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Performance Enhancement of SCM/WDM-RoF-XGPON System for Bidirectional Transmission With Square Root Module

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ABSTRACT The 10-Gigabit Passive Optical Network (GPON), also known as (XGPON), is a key technology for the next generation of optical fibre communication systems that can improve reliability data rate. However, the increment in the transmission distance and data rate will lead to increased dispersion. This paper proposes a model based on the Sub-Carrier Multiplexing/Wavelength Division Multiplexing-Radio over Fibre-10-Gigabit Passive Optical Network system (SCM/WDM-RoF-XGPON) for Radio Frequency (RF) using a conventional Optical Network Unit (ONU) with the Square Root Module (SRM) on the side of the receiver. It is connected to a central office Optical Line Terminal (OLT) via an access network for multi-channel optical fibre transfers with a distance of 80 km and at 10 Gbps data rate. The Optisystem 15 simulation software is used to evaluate the proposed system based on the Bit Error Rate (BER), Quality factor (Q-factor) and eye diagram. The proposed system of bidirectional fibre links uses 1270 nm and 1577 nm wavelengths for uplink and downlink transmissions, respectively. The performance is further enhanced by using SRM to compensate for the square law characteristics, making it suitable for broadband services. Due to the utilisation of SRM in the architecture, the reported results reveal a double enhancement in successful transition performance at an optical fibre length of 80 km distance. The BER displayed significant improvement (less than 1.00E-09) with SRM at 80 km; however, without SRM and at 50 km, the BER is less than 1.00E-09. Investigations have presented an enhancement in the Q-factor's effectiveness with the use of SRM, which helps to increase the XGPON length. When the length of the fibre is 80 km, the Q-factor is 6 with SRM, while it is 3.7 without SRM.

INDEX TERMS 10-Gigabit passive optical network (XGPON), radio over fibre (RoF), square root module (SRM), wavelength division multiplexing (WDM), sub-carrier multiplexing (SCM), optical network unit (ONU), optical line terminal (OLT).

I. INTRODUCTION

The demands for higher bandwidth [1], [2], link reliability and high data rate applications have been significantly growing in the past few years. Therefore, new techniques are required to meet these demands and solve the challenges that may arise [1], [3], [4]. The rapid and expanding demands for multimedia and bandwidth services have shifted research attention to the Passive Optical Network (PON) [5], [6]. PON is a network based on a fibre-optic structure which provides a

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much higher bandwidth in the access network than traditional networks based on copper [7], [8]. The main aim is to transfer high data rates while ensuring network reliability and network coverage. WDM-based PON is one method for increasing transmission capacity. Incorporating WDM in PON authorises a person to support a much higher bandwidth than standard PON, which works in "single-wavelength mode". One wavelength is utilised for the upstream transmission and a separate wavelength is used for the downstream transmission. Thus, WDM-PON will be a revolutionary and scalable technology for broadband access, providing higher bandwidth to end-users. The research aim is to use PON to provide a two-way communication that includes upstream and downstream transmissions via a single two-way fibre at specific distances to reduce network interfaces and minimise cost. In upstream transmission, the data is sent from network units on the receiver side to the transmitter's optical terminal. The process is simultaneously reversed in the downstream direction [9]–[11]. There are two popular types of PONs: Gigabit-PON (GPON) (widely used in America) and Ethernet-PON (EPON) (deployed in Asia). The GPON is a fully optical transmission network that provides a high-speed network connection. It is more useful, more powerful and more profitable with a higher capacity than the EPON [12]–[14].

SCM is a technology used for sending multiple signals over a single optical fibre. It is a network architecture that differs from the usual with a time wavelength division multiplexed (TWDM) or WDM network interface, and it greatly affects the BER of the system. The system's BER increases based on the SCM architecture. The Polarisation Mode Dispersion (PMD) is used to control the state of polarisation, so the BER of the signal will be reduced. This control produces several effects on the signal, including Rayleigh scattering. Thus, in this paper, an SRM filter was built in MATLAB to control the properties of PMD to reduce the BER of the system.

RoF is an analogue transmission system that directly distributes the radio waveform to the frequency of the radio carrier. The analogue signal may be an Intermediate Frequency (IF) signal, RF signal or baseband signal. RoF techniques have been discussed in numerous research works [15]–[20]. This had led to the demand for high-capacity optical transmission systems that possess optical formations with spectral efficiency. The WDM concept can also be applied in the effective use of available bandwidth resources. Thus, WDM-RoF is considered a promising system that can meet the diverse and increasing demands of multiple broadband media services for wireless users [21], [22]. Research on the RoF technique for WDM-EPON has been conducted to support ONU for both wired and wireless services [23]–[25]. The RoF technology can be used with the WDM-EPON system to reduce the cost of Base Stations (BSs) while serving the largest possible number of users. The cell's radius will also become relatively small; thus, it can accommodate many BSs [26], [27]. However, the problem with the RoF system is the chromatic dispersion in the fibre which dramatically limits the transmission distance [28], [29]. The transmitted signal suffers from a linear dispersion, such as polarisation mode dispersion as well as chromatic dispersion, which limits the fibre distribution length since dispersion increases with the length of the fibre. Therefore, a linear equalizer should be employed to compensate for this impact on the receiver side. Since the linear equaliser is designed to minimise the impact of dispersion, the optical communication is not linear due to the use of the square law by the photodiode at the receiver side. This yields a sub-optimal solution. Therefore, SRM is utilised after the photodetector to compensate for the square law effect used by the photodiode, thus improving the linear equalizer's execution at the receiver. The SRM output is less nonlinear than its input [30].

Today, RoF and GPON technologies are promising solutions for supporting wireless internet users with high bandwidth, flexibility and straightforward evaluation. The RoF performance specification, which uses GPON architecture, has been utilised in [20], [31] to analyse the system's physical capabilities in wireless internet transmission. Favourable results have been acquired at the fibres' maximum distance. A higher Optical Signal to Noise Ratio (OSNR) and lower BER have been observed compared to the specified standard value. This work has also computed a reasonable energy budget. The simulation results reveal that the signal data have been captured at the required work frequency with modest confessions for the devices.

The authors in [31] examined the SCM-WDM-PON using a bi-directional reflector filter and periodic Arbitrary Waveform Generator (AWG) to provide uplink/downlink data via a single optical source. The downstream signal for the proposed scheme was modified via a laser diode Continuous Wave (CW) and reconstituted as an upstream signal in the optical network. The results revealed that an increase in the total number of sub-carrier channels essentially affect the scheme's execution. These results can be implemented in a real system that uses broadband services and a TV cable.

The bi-directional Dense Wavelength-Division-Multiplexing (DWDM)-PON architecture was suggested in [32] with the use of optical carrier separation and suppression technology to produce both upstream and downstream wavelength channels from a single laser. This work generated 32DWDM channels and 10-Gb/s symmetric data transmission through a 20-km single-mode fibre (SMF-28) by utilising a pair of wavelengths.

