

# A testbed and a simulation laboratory for training engineering students in optical access network technologies

Noemi Merayo | Juan C. Aguado | Ignacio de Miguel | Ramón J. Durán |  
Patricia Fernández | Rubén M. Lorenzo | Evaristo J. Abril

Optical Communication Group,  
Department of Signal Theory,  
Communications, and Telematic  
Engineering, E.T.S.I. Telecomunicación,  
Universidad de Valladolid, Spain

## Correspondence

Noemi Merayo, Optical Communication  
Group, Department of Signal Theory,  
Communications and Telematic  
Engineering, E.T.S.I. Telecomunicación,  
Campus Miguel Delibes, Paseo de Belén  
15, 47011 Valladolid, Spain.  
Email: [noemer@tel.uva.es](mailto:noemer@tel.uva.es)

## Funding information

European Commission,  
Grant/Award Number: INTERREG V-A  
España-Portugal (POCTEP) jnprogram  
(0677\_DISRUPTIVE\_2\_E); Consejería de  
Educación, Junta de Castilla y León,  
Grant/Award Number: VA085G19;  
Ministerio de Ciencia e Innovación,  
Grant/Award Numbers: TEC2017-84423-  
C3-1-P, RED2018-102585-T

## Abstract

Engineering profiles focused on next-generation optical networks are gaining immense importance due to new emerging services and the amount of data expected in future network scenarios. In fact, not only are optical access networks leading to a major revolution in the network industry, but passive optical networks are the most widely deployed access networks worldwide today. This should be a strong incentive for universities to train their students in these innovative and recent technologies. In this vein, we propose the deployment of an optical communication laboratory with on-site experimental sessions in which students work with commercial equipment and realistic working environments. These working environments are necessary to train professionals in the area of optical networks. However, due to the high cost of the optical communications equipment, it is not possible to have a working place for each group and we combine these experimental sessions with some simulation sessions to complete the training. We present the design of this lab and a qualitative and quantitative study aimed at analyzing students' experiences, the skills they have acquired, and the potential impact on their future careers. This study shows that students have a very positive perception of the lab, emphasizing that working with real equipment helps them improve technical skills and assimilate theoretical knowledge. They also point out they would like a higher number of subjects in their degrees to employ this type of lab. Finally, students perceive these sessions as very useful for their professional future.

## KEYWORDS

engineering curriculum, experimental learning, laboratory, optical communications, simulation

[Correction added after online publication on 16 June 2021: Affiliation has been updated.]

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2021 The Authors. *Computer Applications in Engineering Education* published by Wiley Periodicals LLC

## 1 | INTRODUCTION

The European Higher Education Area (EHEA) has promoted a new educational paradigm that affects many aspects of the teaching process, moving from an educational scenario focused on teaching content to an educational scenario focused on learning skills and competencies. The EHEA has redesigned the structure and contents of curricula, increasing their relationship with professional profiles, and focusing on learning outcomes and competencies students should acquire to accommodate individual, academic, and labor market needs [6]. In this educational context, the professional profile and learning outcomes regarding the area of optical communications are of great importance nowadays, as optical communication systems and networks are essential to efficiently transport the huge volume of data traffic due to new emerging services (Tactile Internet, video gaming, and Internet of Things). Therefore, there is a need to train professionals in this area, and future engineers should acquire knowledge and skills related to next-generation access and core networks based on optical fiber technologies.

In fact, optical access networks are acquiring great relevance due to their strong global deployment, as traditional access technologies (coaxial and copper cable) were unable to cope with the increasing amount of traffic that networks should carry nowadays. Passive optical networks (PONs) are thus becoming the main high-speed solution for wired deployed access in all countries, and they have the potential to reach high market penetration in the short and medium term. In fact, a recent report of the FTTH Council in Europe (April 2020) [8] shows that in 2019, more than 172 million households in Europe were connected to FTTH/B (Fiber To The Home/Building), that is around 38.2% of all households. But the expectations of the FTTH

Council for the next years (2020–2025) are that the number of connected households in 2020 will be 189 million and this value will increase in 2025 up to 263 million [9]. In this future network scenario, PON solutions will be the predominant FTTH architectures, increasing up to 73% of the total deployed access networks by 2025. This fact emphasizes the need to include subjects related to these technologies in the curricula, not only including theoretical knowledge but also practical, mainly by using hardware as closer to the commercial one as possible.

The typical topology of a PON follows a tree scheme between an optical line terminal (OLT), located in the Central Office, and several optical network terminals (ONT), located at the user's houses (Figure 1) [18]. The connection between the OLT and the ONTs is done using optical splitters. These access networks use optical fiber and work on two different channels with a different wavelength dedicated to each channel. In the downstream channel, the connectivity between the OLT and the ONTs is point-to-multipoint, and a wavelength of 1490 nm is used for transmission. In contrast, in the upstream channel, from ONTs to the OLT, PONs have multipoint-to-point connectivity so all ONTs share the same wavelength, which is 1310 nm. Consequently, a MAC (medium access control) protocol based on TDMA (time division multiple access) is deployed to avoid data collisions of different ONTs.

Therefore, PONs can be analyzed from two different perspectives. On the one hand, the analysis of the physical layer in the upstream and downstream channels, because a real-time PON monitoring allows us to detect and locate fiber faults in any branch of the distribution fiber or in the feeder, and this process becomes critical for the flawless performance of a PON. In fact, PON monitoring at the physical layer reduces the provisioning time and the maintenance cost and it increases the quality of experiences of network

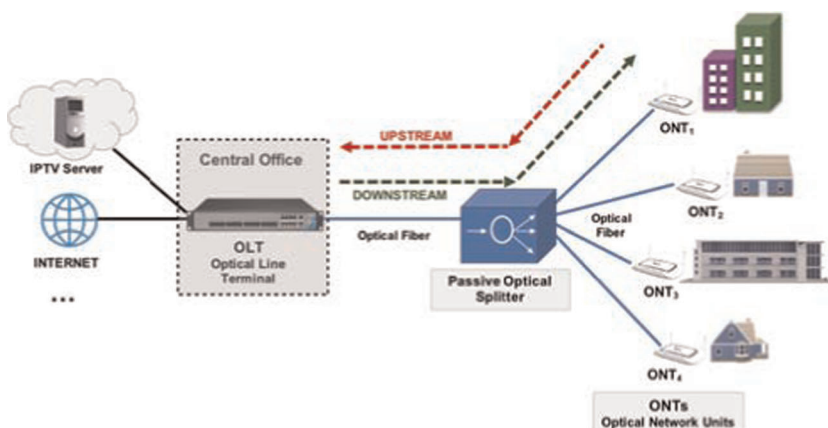


FIGURE 1 Typical topology of a traditional Passive Optical Network (PON) architecture

subscribers. On the other hand, the quality of service (QoS) and efficient management of network resources are also key elements in PONs, especially with the new emerging services and applications. In fact, the end-to-end delay and the allocated bandwidth are becoming important limiting factors for the users' experience [17,19].

Due to the importance of the PON technology in the access network market, and the need to train engineering students in this area, we have deployed a GPON testbed (a PON based on the Gigabit standard) [15] in the optical communications laboratory at the High School of Telecommunications of the University of Valladolid (Spain) [20]. The GPON testbed mimics the configuration of a generic network provider, thus providing different services and having a set of predefined user profiles with different QoS requirements. Students use this network configuration and associated equipment to learn about different topics related to physical layer analysis and performance measurement, as well as to build and test optical connectors and make fusion splices, using professional equipment, thereby acquiring hands-on experience. However, due to the high cost of the optical equipment, all the groups cannot work in the experimental sessions at the same time, so we combine these experimental lab sessions with simulation sessions so that students can achieve the required competencies of the curricula. Even more, the configuration of the GPON environment also opens the door for training students on network configuration, and management and resource allocation in GPONs and PON infrastructures in general. In this paper, we describe the testbed configuration as well as a set of lab sessions related to the physical layer of optical communication networks and systems combining simulation with experimental work. A preliminary description of the laboratory was presented in Valladolid.

The paper is organized as follows. Section 2 briefly reviews the basic competencies and skills required in the area of optical communications and then describes a number of approaches for setting educational labs in this field. Then, Section 3 presents the subjects related to optical communications in the School of Telecommunications and briefly describes the adopted solution, which includes simulation and experimental labs. Section 4 defines the setup of the GPON testbed at the optical communications laboratory, and Section 5 summarizes the experiments students carry out. Section 6 describes the simulation lab sessions. The conducted qualitative and quantitative research study, and the achieved results are presented in Section 7. Finally, Section 8 shows the most relevant conclusions obtained in this study.

## 2 | COMPETENCIES AND SKILLS IN THE AREA OF OPTICAL COMMUNICATIONS AND APPROACHES FOR SETTING EDUCATIONAL LABS

There are many professional profiles related to the area of optical communication systems and networks, ranging from research profiles to sales profiles, and including those focused on the design, management, and certification of these systems [4]. Independent of the future specific professional profile of each student, a set of generic formative objectives can be defined. First, the students should acquire *basic knowledge* of optical communications, including topics like the characteristics of light, the fundamentals of transmission, reception, and pulse propagation, and the kind of components used in these systems. This should provide a solid background for other competencies to be acquired by the students.

The students must acquire a set of *competencies to do analytical calculations, search and employ data sheets and application notes, and finally simulate and design systems and networks using existing tools or implementing them*. Then, the curriculum must also offer the possibility to the students of *acquiring experimental competencies*, including the use of typical optical communication equipment (like power monitors, digital oscilloscopes or optical time domain reflectometers [OTDR]) for measuring basic parameters of optical communication systems. These experimental competencies are aligned with the qualifications published by the FOA (fiber optical activities), an international nonprofit educational association that promotes professionalism in fiber optics through education, certification, and standards [32]. However, the high cost associated with equipment is a significant issue when designing a curriculum in this area.

Of course, there is another set of competencies common to every engineer, no matter what his or her field of work is. This includes *transversal competencies* such as technical writing, oral skills, and teamwork, to name just a few.

