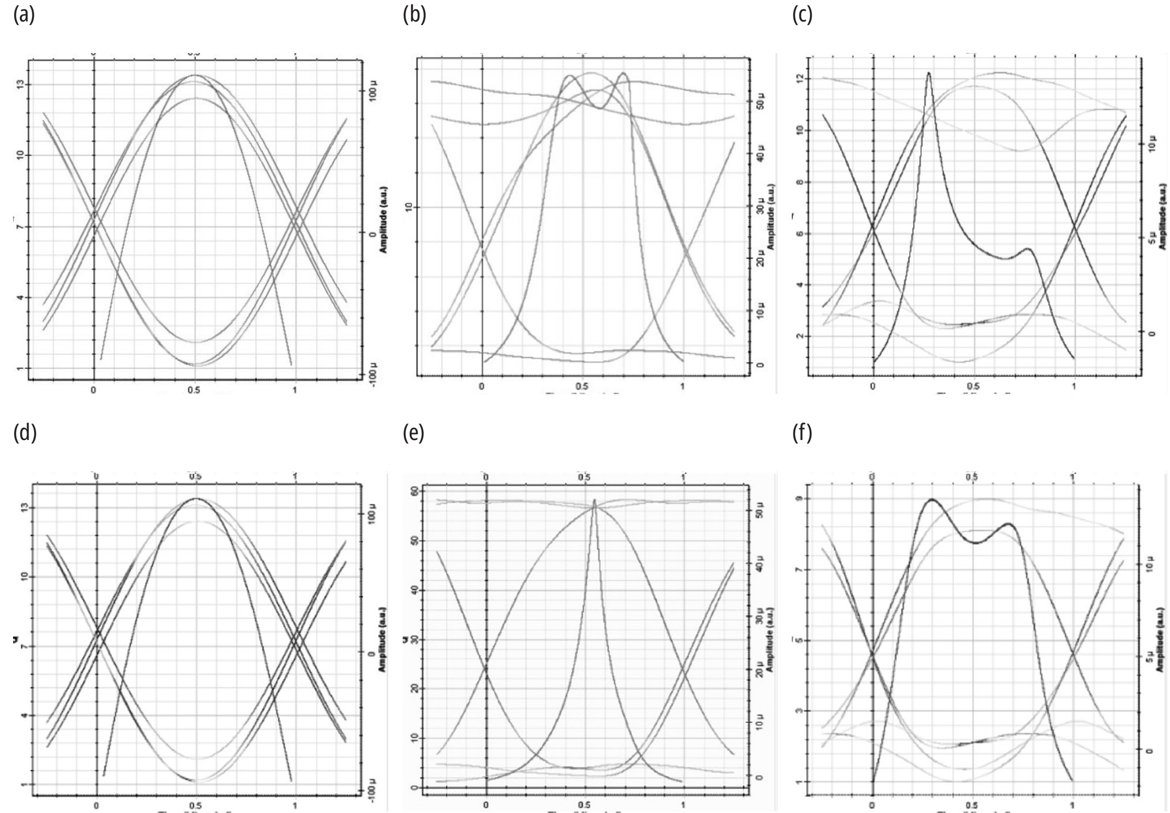
(a) (b)



Source: The authors.

Another essential parameter for evaluating the capacity and quality of any transport network is the eye diagram. In Figure 7 presents six eye diagrams corresponding to the three previously described scenarios, comparing the response with both wide-band and narrowband interrogation. Figures 7(a), 7(b), and 7(c) illustrate the signal quality when using wideband interrogation for one of the SCM signals at 1571 nm, a GPON service with the SCM signal at 1573 nm, and a GPON service with the longest propagation distance, along with an SCM service operating at 1583 nm, respectively.

Figure 7. Signal quality results with wideband interrogation: (a) SCM signal at 1573 nm. (b) GPON carrier. (c) Furthest geographically located point in "La Candelaria" locality. Signal quality results with narrowband interrogation: (d) SCM signal at 1573 nm. (e) GPON carrier. (f) Furthest geographically located point in "La Candelaria" locality



Source: The authors.