On the other hand, Lee *et al.* [33] suggested a GPON system extension of 60 km using Raman Amplification (RA). This system employs a two-way symmetrical traffic with a 2.5 Gbps data rate and 32 subscriber units. The upstream and downstream transmissions are at 1350 nm and 1490 nm, respectively. The proposed system can accomplish a function free of errors with -28 dBm receiving power. Zhu and Nesset [34] presented a purely passive PON network with a 1:64 split ratio up to 60 km through distributed RA. The system works at 2.5 Gbps bi-directionally using the upstream

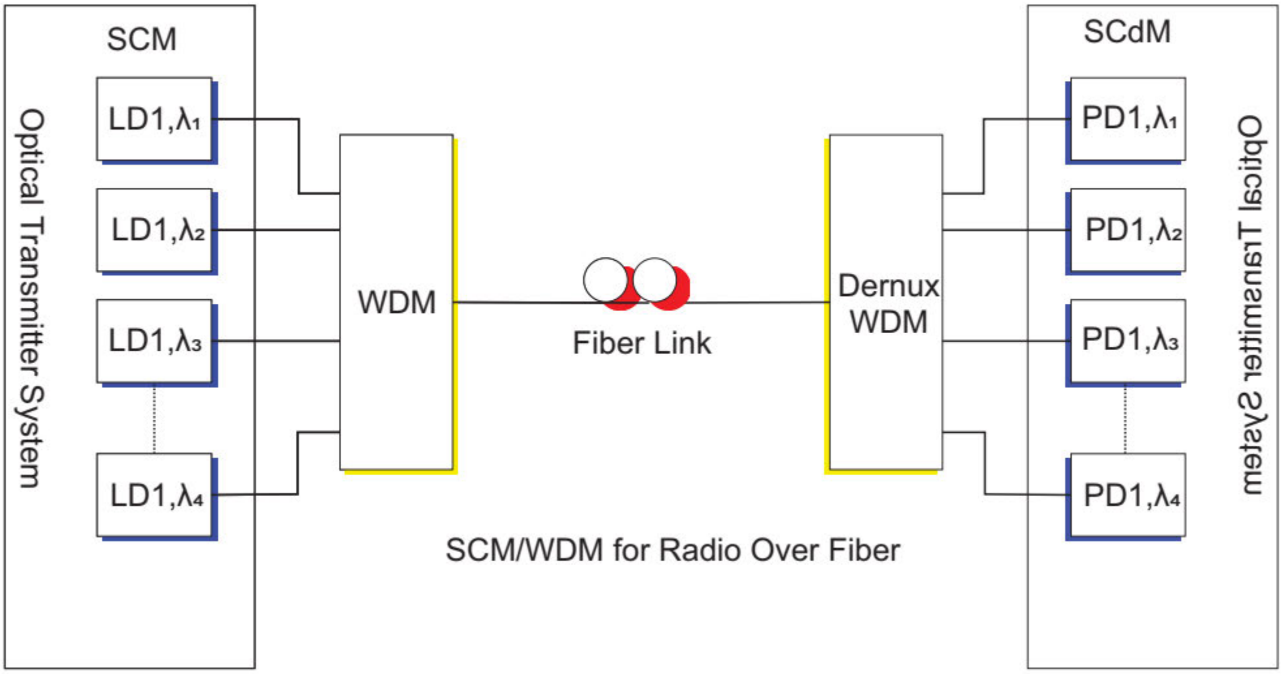


FIGURE 1. RoF-XGPON system [19].

and downstream wavelengths of 1310 nm and 1490 nm, respectively.

XGPON is an impressive and promising solution for bottlenecks in broadband access networks, although it does require a cost-effective upgrade. Accordingly, in this paper, we propose and discuss the SCM/WDM-RoF-XGPON system using ONU with SRM on the side of the receiver for the bidirectional fibre. The proposed system provides broadband services for a fibre link of 80 km with a split ratio of 32 and a data rate of 10 Gbps to further enhance system performance. This proposed scheme represents a practical solution for simultaneously equipping the data rate of optical links in XGPON access networks.

The residual fraction of the paper is orderly as follows: Section II presents the background and related works. Section III describes the proposed system's design model. Section IV introduces the simulation results and performance analysis. Lastly, Section V highlights the concluding remarks of this paper.

II. BACKGROUND AND RELATED WORKS

The presence of new high-speed interactive services through fixed and wireless access networks favours the development of RoF systems because of the high bandwidth provided by optical media. To manage the ever-increasing volumes of data traffic and improve optical spectrum efficiency, the optical transmission application and network concepts (such as WDM) in conjunction with electrical SCM schemes have become attractive options for the infrastructure of the physical layer in PONs. Substantial progress has been made to minimise the operational complexity of these architectures.

A. SCM/WDM-RoF-XGPON SYSTEM

The RoF system integrates wireless and fibre-based technology. In RoF, light is set to a RF and transmitted over fibre optics for easy wireless access. The main objective of the RoF system is to distribute broadband signals to base stations for wireless access utilising a network with optical access. Combining PON with RoF technology provides a high-capacity solution and increased data rate. The XGPON system is a network architecture of point-to-multipoint that spreads optical access lines between the central office and customer sites. The main advantage of applying the XGPON standard is that it is faster than other PON standards. It has been noted that XGPON bandwidth is 10 Gbits/s for an individual subscriber. The basic concept of WDM technology is to combine multichannel optical fibres with different wavelengths. The wavelengths come to a single fibre from various optical sources through multiple transmitters used on the sender side and multiplexer removal tools employed on the receiver side to split WDM channels. WDM is an effective method that can be applied in the fibre optic feeder network to boost the RoF's system capacity, improve the usable fibre bandwidth and increase the number of base stations supported by the central office. SCM technology is a multicast technology used in the optical system to increase bandwidth efficiency. SCM is more sensitive to noise effects, limited data rates and maximum sub-carrier frequencies. As shown in Figure 1, the integration of RoF with the XGPON system design includes

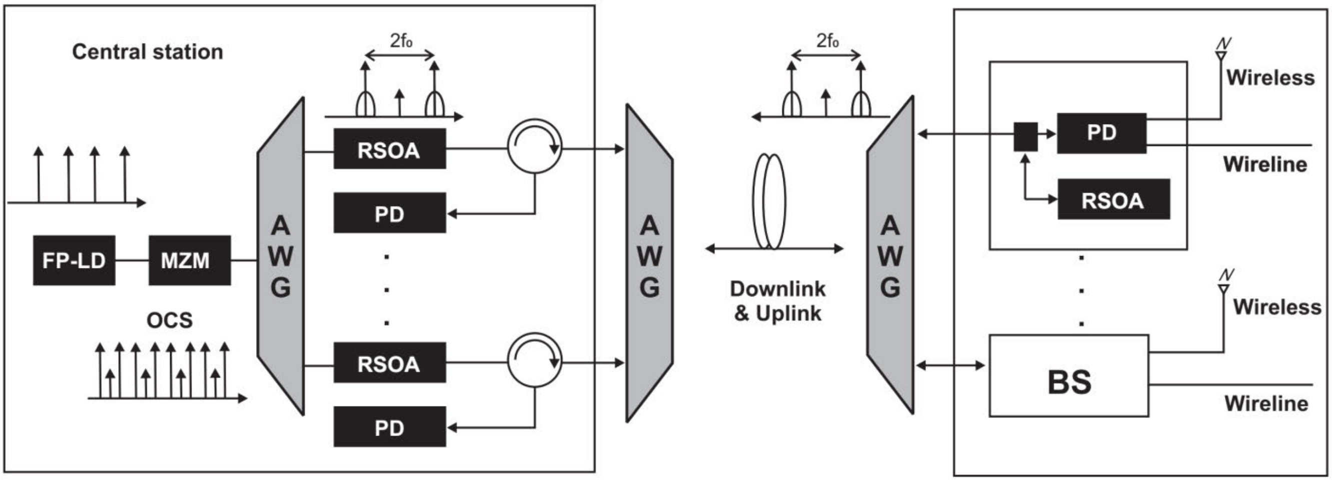


FIGURE 2. **Bidirectional system [44].**

four essential parts: transmitter, fibre channel, splitter and receiver.

B. BIDIRECTIONAL TRANSMISSION

Optical networks commonly rely on transceivers that employ optical fibres to transmit and receive data to and from networking devices. Generally, this type of data transmission raises network deployment costs. However, with the bidirectional optical transceiver and its capability to transmit and receive data over one optical fibre, we can create a much more cost-effective optical network. The bidirectional optical transceiver utilises WDM technology. This is essential since the use of WDM technology allows bidirectional communication over a single fibre, establishing a more straightforward connection to deploy, troubleshoot and configure. The bidirectional optical transceiver is most commonly deployed in high-speed duplex data links over a single optical fibre, and the typical optical wavelength for this transceiver is 1270/1577 nm.