As we have just mentioned, one of the main difficulties of setting labs to train students in optical communications is the high cost of the required equipment. Consequently, many approaches involve combining on-site and virtual laboratories, as well as the use of interactive applications and simulation platforms. For instance, Prado et al. [28] have programmed an interactive and graphic learning tool to understand the operation and performance of single-mode optical fiber in different conditions. Its importance lies in the fact that single-mode optical fiber is one of the most

extended wired transmission media, especially for high-speed network communications, and its efficiency depends on some effects such as attenuation, chromatic dispersion, or nonlinear effects. Merayo et al. [21] have developed a set of Android applications to clarify optical communication concepts required in laboratory subjects, so students are provided with complementary and graphical tools to enforce their learning process. On the other hand, Gamo [11] has developed a virtual laboratory, called OPTILAB, which is used to complement an on-site traditional laboratory. Students can carry out some experiments using the virtual laboratory in advance, and then compare the results of the virtual lab with those obtained in the classroom laboratory, thus making on-site lab sessions more efficient. Besides, Akram et al. [1] have developed a fiber-optic communication educational toolkit platform to perform experiments on-site or remotely using low-cost and flexible equipment (such as FPGAs) to study high-speed communications systems. Other alternatives are related to the use of educational kits like those developed by Newport [23] or Thorlabs [33]. These kits enable performing many classic experiments regarding physics, optics, and photonics. However, this type of approach is less interesting for engineering degrees and more targeted towards physics degrees. On the contrary, virtual reality (VR) is also becoming a reality in engineering education. As an example, the project presented in Reference [12] shows the development of a VR module, which provides a virtual laboratory with realistic VR models of optical devices in which students perform experiments about laser diode characteristics and fiber coupling.

Hinton et al. [14] have developed a technology-enhanced learning environment for an undergraduate course on optical fiber communications, which includes interactive simulations and a virtual lab. Moreover, Ullah et al. [34] have implemented a simulation model of a wavelength division multiplexed passive optical network (WDM-PON) in the simulation environment OptiSystem [25]. This WDM-PON simulator makes it possible to analyze physical parameters such as power penalties, Q-factors, or eye diagrams, which helps to understand the principles of operation of next-generation access networks infrastructures using simulation techniques. Finally, a quite recent paper, by Aydin et al. [2], describes a fiber optic training program that combines real equipment and simulation platforms. This program includes the installation of FTTx and DVB-X (digital video broadcast—satellite, cable) devices typical in fiber optic cable infrastructure, and includes real laboratory experimentation, simulation platforms, and field practices. The experimental part includes splice backbone fiber optic cables and to point-to-point line measurements in digital video infrastructures.

### 3 | DESCRIPTION OF OUR OPTICAL COMMUNICATIONS SUBJECTS

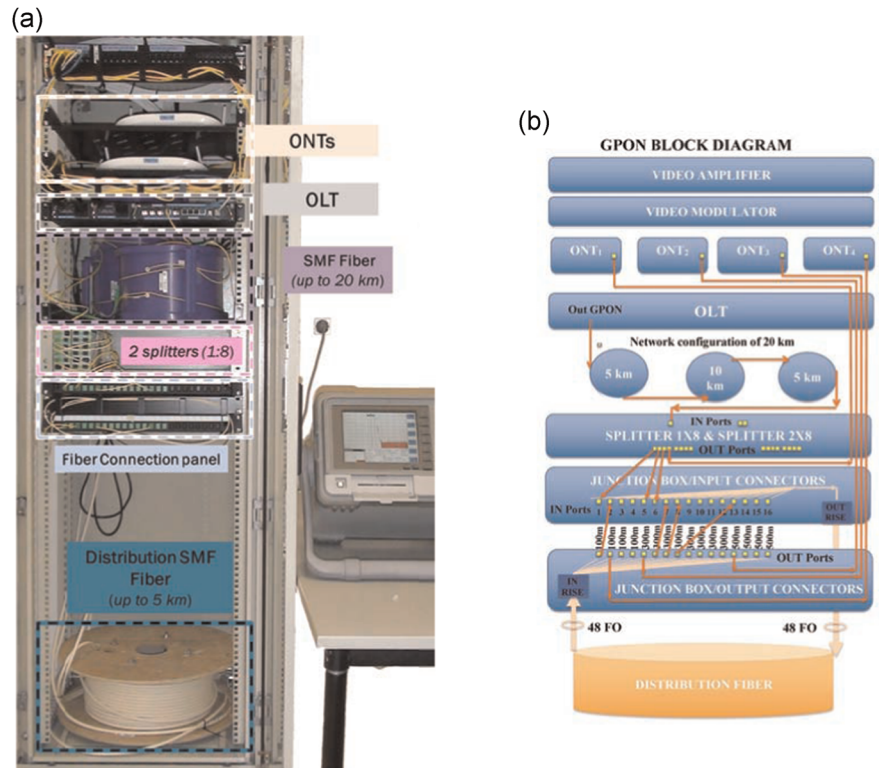
At the time of writing, there are two undergraduate degrees at the High School of Telecommunications of the University of Valladolid [29]. Both degrees have a third-year compulsory subject, focused on the fundamentals of Optical Communications, and a fourth-year elective subject focused on more advanced Optical Communication Systems and Optical Networking. Each of these subjects is taught throughout a semester and has an academic workload of six ECTS (European Credit Transfer and Accumulation System). The third-year subjects usually have around 24–30 students, and the fourth-year subjects around 12–18.

Specific objectives associated with each of the competencies summarized in Section 2 are defined for each subject, and suitable contents and methodologies have been selected for them. These subjects consist of lectures and laboratory sessions about theoretical and experimental optical communications concepts. As we have described in Section 2, there are many approaches to set educational labs in optical communications. Our approach has consisted in combining the use of simulation platforms with experimental work. In this way, the laboratories consist of two distinct parts.

In one of those parts, students work with simulation platforms. In the third-year subjects, students use OptSim, a software developed by RSoft [27] to design and simulate optical communication systems. OptSim is widely employed in optical network research, but also for educational purposes. In the fourth-year subjects, students employ the Net2Plan open-source network planner simulator [22] and the OMNeT++ discrete event simulator [24] to acquire competencies related to network planning and control of optical networks. Therefore, the subjects of both courses (third and fourth) complement each other because the third-year course focuses on the physical layer and the fourth-year course focuses on the control layer.

The other part of the lab in the third year subjects consists of two sessions focusing on experimental issues (3 h each lab session). For this part, the first designed courses included the use of a set of training kits commercialized by Newport [23]. As discussed in Section 2, these kits are well oriented to demonstrate many physical optical concepts (very valuable in that sense), but the type of experiments, components and equipment used, does not really match the ones an optical communications engineer will typically face throughout his career. Consequently, we redesigned our lab by taking a different approach. We have adopted an approach as realistic as possible, employing similar equipment, devices, and networking scenarios students may face in the short or medium term in their careers. In particular, we have

**FIGURE 2** Deployment of the GPON testbed in the Optical Communication Laboratory. (a) Connection between devices and (b) block diagram of the panel connections. GPON, passive optical networks based on the Gigabit standard; OLT, optical line terminal; ONT, optical network terminal; SMF, single-mode fiber



built a laboratory testbed, based on GPON architectures (the most widely deployed high-speed access network technology all over the world), thus transforming the on-site laboratory into a professional environment that brings students closer to a more realistic vision of their future work, increasing their motivation and providing them with meaningful and functional learning experiences. It should be emphasized that companies and associations in the field of fiber optics support the deployment of this type of professional network laboratory for training future engineers. This idea is also aligned with some experiences described in Section 2, for instance, experiments in Reference [2] were based on interviews with industry representatives in fiber optic installations. Besides this, photonic companies (Thorlabs [33] or Fiber Optika [7]) provide educational kits regarding optic technologies and companies (Corning [3]) offer training courses regarding optical networks. Finally, manufacturers of PON equipment, such as Telnet-RI [31], also support this training program in Universities.

In the first session of our experimental lab, aligned with the general competencies of the FOA (described in Section 2), students learn to build fiber connectors and to splice fibers using a professional and automatic optical splicer. In another of our lab sessions, students use OTDR and digital oscilloscopes to analyze and measure performance metrics of the GPON testbed, so this is also consistent with the general experimental competencies outlined in Section 2. However, due to the cost of devices

and equipment (also mentioned in Section 2), a single testbed has been set up in our lab, and we employ a rotatory strategy so that all students can complete the assignments related to the testbed along the semester. Thus, in each lab session, one group of students is working in the testbed, and another in the connection and fiber splicing tasks, whereas the remaining groups are working in the simulation sessions previously mentioned. This approach and strategy have economically allowed us the deployment of this type of network infrastructure in teaching laboratories oriented to engineering degrees. We think this strategy can be followed by other universities. Therefore, in addition to being an affordable approach, it meets the general experimental competencies described in Section 2.

#### 4 | DESCRIPTION OF THE GPON INFRASTRUCTURE AND EQUIPMENT IN THE LABORATORY

The GPON infrastructure of the lab is shown in Figure 2a. The network was set up with equipment and devices from the manufacturer Telnet-RI [31]. In particular, we use the SmartOLT 350 (typically located at the Central Office in a real network), which complies with the ITU-T G.984 [15] and G.988 specifications [16] and implements a GPON interface of 2.488 Gbps in the downstream channel and 1.244 Gbps in the upstream channel. The SmartOLT

includes four ports and each port supports up to 64 ONTs. To connect the OLT with the optical splitter, we have deployed two spools of 5 km and one of 10 km of SSMF (standard single-mode fiber), which give flexibility in configuring the total length of the GPON (plus the length of the distribution fiber, as later described). The GPON testbed also has two optical splitters (1:8) deployed to configure a two-stage splitting topology. Then, the splitters (passive couplers) are connected to the ONTs by distribution fibers. The length of each link can be individually configured by a connection panel from 100 meters up to 5 km, as it is shown in Figure 2b. In this way, the GPON testbed can be used to configure realistic network scenarios where users are located at different distances from the Central Office (OLT). In fact, this flexibility allows, from the teaching point of view, to make different network configurations to be tested by students. Finally, our GPON testbed is equipped with four Level 3 model ONTs (Wave Access 3021) [31], which means that they integrate router functionalities and two Level 2 (without router functionalities) ONTs (Wave Access 512) that comply with the ITU-T G.984.x/G.988 recommendations. Besides this, the OLT provides residential users (via the ONTs) with service profiles of different priorities and characteristics. These services can be configured in two different ways with specific software provided by the vendor: Using a visual tool (TELNET GPON Management System), or directly, accessing the OLT via the Command Line Interface (CLI) through its configuration port. To analyze the physical layer of the GPON testbed, students learn to use OTDRs and digital oscilloscopes. Specifically, they use the Hewlett-Packard 8147 A OTDR [13] to analyze the optical events in the GPON network (Figure 3), and the digital storage oscilloscopes Agilent DSO90254A [26] and 86100B [5] to analyze signals and optical parameters in the physical layer of the GPON (Figure 4). We employ two oscilloscopes models so



FIGURE 3 Picture of the Hewlett-Packard 8147 A optical time domain reflectometer

that students can learn to configure different models and they can train with different equipment.