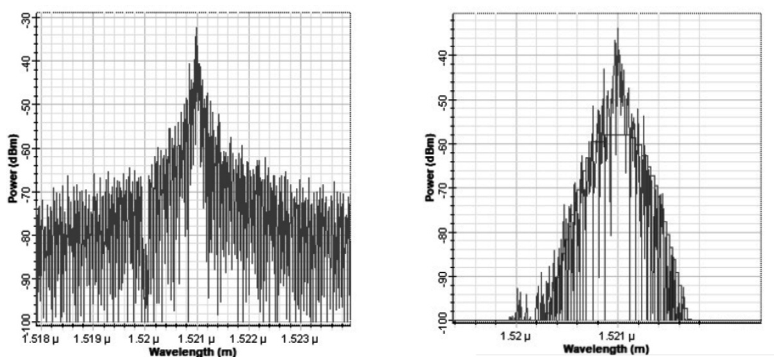
Figures 7(d), 7(e) and 7(f) show the signal quality at the same measurement points but using a narrowband interrogator instead. As observed, the eye diagrams reinforce the results depicted in Figure 6, higlighting the degradation associated with the interrogator and propagation lengths. Overall, the three scenarios operating with both interrogation systems exhibit acceptable values in terms of BER tolerance and eye diagram openings.

Regarding the optical sensors within the architecture of the convergent transport network, Figure 8 presents the response of the spectral components passing through the FBGs. The response reveals a cascade effect among the FBG based sensors, resulting in notches in the spectral components of the interrogation signal.

For instance, Figure 8(a) shows the notch produced by a FBG sensor tuned to 1520 nm on the interrogation signal of nearby FBG sensor tuned to 1521 nm. Figure 8(b) illustrates the FBG reflection in the uplink. While the optical power of the component reflected by the FBG sensor is -32 dBm, its optical power at the central office is -34 dBm. This 2 dB power difference implies a good spectral quality, suitable for detecting picometer variations, which are typical in FBG- based optical sensors.

Figure 8. Spectrum of FBG at 1521 nm at the sensor site (A) and Spectrum of FBG received at the central office (B).

(a) (b)



Source: The authors.

Conclusions

This paper presented a convergent transport system that demonstrates the use of the existing fiber infrastructure in GPON networks to meet the connectivity needs of both wireless and optical sensor networks. The approach employs subcarrier multiplexing (SCM) to transport 5G RF carriers that convey data from wireless sensors, while optical sensors based on FBG are multiplexed within the architecture, creating a unified platform for transporting information from both type of sensors.

A deployment of a 5G stand-alone network was carried out five localities in Bogotá, achieving approximately 95% coverage of the multi coverage zone, which spans a total of 111.13 square kilometers. The system operates transparently in terms of GPON data transmission, addressing the growing demand for resources and higher speeds. The quality of the transported signals, measured through the Bit Error Rate (BER) across all localities, remained below $1x10^{-8}$, regardless of the spectral width of the interrogator. Additionally, a wider spectral width in the interrogator results in higher resolution but also increases processing time, noise vulnerability, and sensitivity to certain spectral components, highlighting the need to balance processing time and spectral width.

The results underscore the system's efficiency and effectiveness in providing extensive and reliable coverage for the intended applications. Notably, the proposed transport system also allows for the integration of more optical carriers to accommodate future needs or the evolution of the current GPON systems. This flexibility demonstrates the system's capacity to handle not only Wavelength Division Multiplexing (WDM) effects but also additional radiofrequency components for Subcarrier Multiplexing (SCM).

References

[1] W. E. Chen, X. Y. Fan, y L. X. Chen, "A CNN-based Packet Classification of eMBB, mMTC and URLLC Applications for 5G," en 2019 International Conference on Intelligent Computing and its Emerging Applications (ICEA), agosto 2019, pp. 140-145. DOI: https://doi.org/10.1109/ICEA.2019.8858305

[2] X. Liu, "Enabling Optical Network Technologies for 5G and Beyond," in Journal of Lightwave Technology, vol. 40, no. 2, pp. 358-367, 15 Jan.15, 2022, DOI: https://doi.org/10.1109/JLT.2021.3099726

[3] Y. J. Aruan, P. T. Daely, G. A. R. Sampedro, J. M. Lee and D. -S. Kim, "The Design of The Emerging 5G Using Hybrid GPON and XGS-PON Technology," 2021 International Conference on Information and Communication Technology Convergence (ICTC), Jeju Island, Korea, Republic of, 2021, pp. 1002-1004, DOI: https://doi.org/10.1109/ICTC52510.2021.9620906

[4] G. Garima, V. Jha and R. K. Singh, "Performance Analysis of Dynamic Service Interval Based DBA Method in XGS-PON based Mobile Fronthaul for Small Cell CRAN," 2022 IEEE 13th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (uemcon), New York, NY, NY, USA, 2022, pp. 0431-0436, DOI: https://doi.org/10.1109/UEMCON54665.2022.9965715

[5] K. Tanaka et al., "1.314-Tbit/s (576 × 380.16-MHz 5G NR OFDM Signals) SDM/WDM/SCM-Based IF-over-Fiber Transmission for Analog Mobile Fronthaul," 2022 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2022, pp. 1-3. DOI:https://doi.org/10.1364/OFC.2022.W4C.2

[6] K. Tanaka et al., "10.51-Tbit/s IF-over-Fibre Mobile Fronthaul Link Using SDM/WDM/SCM for Accommodating Ultra High-Density Antennas in Beyond-5G Mobile Communication Systems," 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 2022, pp. 1-4. [6] K. Tanaka et al., "10.51-Tbit/s IF-over-Fibre Mobile Fronthaul Link Using SDM/WDM/SCM for Accommodating Ultra High-Density Antennas in Beyond-5G Mobile Communication Systems," 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 2022, pp. 1-4.