Compared to the two-fibre transceivers, the WDM technology can be incorporated in bidirectional optical transceivers. This technology separates the data sent and received over the same fibre based on the light's wavelength. However, to work at maximum level, the bidirectional optical transceiver must be deployed in matched pairs and tuned to match the transmitter and receiver's expected wavelength. To enhance the proposed system's execution for the bidirectional fibre link, if one transceiver has a transmitting wavelength of 1577 nm, the other side must have a receiving wavelength of 1270 nm and vice-versa. Figure 2 presents an example of bidirectional transmission in a block diagram.

C. RELATED WORKS

To the best of our knowledge, most studies have depended on the PON. Accordingly, this section reviews the related works on the application of SRM in different PONs and other systems. For brevity, the study examined the general use of SRM in relation to the proposed system, providing several related works in this field.

In [35], a new method to linearise an optical channel has been accomplished by simply applying a mathematical SRM at the receiver side after optoelectronic conversion. The simulation results revealed significant improvement in enduring the chromatic dispersion with the use of SRM. The distance range can be expanded between + 0.6 and + 1 according to the complexity of the linear Electronic Equalizer (EE) in comparison to without the use of EE.

Authors in [36] have described the extended passive GPON compliant accessibility range through the use of distributed RA. The investigation was enhanced by SRM implementation for 60 m distance and 2.5 Gbps data rate. RA is a transmission fibre technology that can ameliorate the budget of PON loss with the addition of appropriate pump lasers to the central office OLT. An effective Q-factor improvement was achieved using SRM, which also helped to increase the GPON length. This work suggests the use of SRM, similar to the one reported in [30]. To improve the performance of the linear equalizer, the SRM in this work has been placed after the photodiode to compensate for the square law characteristic [35].

The execution of the purely passive GPON system has been accomplished in [37]. However, the system's transmission limits the upstream signal due to the discussed ASE Raman noise as well as the nonlinear weakness of the downstream signal due to the high launch power of the tester fibre.

Authors in [38] have introduced a pilot demo of the extended GPON, reaching a distance of 50 km and a PON splitting ratio of 1:64 through the use of RA for the upstream signal with a laser pumping at a strongly absorbed wavelength. This work also presented an enhanced simulation for GPON at a high transmission rate of 2.5 Gbps for 60 km distance using SRM. The GPON system extension of 60 km with the use of RA has been suggested in Reference [33]. The proposed system uses a two-way symmetric traffic with a 2.5 Gbps data rate and 32 mutual units. The upstream and downstream transmissions are at 1350 nm and 1490 nm, respectively. The system has successfully produced an error-free operation with a received power of - 28 dBm.

Authors in [39] have suggested a combination of Traveling-wave Semiconductor Optical Amplifier (TSOA) and SRM for a 50 km fibre length at 10 Gbps, with 40 users in the uplink transmission and 64 users in the downlink transmission. The proposed network uses the operational wavelength of 1550 nm for the downstream transmission and 1300 nm for the upstream transmission, respectively. The (TSOA-SRM) architecture has been analysed and compared to TSOA at different data rates and fibre lengths. The simulation results indicate an improvement in the proposed architecture concerning the Q-factor, bit rate and Signal to Noise Ratio (SNR) with up to 10 Gbps data rate.

Authors in [36] have proposed the design and implementation of the GPON architecture using RA and SR with a 1:64 split ratio for bi-directional transmission at 2.5 Gbps and 60 km length. This system uses 1310 nm and 1490 nm wavelengths for upstream and downstream transmissions, respectively. The proposed architecture has verified performance enhancements in terms of received signal power, signal to noise ratio (SNR) and Q-factor with the use of SRM. The energy budget problem was solved by using different modulation formats in order to have a high split ratio [40]. The authors in [41] have presented another architecture which depends on hybrid intensive wavelength division multiplexing (WDM), using 128 split ratios and extending to 40 km. The energy consumption and cost analysis of various hybrid multiplexing techniques for different data rates and fibre research have been explained in Reference [42].

Authors in [43] have described a bi-directional Fibre To The Home (FTTH) model for PON link with up to 10 Gbps data rate along a 50 km fibre length; TSOA has been used without SRM. This system employs 1300 nm wavelength for uplink transmission and 1550 nm for downlink transmission, accommodating 40 users and 64 ONUs for uplink and downlink transmissions, respectively. The results indicate that the scheme performed well at 10 Gbps for the downstream transmission. The simulation results show that in the case of 32 ONUs, the BER of 9.95e-009 was at 15 Gbps. Likewise, 32 ONUs presented a Q-Factor of 15.04 dB for the upstream transmission.

As mentioned earlier, previous studies have only examined the use of SRM in different applications. In this paper, we develop a bidirectional optical fibre system that integrates RoF with GPON. We, utilise WDM/SCM subcarriers and apply SRM to reduce nonlinearity. In the next section, we discussed the system architecture and presented the proposed system's accomplished results.

III. THE PROPOSED SCM/WDM-ROF-XGPON SYSTEM DESIGN

Figure 3 presents a block diagram of the proposed architecture. The system sends a long wavelength for both downstream and upstream directions at 1577 nm and 1270 nm, respectively, with 80 km fibre length. For broadcasting, an optical splitter with 1:32 split-ratio has been utilised for 32 ONUs at a bit rate of 10Gbps. This paper presents the main layout of the proposed simulation model that relies on the XGPON structure for RF through the use of the simulation scenario in the Optisystem 15 software, as shown in Figure 4. This system consists of four main parts: the transmitter, fibre channel, splitter and receiver. The transmitter part contains two main sides: the electrical side for generating the RF signal with SCM and the optical side for generating an optical signal with WDM. In contrast, the receiver part contains the RF side and the optical side. All design parameters are in accordance to the IEEE 802.3ah standard [45].

Initially, the sent signal is created by the data source, the CW laser source, the Non Return Zero (NRZ) rectangular driver and the optical amplifier modulator. A 10 Gbps bit rate is generated with a pseudorandom sequence (PRBS) given to the block of NRZ pulse generator to produce an encoded NRZ signal. Next, the CW laser and the generated NRZ signal are given to the optical amplitude modulator where the signal passes through bidirectional optical fibres with an attenuation loss of 0.2 dB km.

This paper presents the design of SCM/WDM-RoF-XGPON system using (4 × 10) Gbps. We connected four channels at a spacing of 0.6 nm with the use of thirty-two ONUs. This further connects to a central office (OLT) over an access network of optical fibre using WDM technology at the bit rate of 10 Gb/s. A 64-Quadratic Amplitude Modulation (QAM) scheme with 6 dBm power is utilised, with and without the SRM technique, in the multi-channel transmission using both WDM and SCM techniques. Around 80 km of Single-Mode Fibre (SMF) has been selected as a feeder. In contrast, 8 km of SMF has been chosen for the distribution fibres. The optical spectrum analyser and RF spectrum are utilised in different locations to monitor the signal characteristics.