On the contrary, students learn to build optical connectors commonly used for telecom applications and network environments, as connections between optical devices are crucial for the optimal performance of the optical networks. To build connectors, students learn to prepare the fiber ends, cleaning and cleaving them. For this, a Fujikura CT-06 cleaver [10] is used (Figure 5). Besides this, during the experimental lab sessions students employ an automatic fusion splicer model T-201eVS/M4 of Sumitomo [30] to make fusion splices in multimode fibers (Figure 6).

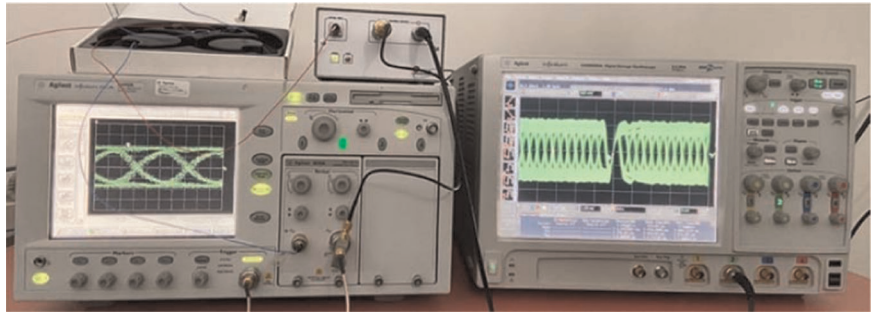
## 5 | SUMMARY OF THE LAB EXPERIMENTS

In this section, we describe the experiments carried out by third-year students using the aforementioned infrastructure and equipment during two lab sessions (3 h each session), one focused on connectors and the other focused on the physical analysis of the GPON testbed. At the end of these lab sessions, the students should be able to use optical instrumentation and equipment to make optical connectors and fusion splices, as well as to measure and analyze signals and basic optical parameters of the physical layer of a GPON, characterizing both upstream and downstream channels. The methodology of the laboratory sessions is summarized as follows:

- o First, at least 1 week in advance of the session, a lab guide is published in the learning management system (LMS) course associated with the subject.
- o Then, during the first 10 min of the on-site session, students must individually fill out a questionnaire to check if they have read and understood the lab guide before proceeding with the experiments.
- o During the on-site session, the instructor provides specific instructions of the steps that students have to follow and supervises the progress of the work.
- o During the on-site session, students have to fill out a template given by the teacher, with the results obtained in the session, and answering related questions.

Moreover, we have published in the link <http://uvadoc.uva.es/handle/10324/46275> these lab guides, the questionnaires given to students at the beginning of the session, the guidelines given during the lab session and the template the students must complete. However, as the original resources are in Spanish, all the documents have also been published at the link <http://uvadoc.uva.es/handle/10324/46274>.

**FIGURE 4** Picture of the optical digital storage oscilloscopes of Agilent model DSO90254A and 86100B



**FIGURE 5** Picture of the cleaver model of the laboratory



**FIGURE 6** Picture of the Sumitomo T-201EVS/M4 fusion splicer

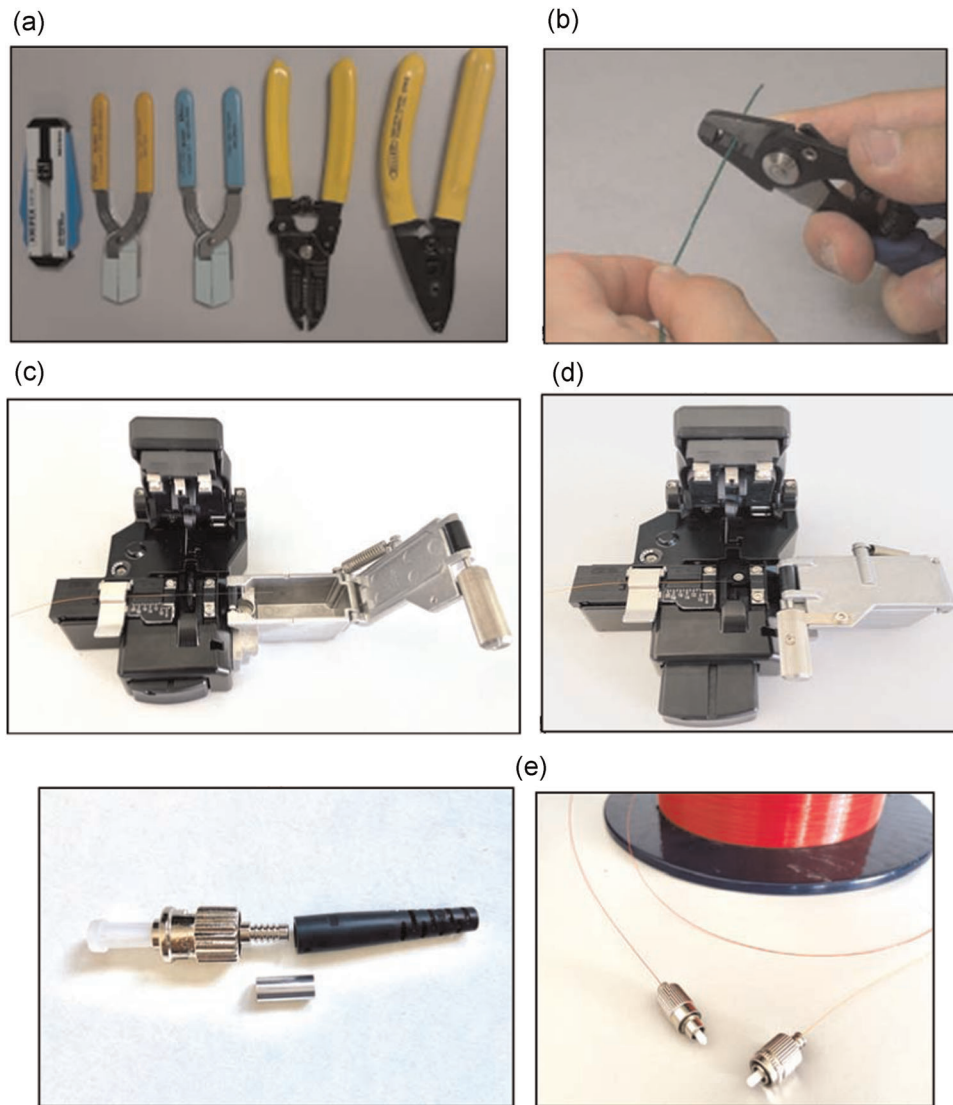
## 5.1 | LAB 1: Connectors and fusion splices

In this lab session, students assemble connectors using the epoxy technique and splice fibers by fusing them. When assembling connectors, the first step consists in the preparation of the fiber ends by

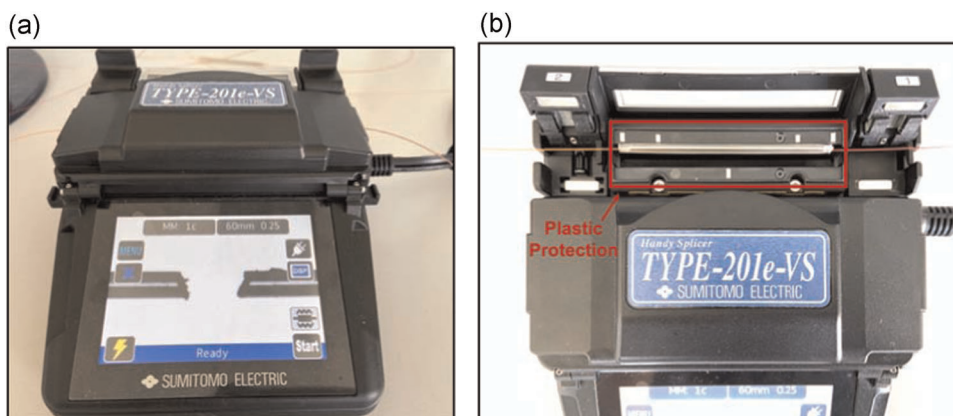
removing fiber coatings using mechanical strippers (Figure 7a,b). Then, the fiber must be cleaved, as the fiber-end faces must be flat, smooth, and perpendicular to the fiber axis to ensure a good fiber connection. This process is made using an automatic cleaver (Figure 7c,d). The last step consists in building the connectors by using FC (Ferrule connector)/PC (physical contact) and ST (straight tip connector)/PC connectors, used in multiple telecom applications and network environments. In fact, Figure 7e shows a ST/FC connector.

To make fusion splicing, students learn to use an automatic fusion splicer (Figure 8). The splicer has several predefined programs that allow to automatically fusion splice different types of fiber, both multimode and single-mode fibers. Figure 8a shows how the fiber ends are aligned inside the fiber holders just before splicing both ends and Figure 8b shows the splice protection of plastic to protect the fusion splice.