[7] L. Q. Huy et al., "Estimation of LP-WAN Coverage using Sparse Measurement and Machine Learning in DaNang City," 2022 IEEE Conference on Antenna Measurements and Applications (CAMA), Guangzhou, China, 2022, pp. 1-3, DOI: https://doi.org/10.1109/CAMA56352.2022.10002586

[8] A. ElSabaa, F. Guéniat, W. Wu and M. Ward, "Enhanced Data-Driven LoRa LP-WAN Channel Model in Birmingham," 2022 IEEE World AI IoT Congress (AIIoT), Seattle, WA, USA, 2022, pp. 766-772, DOI: https://doi.org/10.1109/AIIoT54504.2022.9817253

[9] P. Guan et al., "Novel Hybrid Radio-Over-Fiber Transmitter for Generation of Flexible Combination of WDM-ROF/WDM Channels," 2019 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2019, pp. 1-3. DOI: https://doi.org/10.1364/OFC.2019.W1I.6

[10] B. J. Hamza et al., "Performance Enhancement of SCM/WDM-RoF-XGPON System for Bidirectional Transmission With Square Root Module," in IEEE Access, vol. 9, pp. 49487-49503, 2021, DOI: 10.1109/ACCESS.2021.306528. DOI: https://doi.org/10.1109/ACCESS.2021.3065285

[11] D. Welch et al., "Point-to-Multipoint Optical Networks Using Coherent Digital Subcarriers," in Journal of Lightwave Technology, vol. 39, no. 16, pp. 5232-5247, 15 Aug.15, 2021, DOI: https://doi.org/10.1109/JLT.2021.3097163

[12] D. Welch, et al., "Digital subcarrier multiplexing: enabling software-configurable optical networks," Journal of Lightwave Technology, vol. 41, no. 4, pp. 1175-1191, año 2023. DOI: https://doi.org/10.1109/JLT.2022.3211466

[13] M. Götten, S. Lochmann, A. Ahrens, E. Lindner, J. Vlekken and J. Van Roosbroeck, "A CDM-WDM Interrogation Scheme for Massive Serial FBG Sensor Networks," in IEEE Sensors Journal, vol. 22, no. 12, pp. 11290-11296, 15 June15, 2022, DOI: https://doi.org/10.1109/JSEN.2021.3070446

[14] Base Station, "Radio Transmission and Reception (Release 15)," 3GPP, Technical Specification (TS), vol. 36, p. 12, 2017.

[15] MinTIC, "5G es una realidad para el país," [Online]. Available: https://mintic.gov.co/portal/inicio/Sala-de-prensa/Noticias/333419:5G-es-una-realidad-para-el-pais-Ministro-Mauricio-Lizcano

[16] Ubiquiti Networks, Inc., "airMAX Sector Antennas Datasheet," [Online]. Available: https://dl.ui.com/datasheets/airmaxsector/airMAX_Sector_Antennas_DS.pdf

[17] S. Sun et al., "Investigation of Prediction Accuracy, Sensitivity, and Parameter Stability of Large-Scale Propagation Path Loss Models for 5G Wireless Communications," in IEEE Transactions on Vehicular Technology, vol. 65, no. 5, pp. 2843-2860, May 2016, DOI: https://doi.org/10.1109/TVT.2016.2543139

Cristian Camilo Quevedo Beltran,
Gustavo Adolfo Puerto Leguizamón

5G/GPONI A Convergent Architecture Wireless and Optical Sensor Networks in Bogotá City*
5G/GPON: una arquitectura convergente para redes de sensores inalámbricas y ópticas en la ciudad de Bogotá
5G/GPON: Uma Arquitetura Convergente para Redes de Sensores Sem Fio e Ópticos na Cidade de Bogotá

Ciencia e Ingeniería Neogranadina
vol. 34, no. 2, p. 11 - 22, 2024
Universidad Militar Nueva Granada,
ISSN: 0124-8170
ISSN-E: 1909-7735

DOI: https://doi.org/10.18359/rcin.7262