Table 1 presents the design parameters used in this work. The WDM MUX is launched to incorporate signals for further transmission, and the results for various fibre lengths and input powers for each transmitter have been compared. In addition, the 5.8 GHz RF signals are modified using the Mach-Zehnder (MZ) modulator at the carrier frequencies of the CW laser array, which pumps the optical carrier through four channels, starting from 193.1 to 193.4 THz at 0 dBm power, as shown in Figure 4(a). The WDM-Mux output is sent by the bi-directional optical fibre with 25 GHz channel bandwidth and 100 GHz channel spacing. This is amplified by an optical amplifier which gains 20 dB as well as a noise figure of 4 dB. The output is equally distributed by using the splitting ratio of 1:32 where each output will feed the

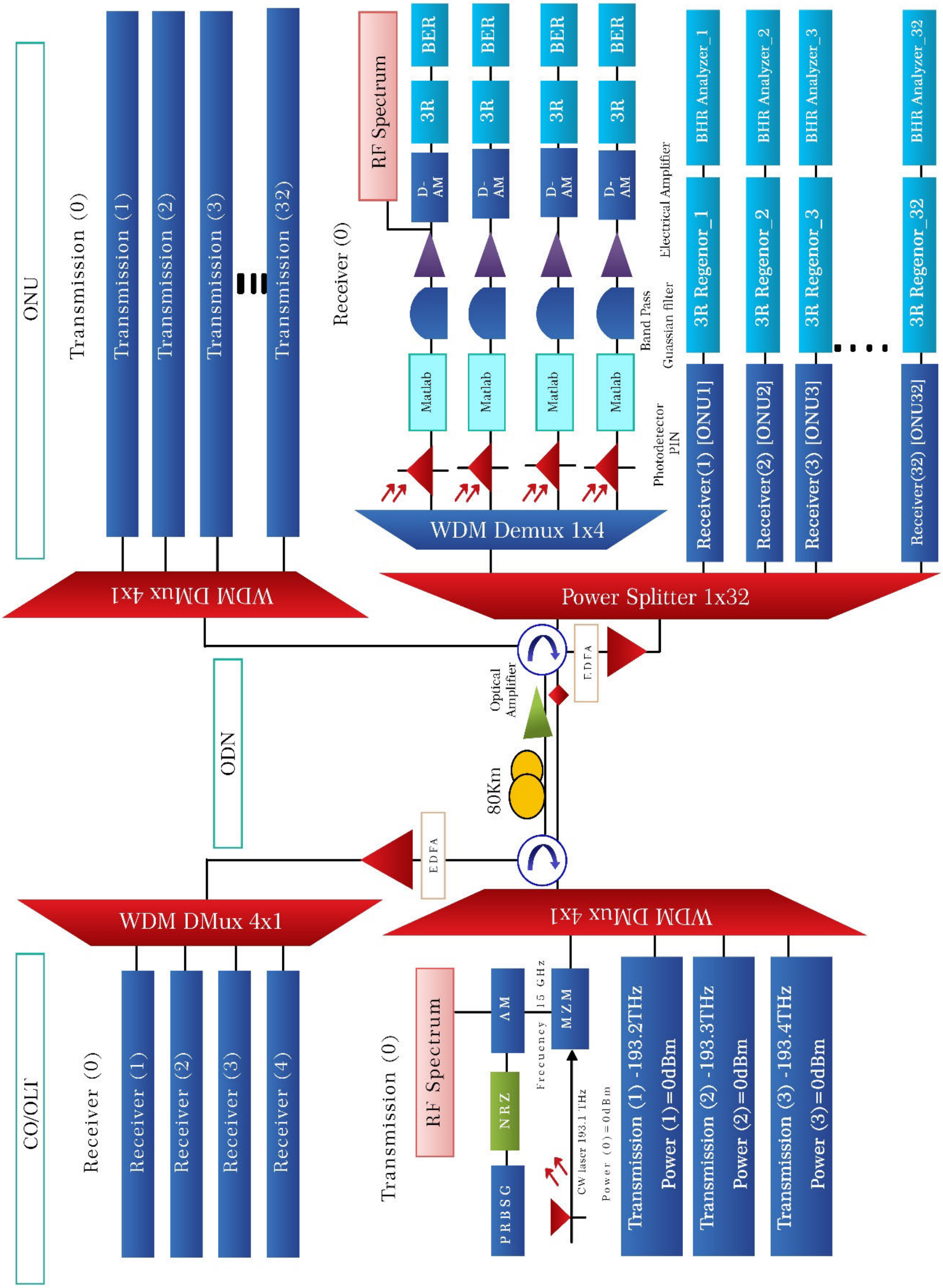
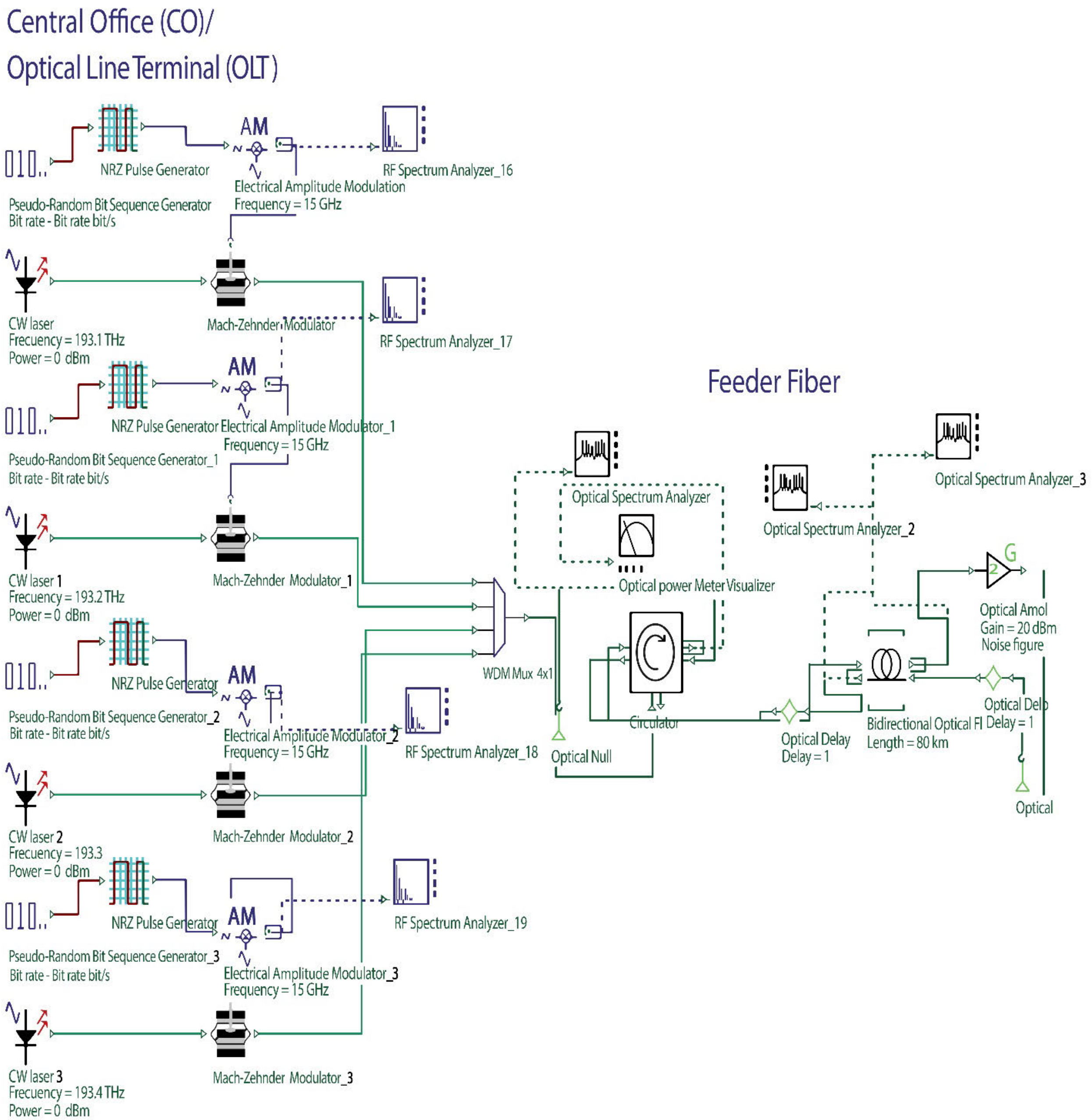


FIGURE 3. Block diagram of the proposed SCM/WDM-RoF-XGPON system.