Students also have to check the characteristics of the connectors and fusion splices they made, by using optical fiber microscopes and OTDRs, respectively. The OTDR is an optoelectronic instrument used to characterize optical fibers. It injects optical pulses into the fiber under test in one of its ends, and extracts, from the same end, the light that is reflected back (scattered) from points along the fiber (Rayleigh Backscatter phenomena). The reflected light is used to characterize the attenuation of the optical fiber and the strength of the returned pulses is measured and plotted as a function of the fiber length. Besides this, a microscope for fiber inspection is used for visual inspection of connectors. This kind of microscope has a fixture to hold the fiber or connector steady in the field of view and a light source to illuminate the connector. Therefore, this lab session also permits students to acquire experimental competencies related to the use of optical communication measurement equipment. Therefore, in summary, in this lab session, students have to use different optical components and tools to achieve the next learning objectives:



**FIGURE 7** Some pictures regarding building connectors. (a) Removing fiber coating with mechanical strippers, (b) process to prepare the fiber ends, (c) insertion of the fiber inside the cleaver, (d) fiber cleaved, and (e) visualization of an assembled connector (straight tip connector/Ferrule connector)



**FIGURE 8** Some pictures regarding the automatic fusion splicer. (a) Visualization of the fusion made by the automatic fusion splicer and (b) visualization of the made fusion with the plastic protection



- o To build a fiber optic connector using the epoxy technique.
- o To check the quality of these connectors using fiber optic microscopes/inspectors.
- o To perform fusion splices in multimode fibers.
- o To check the performance of fusion splices using an OTDR.

## 5.2 | LAB 2: Physical analysis of the GPON testbed

This second lab consists of two different parts focused on the GPON testbed. In the first part of the lab, students use the OTDR to analyze the physical parameters of the fiber and the infrastructure. In the second part, students use digital oscilloscopes to analyze the transmitted signals and related optical parameters. The setup of the GPON testbed and the measurement equipment is shown in Figure 9.

### 5.2.1 | Use of the OTDR to analyze physical parameters of the fiber in the GPON testbed

As described in the previous section, an OTDR is an optoelectronic instrument used to characterize optical fibers and the strength of the returned pulses is measured and plotted as a function of the fiber length, as it can be observed in Figure 10a. An OTDR helps to check if the optical links of a network comply with the basic quality of transmission requirements. These requirements can be related to the accumulative attenuation in



FIGURE 9 The GPON (passive optical networks based on the Gigabit standard) testbed and the optical instrumentation used during the experimental sessions

the link or to detect problems (points with massive reflections or abrupt attenuations) at any place of the link. Therefore, this device visually shows information of every detected event in the optical link, such as the location, length, and state of passive components such as splices or connectors. The OTDR can as well detect cuts or abnormal performance of the optical fiber and their location in the link. The detection of these events is very dependent on the configuration of the optical pulses. As described in Section 4, the flexibility of the GPON testbed allows the instructor to set up different network link scenarios to be tested by students. Students should achieve, in this part of the lab session, the next main objectives:

- o To configure and use the OTDR correctly and efficiently to obtain information of a fiber installation, in that case in the GPON testbed.
- o To locate and to interpret the different events visualized by the OTDR along the GPON link in both directions, downstream and upstream. To visualize the events in the GPON link, we should connect the OTDR to one end of the network, so we disconnect the fiber cable from an ONT and connect the said cable to the OTDR input, as we can observe in the setup of Figure 10b. Besides this, an event is any situation in which there are reflections or losses other than the dispersion produced by the fiber. Examples of such events are:
  - *Connectors*. They are characterized by causing a strong reflectivity (spike). Moreover, the normal situation in a fiber link is to have one connector at the beginning and one at the end of the link, so there will be two strong reflectivity peaks at both ends. The difference between the two is that at the extreme end, once the effect of the connector has passed, the signal level drops to the noise level of the device, as we can observe at the end of Figure 10a.
  - *Fiber failures such as breaks/cuts*. They are nonreflective events and there is a drop in intensity down to the noise level.
  - *Fusion splices*. They don't cause a strong reflectivity (spike) as a refractive index jump does not occur. In this situation, it is normal to detect some type of loss (very small) in the fiber (Figure 10b).
  - *Cracks*. A fiber that is partially damaged but whose continuity has not been completely destroyed. It will introduce reflections and losses.
  - *Curvatures*. They are nonreflective events so the pattern will be the same as in the case of a fusion splice. To distinguish both types of events is quite useful to

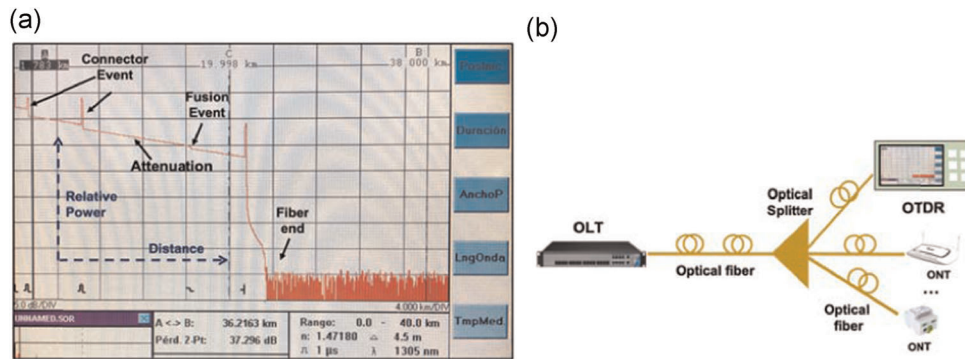


FIGURE 10 Visualization of events using the optical time domain reflectometer (OTDR). (a) Visualization of events in the fiber of the GPON (passive optical networks based on the Gigabit standard) testbed and (b) setup block diagram

test the system at different wavelengths as curvatures have greater losses at a higher wavelength, compared to splices whose losses are independent of the wavelength.

- o To understand the impact of using different configurations of the OTDR. Therefore, to locate events on the fiber, it is necessary to establish a suitable OTDR configuration. Thus, the most important OTDR configurable parameters are:
  - *Pulse width.* This parameter determines the duration of the pulse emitted to the fiber optic link. Shorter pulse width is selected for short lengths as this maximizes resolution while minimizing power output. Short pulse widths are especially useful for evaluating cable segments closer to the OTDR and for detecting events near a connector or splice. Besides this, longer pulse widths are useful when testing longer fiber links, as more optical power is required to produce sufficient backscatter at long distances from the OTDR.
  - *Averaging time.* In general, more accurate measurements are usually achieved by calculating the average of several repetitions of the same test. This principle is also valid for OTDR measurements. Longer averaging times, that is, based on a greater number of repetitions of the same test, will provide a measurement with a better signal-to-noise ratio, although it will require more time.
  - *Dynamic range.* The dynamic range of an OTDR determines how long a fiber can be measured (it is listed as a dB value) and larger values generally mean longer distance measurement capability.
  - *Refractive index.* An OTDR calculates distances by measuring the time elapsed from the transmission of a light pulse to the reception of its reflection and the calculation of the distance from time is done by means of the refractive index. Therefore, it is necessary to

know exactly the fiber that we are using to calculate the distance.

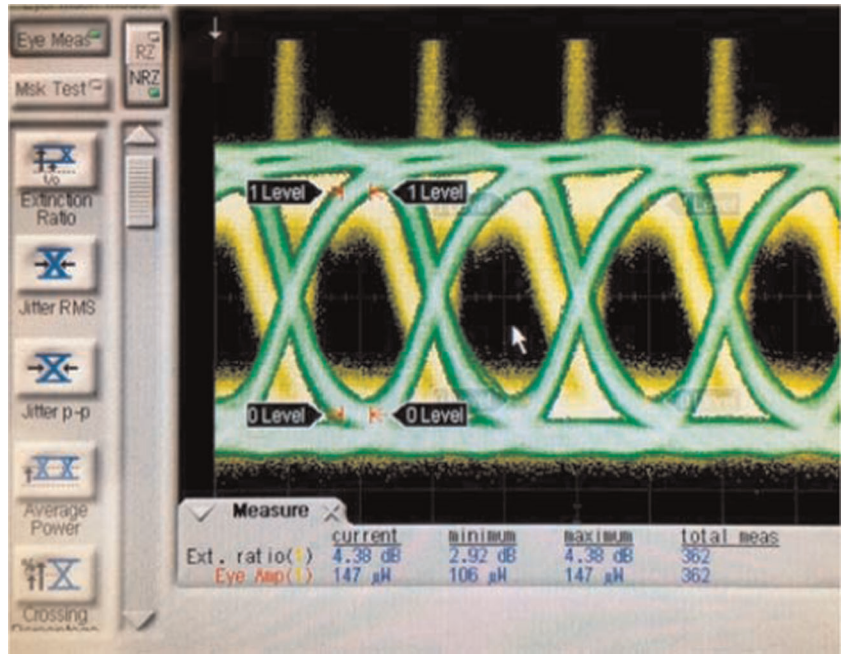
### 5.2.2 | Use of digital oscilloscopes to analyze physical parameters of the GPON testbed

In this part of the lab session, students learn to use digital oscilloscopes to analyze the optical signals transmitted by the OLT and by the ONTs (located at the user's side), evaluating the eye diagrams, the mask test on the eye diagrams, the Q-factor, the bit error rate (BER), the extinction ratio, and the rise/fall times of the transmitters, which are key elements to assess the performance and quality of optical signals.

First, students analyze the optical and electrical signals at the output of the OLT with the aim that students can be able to detect the difference of the signals in both domains, that is, optical and electrical. To simultaneously visualize and analyze the optical and the electrical eye diagrams (Figure 11), the output of the OLT is connected to an optical coupler, which divides the optical signal into two outputs (Figure 12a). One output of the coupler directly goes to Channel 1 of the oscilloscope and the other goes to an optical receiver that converts the optical signal to electrical, and this signal is connected to Channel 2 of the oscilloscope, as we can observe in the setup of Figure 12b. Moreover, the same setup is done to visualize the frames of ONTs, but in this case connecting the output of the ONTs to the digital oscilloscope (Channels 1 and 2).

Students also have to visualize and analyze using the oscilloscope the data frames transmitted by the OLT (Figure 13) and by the ONTs (Figure 14). For instance, Figure 14 shows a sequence of data frames sent by different ONTs (each of them with different instantaneous optical powers) for a period of time (called slot time in Figure 14) which depends on the TDMA protocol used in

**FIGURE 11** Optical (yellow) and the electrical (green) eye diagrams at the output of the optical line terminal



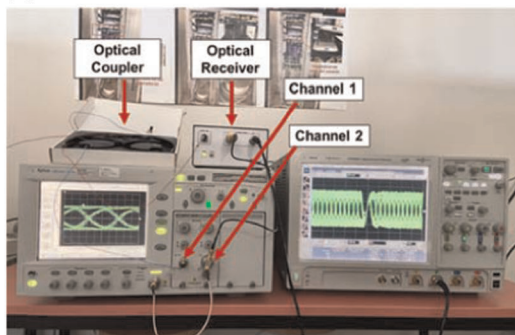
the upstream channel (medium access control protocol used in GPON). As we can see in Figure 14, each ONT transmits during a different slot time, as all ONTs share the same upstream wavelength and the OLT allocates a different slot time to each ONT. Moreover, the guard time and the preamble of the frames transmitted by ONTs can also be observed and analyzed in Figure 15. Finally, students also analyze the eye diagram of the signals transmitted by the ONTs. Indeed, several physical-layer parameters are used to characterize optical signals, and most of these have specific limits and test conditions. Thus, in summary, the experimental setup is shown in Figure 12a,b permits students to attain the following objectives:

- o To use digital oscilloscopes to visualize and compare the optical and the electrical eye diagrams,

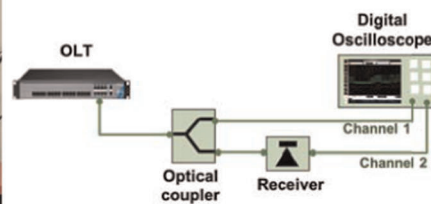
permitting students to detect differences between signals in both domains (optical and electrical), for instance, the overshooting effect of the laser of the OLT in the optical domain. Indeed, students compare the same signal in the digital oscilloscope using Channel 1 (optical signal) and 2 (electrical signal) as was previously explained.

- o To measure and compare rise/fall times, extinction ratio measurements or the eye patterns (eye diagrams) of GPON signals. In this way, extinction ratio measurements are typically performed on eye diagrams using a digitizing oscilloscope and it is an important measure of the quality of an optical signal. The extinction ratio is the relationship between the power used to transmit a binary “1” and the power to transmit a binary “0” (in dB) and it is desirable to have large differences between these powers to achieve

(a)



(b)



**FIGURE 12** Connection of the optical line terminal (OLT) to the digital oscilloscope to visualize the optical and electrical eye diagrams (a) real deployment in the laboratory (b) setup block diagram

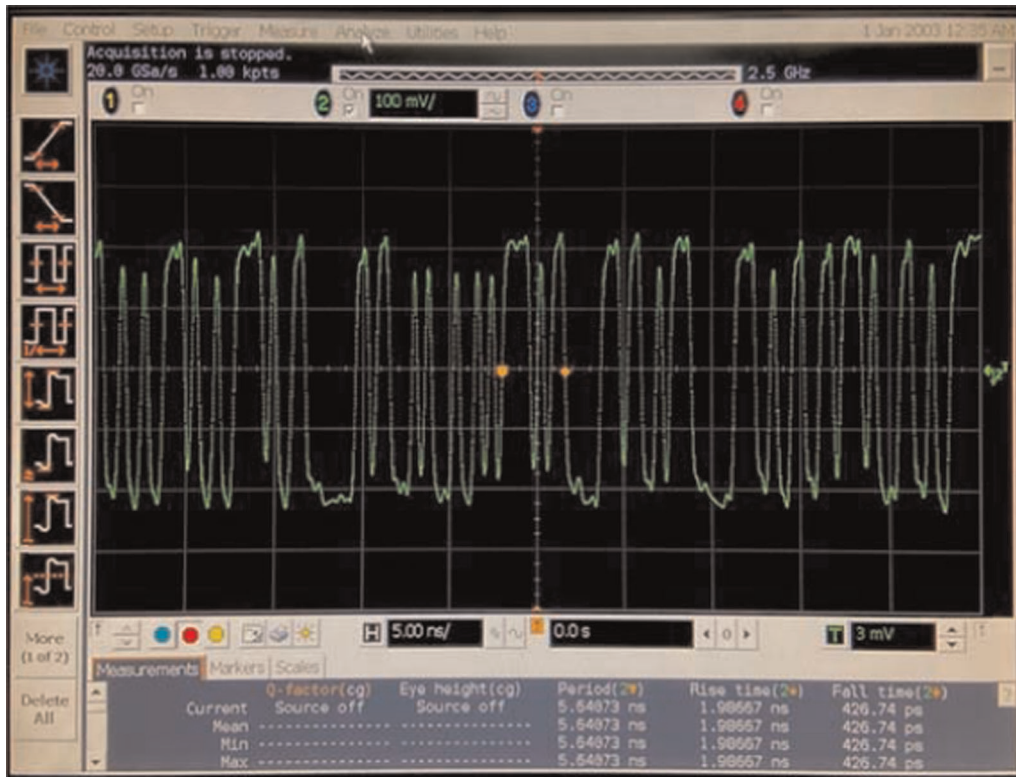


FIGURE 13 Data frames with the information transmitted by the optical line terminal

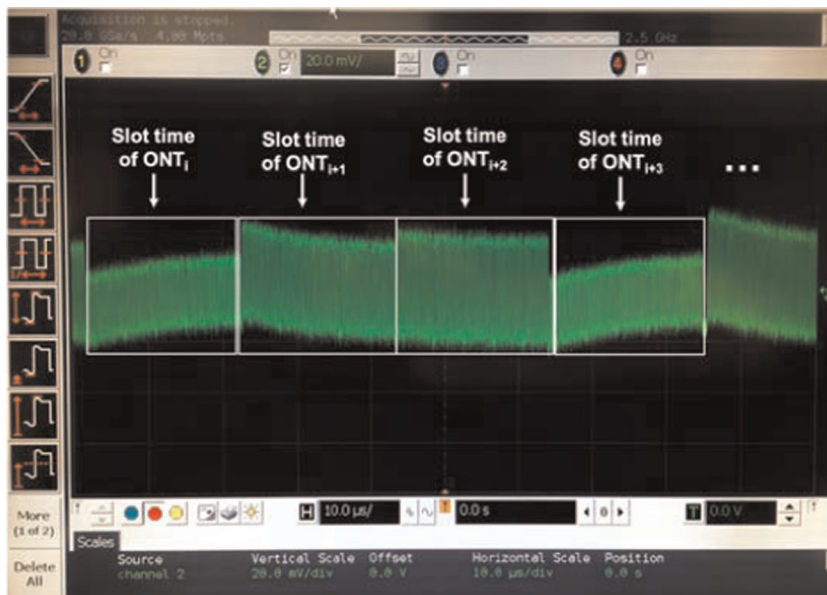
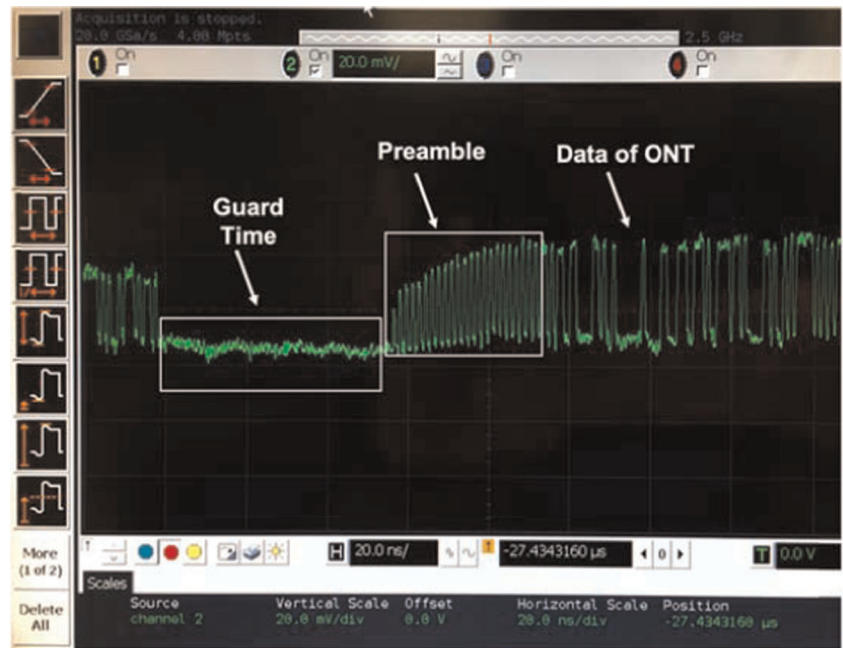


FIGURE 14 Data frames transmitted by the connected optical network terminals

high network performance. Besides this, eye patterns are widely used for analyzing the quality and the stability of optical systems. Then, open eye patterns correspond to minimal signal distortion and close eye patterns correspond to high signal distortion (noise or interference). The values of these parameters can be directly visualized in the digital oscilloscope using the setup configuration of Figure 12b.

- o To measure the Q factor associated with a GPON signal, and then to calculate the BER value using this Q value. In fact, the BER is the percentage of bits that have errors relative to the total number of bits received and the Q factor suggests the minimum signal-to-noise ratio required to obtain a specific BER. Therefore, when these levels are above or below certain levels (the most typical maximum BER is of

**FIGURE 15** Preamble and guard time of data frames transmitted by optical network terminals (ONT)



$10^{-9}$ ), they can cause poor or high network performance. Thus, students directly can observe these parameters using the setup of Figure 12a,b and they should discuss if these values cause poor or high network performance.

- o To visualize and analyze the data frames transmitted by the OLT and ONTs, using the configuration of Figure 12b. In fact, students will be able to distinguish data frames of different ONTs (slot time), as well as the guard time and the preamble of frames transmitted by ONTs (Figures 13–15).