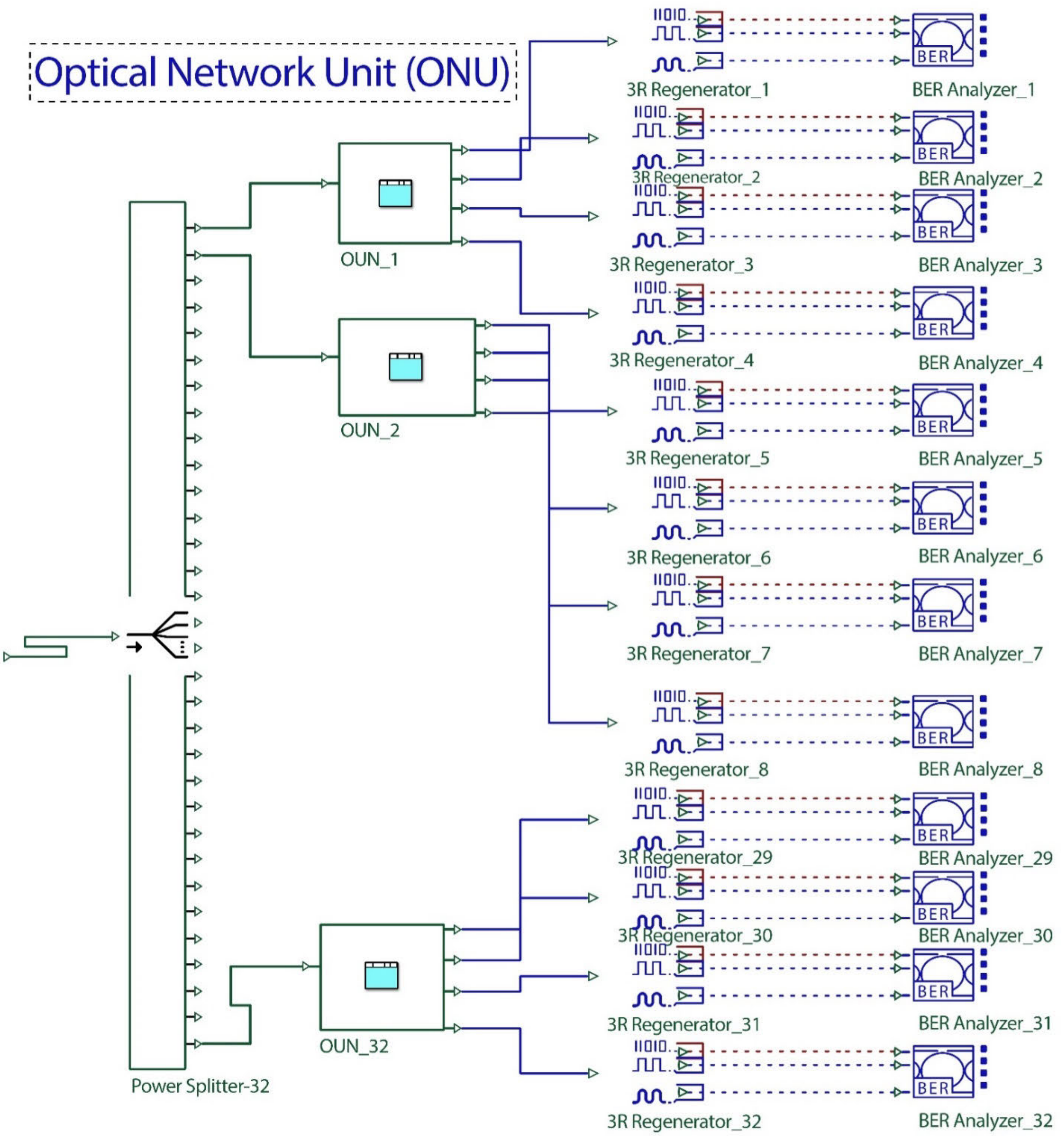
(a) Subsystem-1 (Transmitter Section)

FIGURE 4. The main layout of the proposed simulation model for the SCM/WDM-RoF-XGPON System with SRM.

WDM DEMUX, as shown in Figure 4(b). This is used to detect the signal on the side of the receiver with the same channel frequency, and is divided into four ONUs. The ONUs consist of a photodetector PIN that is employed to transfer the optical signal to the electrical signal and is selected with (10 A) dark current, 1 A/W response, 800 GHz sample rate, 15 GHz for the AM demodulator, 0.9375 GHz cut-off frequency, Bessel filter with 15 GHz band pass frequency (BPF) and 2.5 GHz bandwidth (BW) for electric transmission. The electrical signal then passes through the SRM, which is simulated in MATLAB and received by a 3R generator after passing the signal through a low-pass filter (LPF). The analyser calculates the performance of the system such as the Q-factor, BER and eye aperture.

However, many parameters must be compared to obtain the best pattern for BER; thus, we connected BER analysers and two 3R generators for two different carrier frequencies to analyse the receiver side. The PIN photodetector results in the modulus square operation when directly detecting the incoming optical power factor (which is proportional to the electrical current in the photodetector output) are as follows:

$$I_{Rx} = |E_{in}|^2 \tag{1}$$



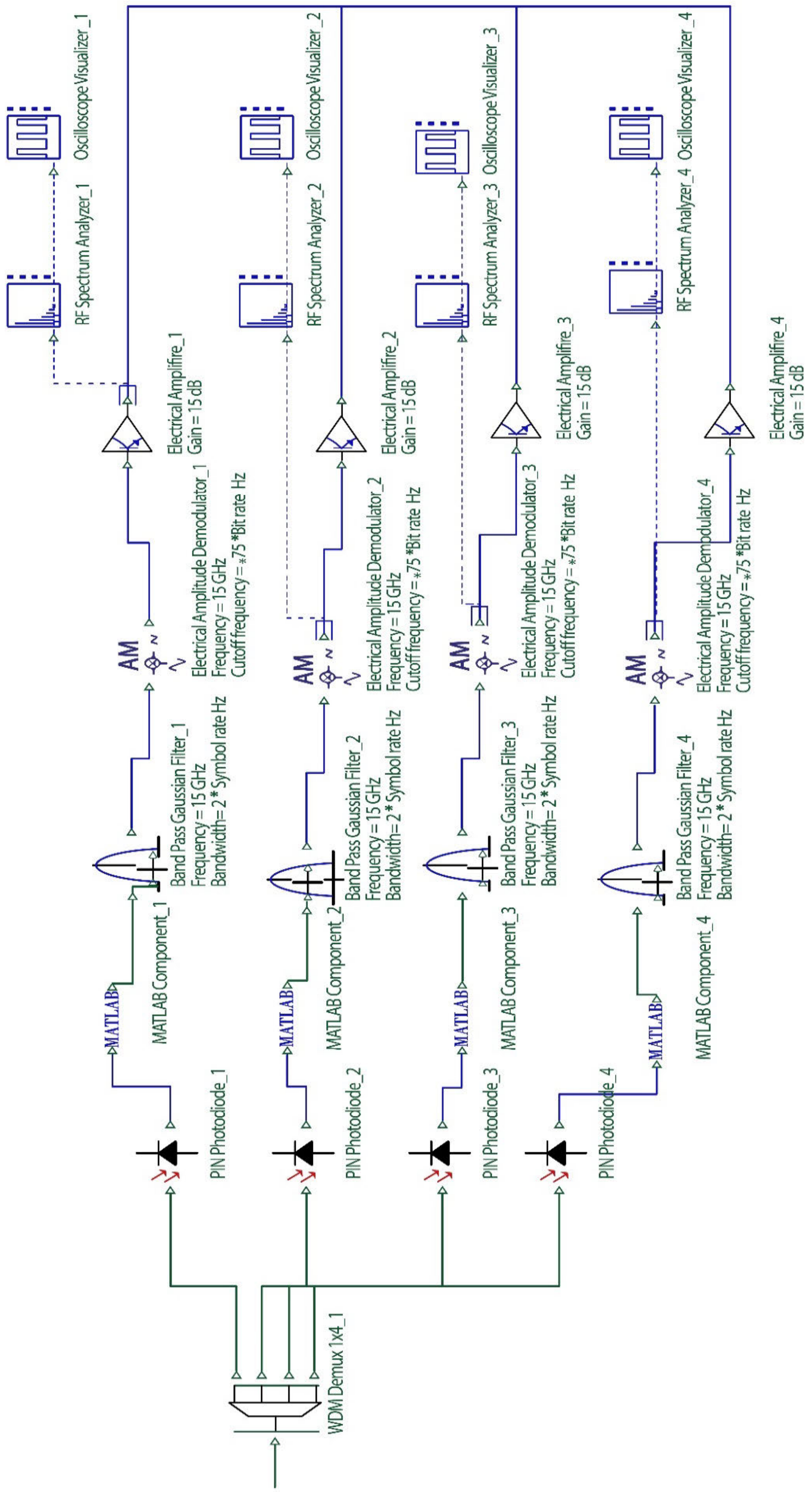
(b) Subsystem-2 (Receiver Section)