## 6 | SUMMARY OF THE SIMULATION EXPERIMENTS

As mentioned before, our laboratory consists of combining experimental sessions with simulation lab sessions to acquire the required competencies. Therefore, we follow previous experiences from different authors that combine on-site with virtual laboratories. In our case, in the third-year subjects, students use the OptSim simulation platform to design and simulate optical communication systems. The methodology of these laboratory sessions is the same as the one described in the previous section. Specifically, during the simulation sessions (3 h each session), students focus on:

- o Session 1: Analyzing different optical modulation techniques and fibers.
- o Session 2: Analyzing the impact of attenuation in optical communications systems.

- o Session 3: Analyzing the impact of dispersion in optical communication systems.
- o Session 4: Analyzing a GPON network and its performance at the physical layer using simulation techniques to characterize the downstream channels (Figure 16).

With these simulation sessions, students acquire a set of competencies related to the simulation and design of systems and networks, as was described in Section 2. Moreover, these lab sessions help students to understand certain complex and abstract processes and phenomena regarding optical communications which have been explained to them in the classroom. In addition, the lab session regarding GPONs helps students to relate the simulation performance with the performance of a real network and consequently they learn to design optical networks using simulation techniques.

## 7 | RESEARCH STUDY OF STUDENT FEEDBACK AND DISCUSSION

To analyze the benefits of using professional optical instrumentation and realistic network scenarios, students of the academic year 2018/19 were given an ad-hoc questionnaire, including quantitative and qualitative questions. The number of students that answered this questionnaire was 26, very close to the total number of students enrolled. Unfortunately, the experimental lab could not be carried

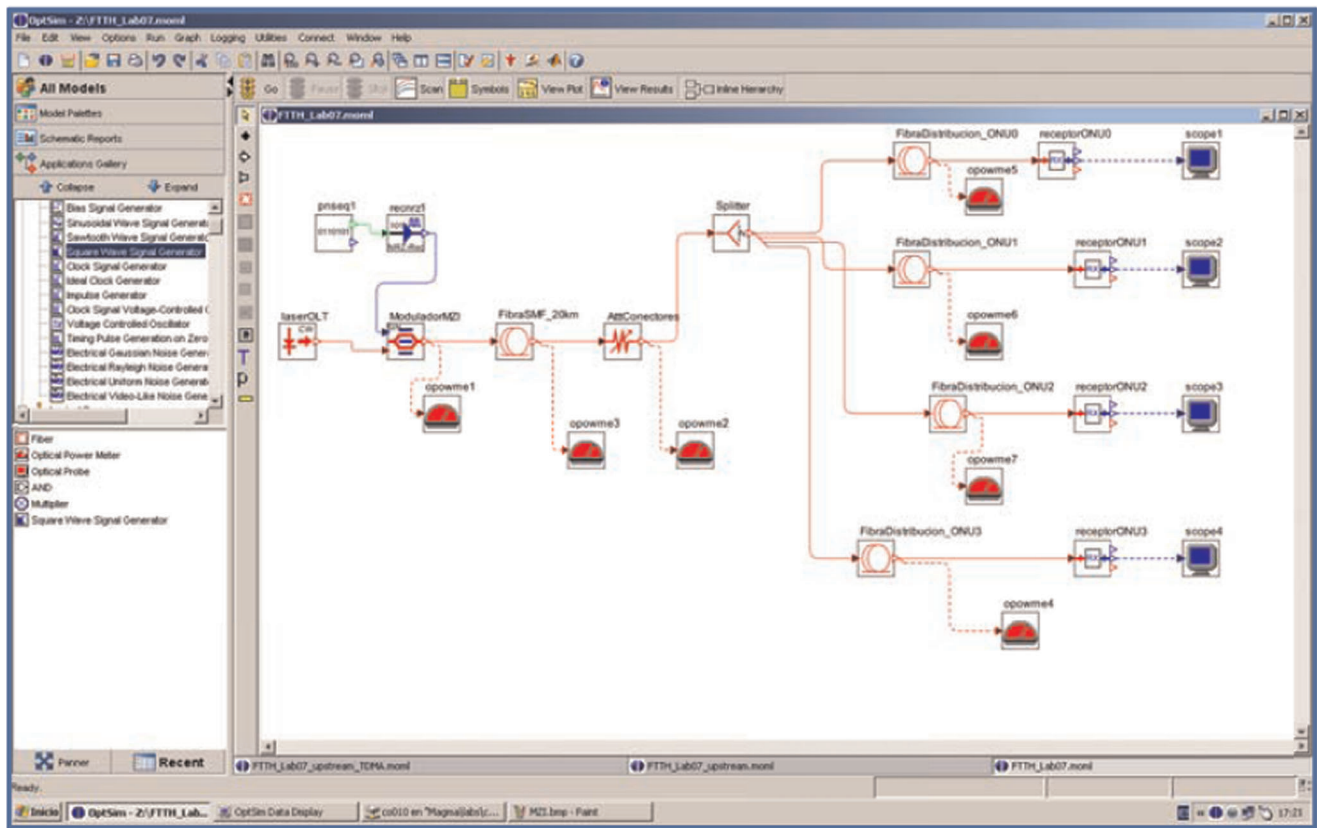


FIGURE 16 Simulation of a passive optical networks based on the Gigabit standard (GPON network) using the Optisim Platform

out in the 2019/20 academic year due to the COVID-19 pandemic, so only 2018/19 results are presented.

Regarding the quantitative analysis, students had to score a set of statements between 0 and 5, according to

the Likert scale, being 0 “Do not agree,” 1–2 “Little agreement,” 3–4 “Quite agree,” and 5 “Totally agree.” Table 1 summarizes the specific questions and the mean score given by the students. As it can be observed, the

TABLE 1 Quantitative questions of the questionnaire with the mean score given by students to each

Questions	Mean score
Q1: Lab sessions with real equipment/instrumentation have allowed me to improve knowledge in instrumentation and optical systems.	4.7
Q2: Lab sessions with real equipment/instrumentation have allowed me to improve technical skills related to the use of instrumentation	4.7
Q3: Lab sessions helped me assimilate/consolidate theoretical knowledge related to the subject and to relate practice with theory	4.7
Q4: Lab sessions have allowed me to understand certain parameters studied in the classroom (attenuation, losses, powers, bit error rate, and eye diagram)	4.6
Q5: Lab sessions have allowed me to handle certain components/devices and understand procedures studied in the classroom (fiber, connectors, fusions, optical time domain reflectometer, etc.)	4.8
Q6: Lab sessions have provided me the chance to work with devices/technologies that could be useful for my future career if I work in the field (optical networking)	4.4
Q7: Lab sessions with real and current instrumentation/devices is a relevant resource to acquire knowledge in subjects	4.75
Q8: Lab sessions are up to date regarding cases that I could find or analyze in current networks	4.2

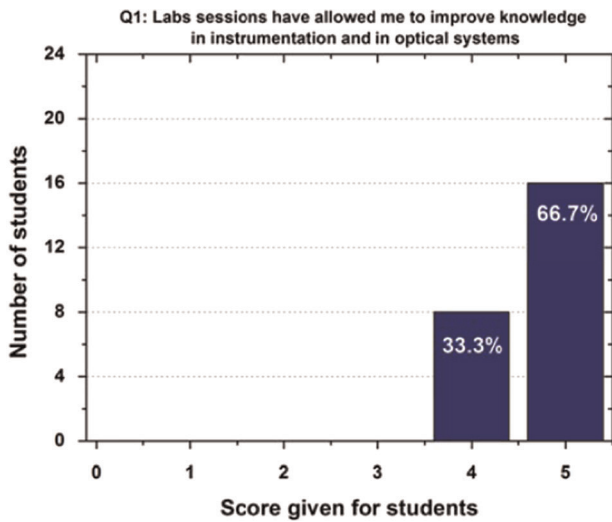


FIGURE 17 Average score given by students to question Q1

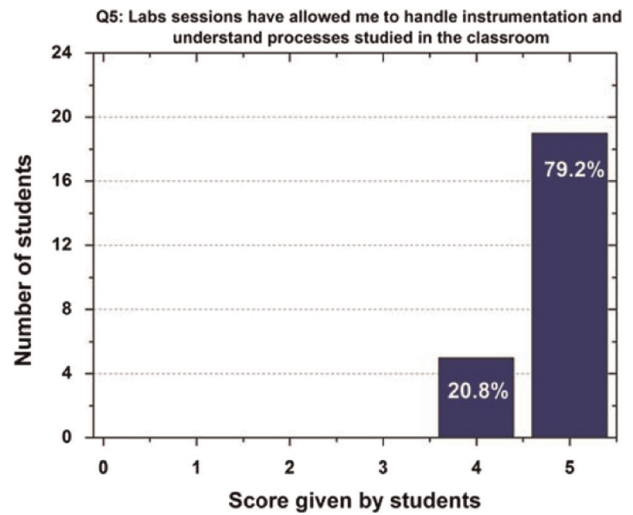


FIGURE 19 Average score given by students to question Q7

mean score given by the students to each question is always higher or equal to 4.2 over 5, with a global average value, considering all the questions, of 4.6.

To analyze these results in more detail, histograms associated to some of these questions are shown next. First, Figures 17–19 show the answers of the students regarding questions Q1, Q5, and Q7, respectively. Figure 17 shows that 66.7% of students totally agree with the statement that the experimental lab sessions have helped them improve their knowledge of instrumentation and optical systems (score of 5) and the remaining 33.3% of them quite agree with this fact (score of 4).