FIGURE 4. ***(Continued.)*** **The main layout of the proposed simulation model for the SCM/WDM-RoF-XGPON System with SRM.**

where I_{Rx} refers to the discovered electric current and E_{in} represents the optical input field at the side of the receiver [35]. We designed the SRM block using MATLAB programming and placed after the PIN photodiode on the receiver side to compensate for the properties of the square law of the photodiode and its non-linearity. Finally, we placed the electrical amplifier (with 16 dB gain) after the SRM. The results are obtained through various measuring components, such as the optical and electrical spectrum analysers and the BER analysers. The Q-meter setting for evaluation of the execution of the Q-factor is determined as [35]:

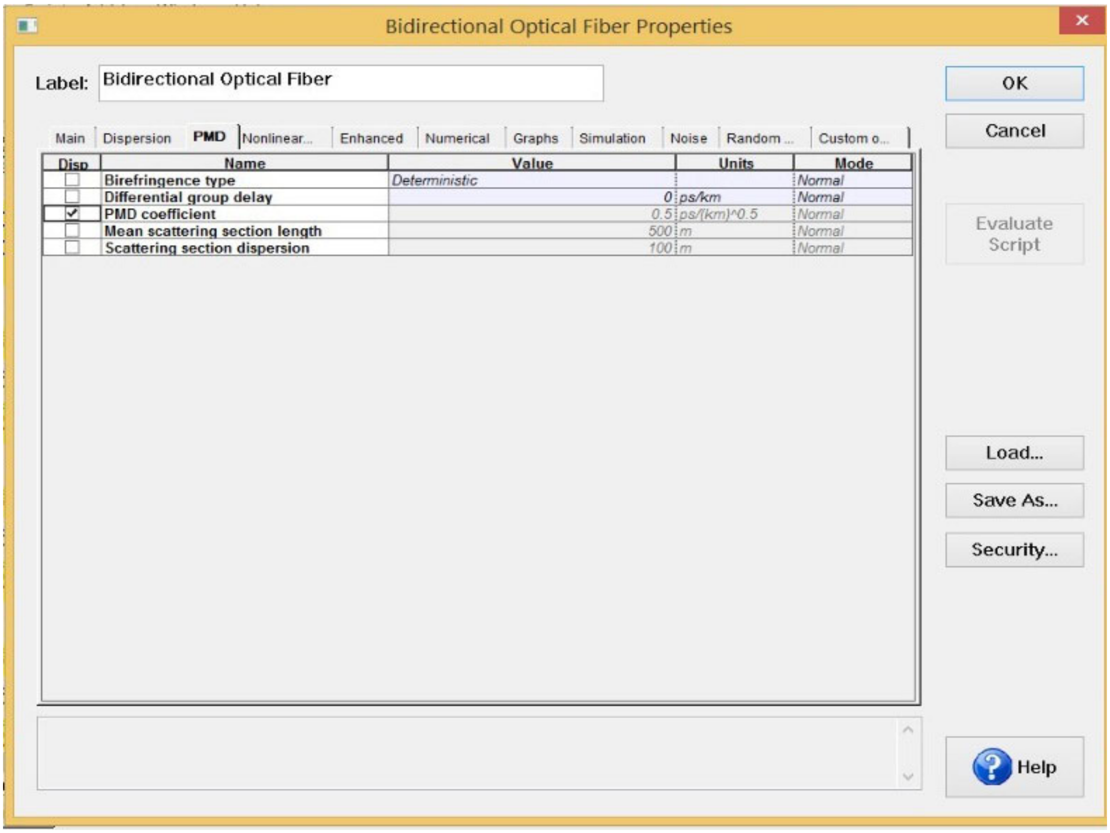
$$Q_{dB} = 20\,\log_{10} Q = 10\log_{10}\left[Erfc^{-1}\left(2BER\right)\right] \tag{2}$$

Hence, the function of the entire system transfer of an optical communication system is made nonlinear through the operation of the photodiode's square law. The optical linear impacts that generate Inter Symbol Interference (ISI) are no longer linear after that.



(c) Designing inside ONU (Receiver Section)

FIGURE 4. ***(Continued.)*** **The main layout of the proposed simulation model for the SCM/WDM-RoF-XGPON System with SRM.**



Label: Bidirectional Optical Fiber

Disp	Name	Value	Units	Mode
☐	Birefringence type	Deterministic		Normal
☐	Differential group delay	0	ps/km	Normal
☑	PMD coefficient	0.5	ps/(km)^0.5	Normal
☐	Mean scattering section length	500	m	Normal
☐	Scattering section dispersion	100	m	Normal

FIGURE 5. **The PMD system parameters.**

The power budget is used for measuring the power that defines the total permissible attenuation values between the firing power and energy sensitivity, as shown in Figure 5. However, it mainly assesses the losses at each stage of the system such as: overall conductor losses, distance attenuation, splitter losses, coexistence component (CE) losses and fusion splice losses. The optical path losses (OPL) use in the power budget calculation according to the standards of ITU-T for the XGPON system is shown in Eq. (3) [46, 47].

$$\alpha_{Tot.} = \alpha L + \alpha_c N_c + \alpha_s N_s + S_p \tag{3}$$

where $\alpha_{Tot.}$ is the total attenuation of the system (dB), α is the optical fibre attenuation stand (dB/Km), L is the optical fibre connection length (Km), N_c is the number of connectors, N_s is the number of connections and S_p is the damping splitter (dB).

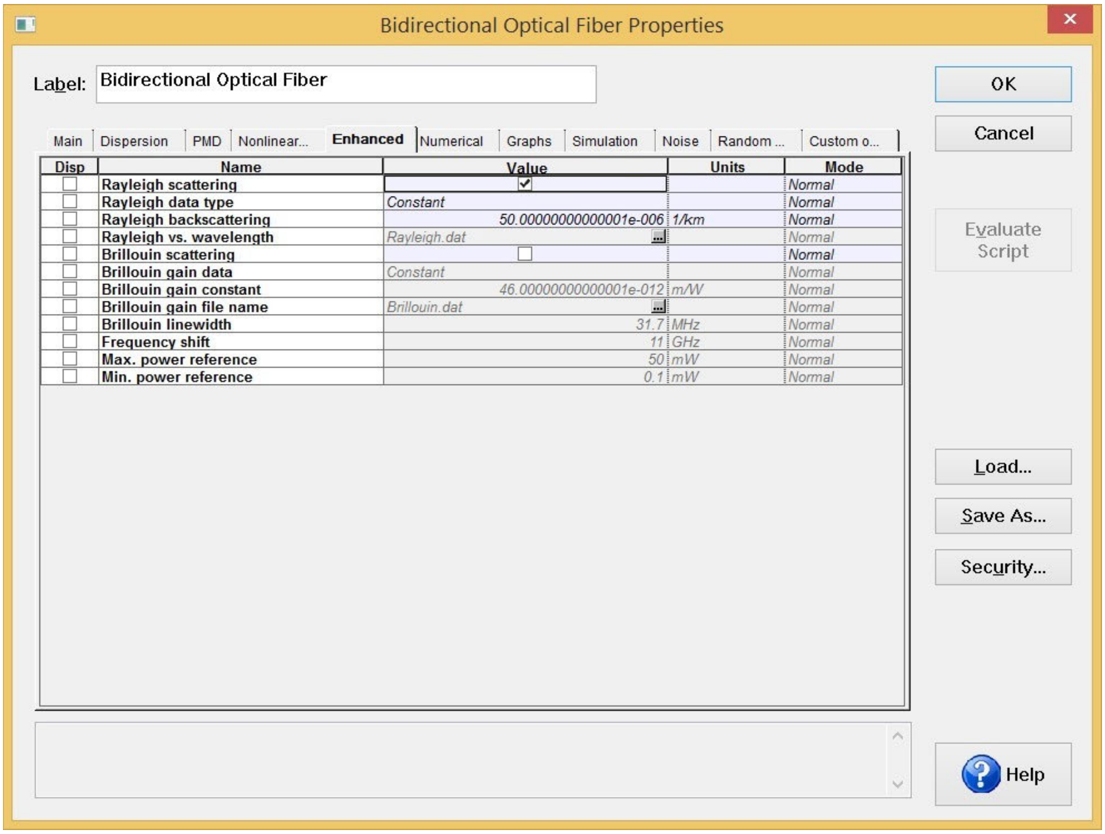
IV. SIMULATION MODEL

The simulation model of 10 Gbps for SCM/WDM-XGPON-RoF bidirectional transmission along a fibre length of 80 km is analysed with and without SRM. The upstream and downstream transmissions are transmitted at 1577 nm and 1270 nm wavelengths, respectively. The proposed system is evaluated and simulated through the Optisystem software. Initially, the system was analysed without using SRM. The system performance improves with the utilisation of SRM on the receiver side. The component parameters are set according to the standards of IEEE 802.3ah, as shown in Table 1. The RF signal with a 15 GHz frequency for the AM modulator is modulated using an optical signal that has 0 dB power and 1270 nm wavelength in four ONUs. It is then combined with the use of a combiner and sent to the OLT side.

Optical networks rely on transmitter and receiver systems, with one optical fibre used to send data and the other for receiving data from network devices. This type of data transfer usually raises network deployment costs, however, by utilising a bidirectional optical transmitter and receiver with the ability to send and receive data through a single optical fibre, a more cost-effective optical network can be created. The bidirectional optical transmitter and receiver device is a type of optical transceiver that applies WDM technology. Its usage is necessary since it allows bidirectional communication through single fibres which enables simpler connection deployment, troubleshooting and configuration. The bidirectional optical transmitter and receiver device is generally posting in duplex data links with high speed through a single optical fibre. The usual optical wavelength of this transceiver is 1270/1577 nm and it is utilised in the applications of optical bi-directional data and optical communication. The key features that distinguish bi-directional optical transmitters and receivers from standard two-way optical transmitter and receiver devices is that the former can transmit

TABLE 1. System design parameters for RoF-XGPON technology according to the IEEE 802.3ah standard.

PARAMETERS	VALUE	PARAMETERS	VALUE
Downstream Max. bit rate-XGPON	10 Gbps	Splitter ratio-XGPON	32
Upstream Max. bit rate-XGPON	2.5 Gbps	Modulation format	64 QAM
Downstream long wavelength-XGPON	1577 nm	OLT power	0 dB
Upstream long wavelength-XGPON	1270 nm	ONU power	0dB
Bi-directional optical fibre length	80 km	Frequency (AM modulator)	15 GHz
Attenuation constant	0.2 dB/km	Carrier frequency (first-MZ modulator)	193.1 THz
BW (WDM MUX 2:1)	10 GHz	Carrier frequency (second-MZ modulator)	193.2 THz
Dispersion	16.75 ps/nm/km	Carrier frequency (third-MZ modulator)	193.3 THz
Dispersion slope	0.075 ps/nm2/km	Carrier frequency (fourth-MZ modulator)	193.4 THz



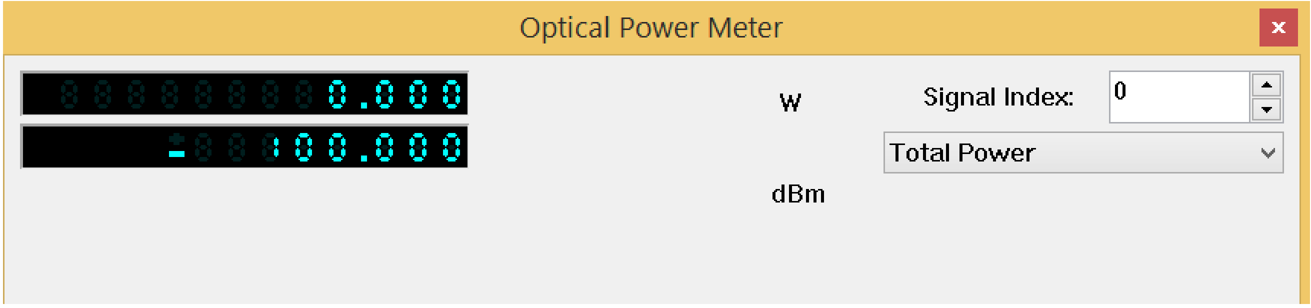
Label: Bidirectional Optical Fiber

Disp	Name	Value	Units	Mode
☐	Rayleigh scattering	☑		Normal
☐	Rayleigh data type	Constant		Normal
☐	Rayleigh backscattering	50.00000000000001e-006	1/km	Normal
☐	Rayleigh vs. wavelength	Rayleigh.dat		Normal
☐	Brillouin scattering	☐		Normal
☐	Brillouin gain data	Constant		Normal
☐	Brillouin gain constant	46.00000000000001e-012	m/W	Normal
☐	Brillouin gain file name	Brillouin.dat		Normal
☐	Brillouin linewidth	31.7	MHz	Normal
☐	Frequency shift	11	GHz	Normal
☐	Max. power reference	50	mW	Normal
☐	Min. power reference	0.1	mW	Normal

FIGURE 6. The rayleigh scattering system parameters.

and receive optical light data via a single fibre, introducing the implementation of a compact WDM technology within its design. This technology separates the transmitted and received data through the same fibre depending on the light wavelengths. However, the bidirectional optical transmitter and receiver must be posting in identical pairs to operate at maximum level. The transmitter and receiver are set to match the expected wavelength of the sending and receiving data (to and from). To enhance the performance of the proposed bidirectional fibre linking system, if one of the transceivers is sending a 1577 nm wavelength, then the other side should have a receiving wavelength of 1270 nm and vice versa.

The energy launch intensity is measured through the use of an optical power meter while parameters are changing in the bidirectional optical fibres, as shown in Figures 5 and 6, respectively. The figures represent the parameters that have been applied in the proposed system to determine the effects, the losses as well as the power budget. Figure 7 displays the assessed losses at each stage of the system.