The answers to question Q5 (Figure 18) show that 79.2% of students give a score of 5 (“Totally agree”) and the remaining 20.8% a score of 4 (“Quite agree”). Consequently,

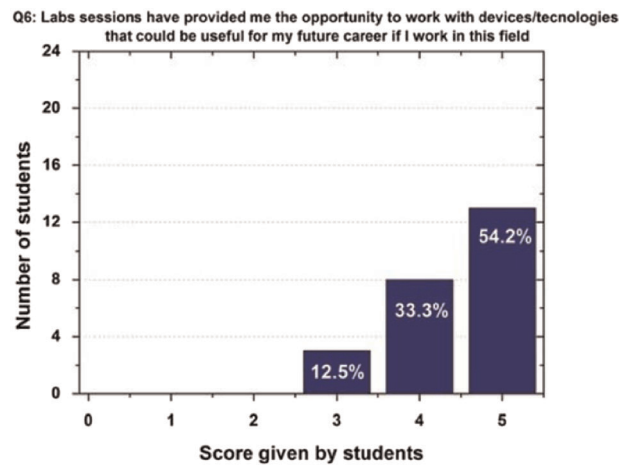


FIGURE 20 Average score given by students to question Q6

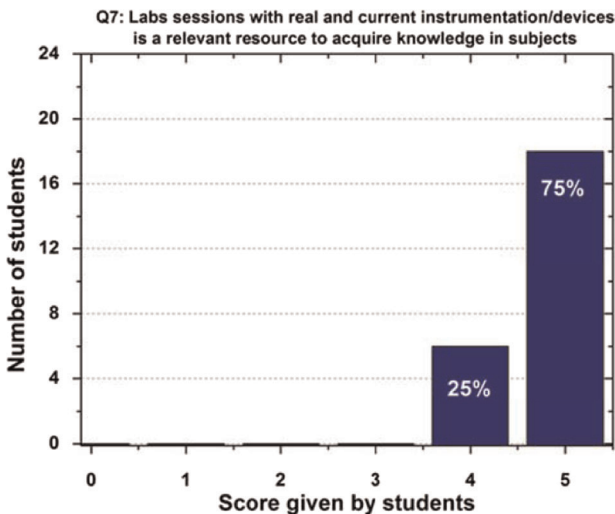


FIGURE 18 Average score given by students to question Q5

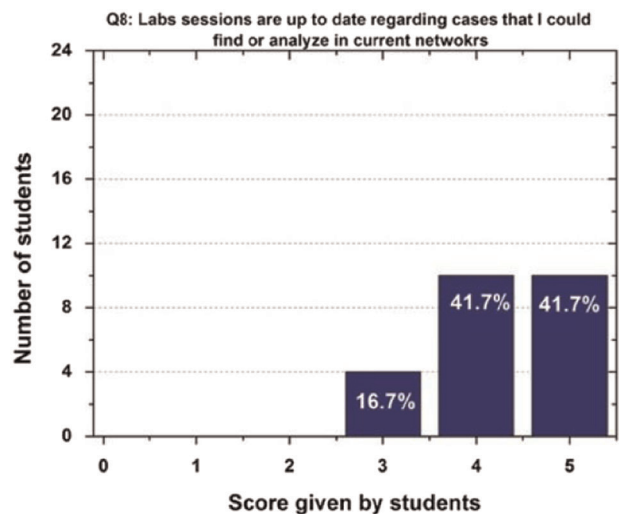


FIGURE 21 Average score given by students to question Q8

TABLE 2 Quantitative questions of the questionnaire with the mean score given by students to each question

Questions	More most repeated responses
Q10: What was the best part of the experimental lab sessions?	<ul style="list-style-type: none"> <li>• To experiment with real optical equipment and instrumentation used at a professional level.</li> <li>• To make fusion splicing in optical fibers</li> <li>• Adequacy of laboratory content with theory.</li> <li>• To experiment with real networks on a physical level.</li> </ul>
Q11: What was the worst part of the experimental lab sessions?	<ul style="list-style-type: none"> <li>• To have only two experimental sessions. We would like to replace more simulation sessions with experimental work in the lab.</li> <li>• To have so few experimental lab sessions.</li> </ul>
Q12: Do you have any additional comments, suggestions?	<ul style="list-style-type: none"> <li>• Experimental sessions are very attractive and enjoyable.</li> <li>• Regarding optical connectors and fiber splicing, we can observe how every little detail matter and helps us understand how they behave physically.</li> <li>• Regarding the GPON testbed, it is a very good example to put us in a real situation of analysis.</li> <li>• Experimental sessions have a plus of placing us in an environment that may be similar to the one we can find in a future.</li> <li>• Experimental sessions are essential for the student to complete their training with a methodology that is sometimes scarce throughout the degree.</li> </ul>

students clearly perceive that the experimental sessions help them to handle real optical components and devices and understand processes studied in the classroom. Furthermore, regarding question Q7, it can be seen in Figure 19 that 75% of students give a score of 5 (“Totally agree”) and 25% of them a score of 4 (“Quite agree”). One more time, it can be stated that the proposed lab sessions with real and commercial instrumentation is, according to the students, a relevant resource to better acquire knowledge in the subjects.

On the contrary, students perceive that the technologies and devices used in the lab could be very helpful for their professional career if they worked in the future in this area (question Q6), as 54.2% of students give a score of 5 (“Totally agree”), 33.3% of them a score of 4 (“Quite agree”) and 12.5% a score of 3 (“Quite agree”), as shown in Figure 20. Finally, Figure 21, regarding question Q8, shows that students also perceive that these sessions are quite up to date according to cases that they could find or analyze in current optical networks and systems. This perception of the students is also supported by the teacher’s feedback and certain extra homework that students are encouraged to do. Indeed, during these specific lab sessions, students are explained the importance of FTTH/PON deployments worldwide and its penetration forecast for the next few years. In addition, students are encouraged to look for recent news regarding the current deployment of these technologies and their short-term trends in the coming years.

To complement the quantitative research, the questionnaire also included qualitative questions. Students were asked for the best and worst points of the experimental laboratory, as well as for any comments or suggestions they could have. These questions, with the most repeated responses given by students, are shown in Table 2. When

students were asked for the best part of the lab sessions (Q10), they emphasized the utilization of commercial and up-to-date optical equipment, the analysis of real networks, and the realization of real procedures regarding optical technologies. In fact, most of the additional comments of the students (Q12) were also along those lines. They stated that experimental sessions were very attractive, and they highlighted the realistic settings of the labs, which they consider very relevant as part of their training. Regarding the negative points (Q11), they stressed the need for additional time to complete the experiments in these sessions. It is also worthy to note that the students also mentioned as a negative point not having more experimental sessions in the subject. Indeed, students show a desire for eminently experimental laboratories, not only in this, but also in other subjects (Q12).

## 8 | CONCLUSIONS

The EHEA has changed the curricula of higher education engineering degrees, promoting professional profiles and relating the educational system with the needs of the labor market. In this scenario, the learning outcomes for optical communications are crucial as optical communication systems and networks become essential to support the future network traffic and the needs of new emerging services. Therefore, it is necessary to train professionals in these areas, and consequently, students should acquire experimental skills related to next-generation fiber networks and technologies.

Therefore, in this paper, we have proposed the design of an optical communication laboratory with specific on-site experimental and simulation sessions in which students



train with commercial optical instrumentation and realistic network environments. On the one hand, students learn to build fiber connectors and make fiber splices using professional equipment. Besides, we have described the deployment of a GPON testbed, which allows the instructor to set up different network link scenarios to be tested by students. In this way, students learn to use an OTDR to detect physical events (connectors, fusion splices, splitters, attenuation), analyze the impact of these events, and diagnose problems in the optical fiber of the GPON testbed. Moreover, students learn to configure digital oscilloscopes to analyze data frames and eye diagrams, and to measure optical parameters like Q factors, extinction ratio, or rise/fall times. Furthermore, students learn to build optical connectors commonly used for telecom applications and network environments, as connections between optical devices are crucial for the optimal performance of network technologies. Furthermore, our approach also integrates simulation lab sessions to overcome the high cost of optical communication equipment in educational scenarios.

These laboratory experiments provide future telecom engineers with important experimental skills and knowledge regarding the most deployed next-generation optical networks in the world. One remarkable advantage of these lab sessions is that students experience the professional instrumentation handling related to updated optical network infrastructures. The results of the conducted qualitative and quantitative research have supported these ideas, as students emphasized the impact of experimental sessions on their future career, for the acquisition of knowledge in optical systems, and for their learning improvement in this area. In fact, students have shown the need for more experimental sessions not only in this subject but also in others of the engineering degrees. Even more, it is also important to mention that the GPON testbed is ready to be used in other two more specialized fourth-grade subjects. In these advanced subjects, students learn to deal with QoS concepts in networks and the efficient management of network resources creating services and profiles with different requirements and thus emulating the tasks of a real service provider.

Finally, it should be emphasized that although the cost of devices and equipment is an important issue, a single GPON testbed can be used by all students along the semester applying rotatory strategies. Thus, in each lab session, one group of students can work in the testbed, and another in the connection and fiber splicing tasks, whereas the remaining groups are working in the simulation labs previously mentioned. Therefore, the implementation of this proposal can be affordable and extrapolated to other universities for their application in teaching laboratories of engineering degrees that focus on these emerging areas.

## ACKNOWLEDGMENTS

We would like to acknowledge the support received from Telnet-RI in the deployment and start-up of the GPON. This study has been funded by Consejería de Educación de la Junta de Castilla y León (VA085G19), by the Spanish Ministry of Science, Innovation, and Universities (TEC2017-84423-C3-1-P, RED2018-102585-T), and by the INTERREG V-A España-Portugal (POCTEP) program (0677\_DISRUPTIVE\_2\_E).

## DATA AVAILABILITY STATEMENT

Data available on request from the authors.

## REFERENCES

1. A. Akram, A. Abu-aisheh, A. Hadad, S. Khader, and O. Hasan, *Implementation of dual use fiber optic communications laboratories*, Int. J. Online Eng. (iJOE) **7** (2011), 74–79.
2. S. Aydin, A. Sarikas, A. Ak, A. Yaila, U. Kesen, and B. Oral, *Fiber optic training program with intensive experiments using both real laboratory and simulation environments*, Computer Applications in Engineering Education **27** (2019). (no.1.), 1419–1428.
3. Corning Optical Communications official website, available at <https://www.corning.com/optical-communications/cala/en/home/training-and-events/training-programs/design-and-installation.html>
4. I. de Miguel, P. Chamorro-Posada, J. Durán, E. Gómez, R. Durán, J. C. Aguado, J. Blas, P. Fernández, R. M. Lorenzo, and E. J. Abril, *Optical communications at University of Valladolid: Learning outcomes, contents and methodology, under the creation of the European Higher Education Area*, 9th Eur. Conf. Netw. Optical Commun. (NOC), Eindhoven, 2004, pp. 413–420.
5. Digital Storage Oscilloscope Agilent Model 86100B, available at <http://literature.cdn.keysight.com/litweb/pdf/5989-0278EN.pdf>
6. European Higher Education Area and Bologna Process, available at <http://www.ehea.info/>
7. Fiber Optika official website, available at <https://fiberoptika.com/products/>
8. FTTH Council Europe-Panorama, available at <https://www.ftthcouncil.eu/documents/FTTH%20Council%20Europe%20-%20Panorama%20at%20September%202019%20-%20Webinar%20Version4.pdf>
9. FTTH Forecast for EUROPE, available at <https://www.ftthcouncil.eu/documents/Reports/2019/FTTH%20Council%20Europe%20-%20Forecast%20for%20EUROPE%202020-2025.pdf>
10. Fujikura CT-06 Precision Cleaver, available at <https://www.fusionsplicer.fujikura.com/products/index.html>
11. J. Gamo, *Assessing a virtual laboratory in optics as a complement to on-site teaching*, IEEE Trans. Educ. **62** (2019) (no.1.), 119–126.
12. D. Hayes, C. Turczynski, J. Rice, and M. Kozhevnikov, *Virtual-reality-based educational laboratories in fiber optic engineering*, 12th Educ. Training Optics Photonics Conf., Porto, Portugal, 2013.
13. Hewlett-Packard, *8147A optical time domain reflectometer*, available at <http://www.rlsscientific.com/documenti/E4310A.pdf>
14. H. S. Hinton, R. Gonzalez, L. L. Tedder, S. Karandikar, H. Behl, P. C. Smith, J. Wilbanks, J. Humphrey, M. Gordon, and M. Lightner, *A technology-enhanced learning environment*

for a graduate/undergraduate course on optical fiber communications, The 2000 Front. Educ. Conf., Kansas City, Missouri, 2000, pp. 19–21.

15. ITU-T, *G.984.1 Recommendation: Gigabit-capable passive optical networks (GPON): General characteristics*, available at <https://www.itu.int/rec/T-REC-G.984.1/en>
16. ITU-T, *G.988 Recommendation: ONU management and control interface (OMCI) specification*, available at <https://www.itu.int/rec/T-REC-G.984.1/en>
17. G. Kramer, B. Mukherjee, and G. Pesavento, *IPACT: A dynamic protocol for an Ethernet PON (EPON)*, IEEE Commun. Magazine **40** (2002), 74–80.
18. B. Lung, *Fiber to the home using a PON infrastructure*, IEEE/OEA J. Lightwave Technol. **2** (2006), 4568–4583.
19. M. McGarry, M. Reisslein, and M. Maier, *Ethernet passive optical network architectures and dynamic bandwidth allocation algorithms*, IEEE Commun. Surveys Tutorials **10** (2018), 46–60.
20. N. Merayo, J. C. Aguado, C. M. Miguel, R. J. Duran, I. de Miguel, P. Fernandez, R. M. Lorenzo, and E. J. Abril, *Testbed laboratory for the physical analysis of Gigabit passive optical access networks (GPONs)*, 56th FITCE Congr., Madrid, 2017, pp. 63–67.
21. N. Merayo, P. Prieto, R. J. Durán, J. C. Aguado, P. Fernandez, I. de Miguel, R. M. Lorenzo, and E. J. Abril, *M-learning and E-learning Interactive applications to enhance the teaching-learning process in optical communications courses*, Int. J. Eng Educ **31** (2015(no.1.)), 74–588.
22. Net2Plan official website, *The open-source network planner*, available at <http://www.net2plan.com/>
23. Newport Company, *Laboratory educational kits*, available at <https://www.newport.com/c/laboratory-educational-kits>
24. OMNeT++ official website, *OMNeT++ discrete event simulator*, available at <https://omnetpp.org/>
25. OptiSystem, available at <https://optiwave.com/category/products/system-and-amplifier-design/optisystem/>
26. Oscilloscope Agilent, *Model DSO90254A*, available at [https://www.naic.edu/%7Ephil/hardware/oscilloscopes/9000A\\_Series\\_User\\_Guide\\_10\\_2009.pdf](https://www.naic.edu/%7Ephil/hardware/oscilloscopes/9000A_Series_User_Guide_10_2009.pdf)
27. Photonic System Design and Simulation, available at <https://www.synopsys.com/photonic-solutions/rssoft-system-design-tools.html>
28. R. P. Prado, M. García-Cárdenas, S. García-Galán, and J. E. Muñoz-Expósito, *Interactive tool for learning propagation in single-mode optical fibers in telecommunication engineering*, Comput. Appl. Eng. Edu. **27** (2019), 789–813.
29. School of Telecommunications web page, available at <http://www.tel.uva.es>
30. Sumitomo Electric, *TYPE-201e-M4 Fusion Splicer*, available at <http://tienda.fibercom.es/equipos-y-herramientas/fusionador-as-de-fibra-optica/fusionadora-sumitomo-t-201vs.html>
31. Telnet-RI vendor web page, available at <http://www.telnet-ri.es/en>
32. The Fiber Optic Association Inc, available at <https://www.thefoa.org>
33. Thorlabs Company, *Physics lab experiments for college*, available at <https://www.thorlabs.com/>
34. R. Ullah, L. Bo, S. Ullah, M. Yaya, F. Tian, and X. Xiangjum, *Proposing simulation model for multiwavelength source offering 40 Gbps WDM-PON using AWG with a single laser*, Comput. Appl. Eng. Educ. **27** (2018), no. 6, 1299–1307.

## AUTHOR BIOGRAPHIES



**NOEMI MERAYO** received the Telecommunication Engineer degree in engineering from the Valladolid University, Spain, in February of 2004 and the PhD degree in the Optical Communication Group at the Universidad de Valladolid, in July 2009. Since 2005, she works as Lecturer at the Universidad de Valladolid. she has also been a Visiting Research Fellow at the University of Hertfordshire in the Optical Networks Group, Science and Technology Research Institute (STRI), another at the TOyBA research group of the University of Zaragoza and more recently in the Technology University or Munich (TUM). Her research focused on the design and performance evaluation of optical networks, especially passive optical networks and the application of artificial intelligence techniques. She is currently coordinating the Master in Physics and Technology of lasers at the University of Valladolid and the University of Salamanca.



**JUAN C. AGUADO** received the Telecommunication Engineer and PhD degrees from the University of Valladolid, Spain, in 1997 and 2005, respectively. Since 1998, he has been working as a Junior Lecturer at the University of Valladolid, where he is currently an Associate Professor. His current research interests focus on design and performance evaluation of optical networks and the application of artificial intelligence techniques. He has also been a Postdoctoral Researcher with the Group of Transmisiones Ópticas de Banda Ancha (TOyBA) at University of Zaragoza.



**IGNACIO DE MIGUEL** received his Telecommunication Engineer degree in 1997, and his PhD degree in 2002, both from Universidad de Valladolid (UVa), Spain. Since 1997, he has worked as a Lecturer at UVa, and he is currently an Associate Professor. He is the coordinator of the Master in Telecommunication Engineering and of the Master in Big Data Science at UVa. He has also been a Visiting Research Fellow at University College London, UK. He has been a member of the TPC of several international conferences, besides being chair of the TPC and of the local organizing committee of NOC 2009. His research interests are mainly focused on the

design, control and performance evaluation of optical networks, edge computing, and the application of artificial intelligence techniques in those environments. Dr. de Miguel is the recipient of the Nortel Networks Prize to the best PhD Thesis on Optical Internet in 2002, awarded by the Spanish Institute and Association of Telecommunication Engineers (COIT/AEIT)



**RAMÓN J. DURÁN** received his Telecommunication Engineer degree in 2002 and his PhD degree in 2008, both from the University of Valladolid, Spain. He works as an associate professor at the University of Valladolid and currently he

is also Deputy Director of the Faculty of Telecommunication Engineering. His current research focuses on the use of artificial intelligence techniques for the design, optimization and operation of future heterogeneous networks, multiaccess edge computing and network function virtualization. Dr. Durán is the author of more than 100 papers in international journals and conferences. Dr. Durán is the coordinator of the Spanish Research Thematic Network “Go2Edge: Engineering Future Secure Edge Computing Networks, Systems and Services” composed of 15 entities.



**PATRICIA FERNÁNDEZ** received her Telecommunication Engineer Degree from the Universitat Politècnica de Catalunya, BarcelonaTech (UPC), Spain, in 1997. After that, she joined the Optical Communications Group of the University of Valladolid where she obtained my PhD Degree in 2004. She is author of more than 100 papers in international journals and conferences. Currently, she is a Professor and she was the Head of the Technical School of Telecommunications Engineering at the University of Valladolid.



**RUBÉN M. LORENZO** received his Telecommunication Engineer and PhD degrees from the University of Valladolid, Spain, in 1996 and 1999, respectively. From 1996 to 2000, he was a Junior Lecturer at the University of Valladolid

and joined the Optical Communications Group. Since 2000, he has been a Lecturer. His research interests include Integrated Optics, Optical Communication Systems and Optical Networks. He was the Head of the Technical School of Telecommunications Engineering at University of Valladolid and Research Director of CEDETEL (Center for the Development of Telecommunications in Castilla y León).



**EVARISTO J. ABRIL** received his Telecommunication Engineer and PhD degrees from Universidad Politécnica de Madrid, Spain, in 1985 and 1987, respectively. From 1984 to 1986, he was a Research Assistant at Universidad Politécnica de Madrid, becoming Lecturer in 1987. Since 1995, he has been Full Professor at Universidad de Valladolid, Spain, where he founded the Optical Communications Group. His research interests include Integrated Optics, Optical Communication Systems and Optical Networks. Prof. Abril is the author of more than 100 papers in international journals and conferences.

**How to cite this article:** N. Merayo, J. C. Aguado, I. de Miguel, R. J. Durán, P. Fernández, R. M. Lorenzo, and E. J. Abril, *A testbed and a simulation laboratory for training engineering students in optical access network technologies*, *Comput. Appl. Eng. Educ.* (2021), 1–19.

<https://doi.org/10.1002/cae.22429>