Optical Power Meter

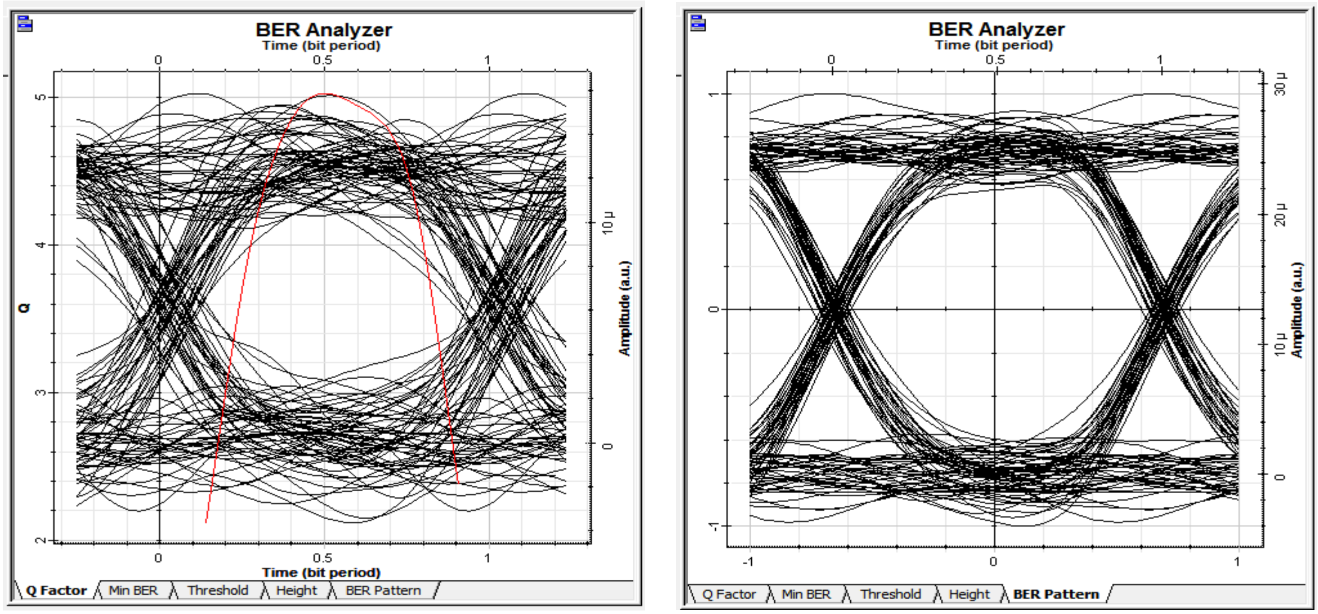
0.000 W

-100.000 dBm

Signal Index: 0

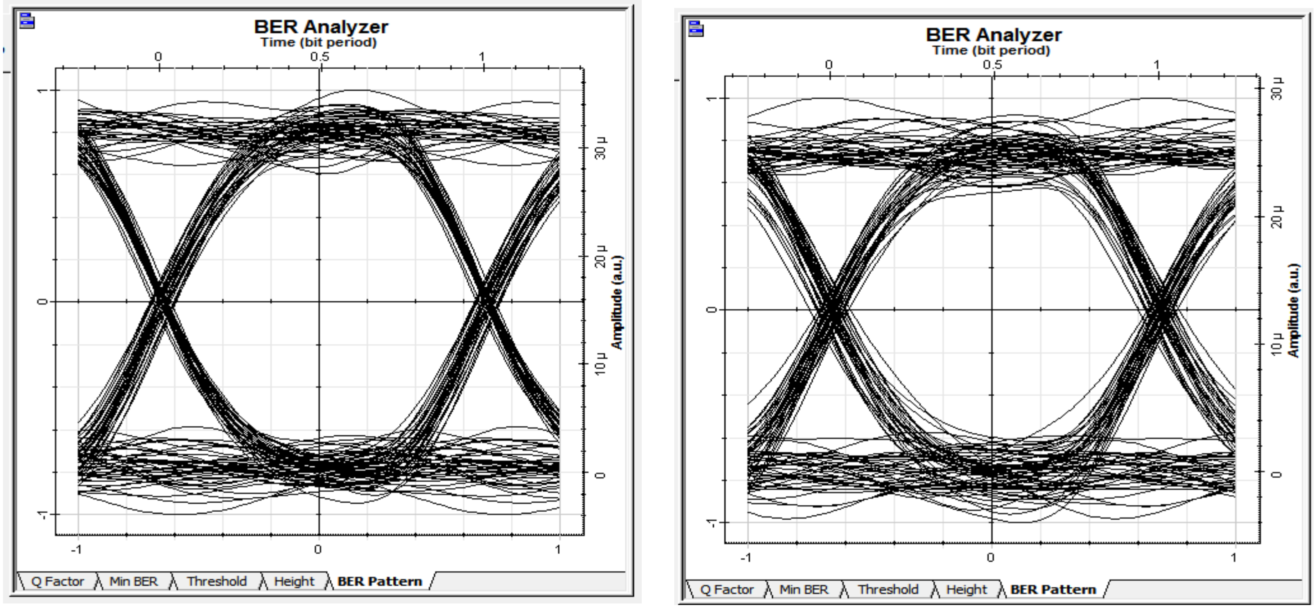
Total Power

FIGURE 7. The rayleigh scattering system parameters.



(a) Without SRM

(b) With SRM at 50 km



(c) With SRM after 20 km

(d) With SRM after 50 km

FIGURE 8. The eye diagram of the received signal for the proposed system, with and without SRM, for different optical fibre lengths.

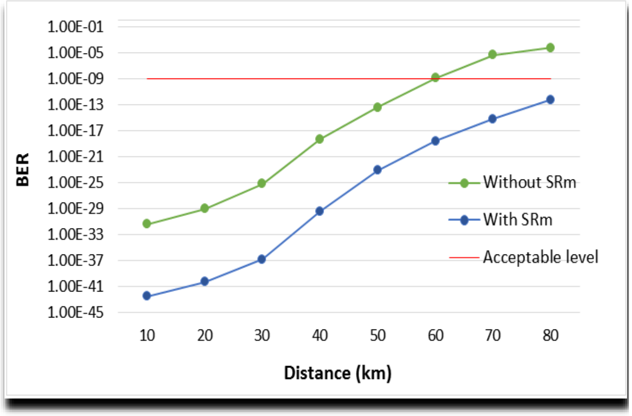


FIGURE 9. BER versus length optical fibre with and without SRM.

V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In order to evaluate the performance of the proposed SCM/WDM-XGPON-RoF system, this section presents a set of simulation results through analysed the proposed model with used the aforementioned simulation parameters, and comparing the results with and without SRM.

The eye diagram at the receiver side of ONUs for different optical fibre lengths is analysed with and without SRM, as shown in Figure 8. We noticed that the opening of the eye is higher with SRM compared to without after 20 km and 50 km. Thus, the performance of the proposed system has improved by double with the use of SRM on the side of the receiver. This offsets the characteristics of the photodiode's square law, enabling successful system transmission.

Figure 9 displays the BER versus the length of the optical fibre when changing the distance from 10 km to 80 km, with and without SRM. The BER analyser is placed on the side of the receiver for the output analysis. By comparing the BER patterns from the results in Figure 9, it can be seen that the BER is less than the acceptable level at 80 km optical fibre length: with SRM, it is 1.00E-09, which is equal to 1.00E-12; while without SRM, it is higher than 1.00E-09, which is equal to 1.00E-6. The BER is also less than 1.00E-09 for the optical fibre length of 50 km without SRM (equal to 1.00E-13), while it is less than 1.00E-21 with SRM for the same optical fibre length. This indicates that the BER with SRM exhibited an improvement compared to without SRM.

From Figure 10, an enhancement in the Q-factor can be observed using the proposed system with SRM compared to without. The Q-factor is 6.4 when the length of the fibre is 50 km without SRM, while it is 9.15 with SRM. This figure further reveals that the Q-factor decreases with the increase in distance, from 10 km to 80 km. The Q-factor is 3.75 without SRM when the length of the fibre is 80 km, while it is equal to 6 with SRM for the same fibre length.

The variation of BER and Q-factor compared to the distance, which represents the length of the optical fibre, has been obtained for the proposed transmission link with the different input powers received (- 2, 2 and 6 dBm), as shown in Figures 11 and 12. From the simulation results, the BER value increases when the fibre length increases from 10 km to 80 km, while the Q-factor decreases when the fibre length increases. This is due to attenuation and the loss of dispersion which increase with the length of the fibre. The BER value also increases from 1.00E-17 to both 1.00E-16 and 1.00E-11 when the input power decreases from 6 dBm to

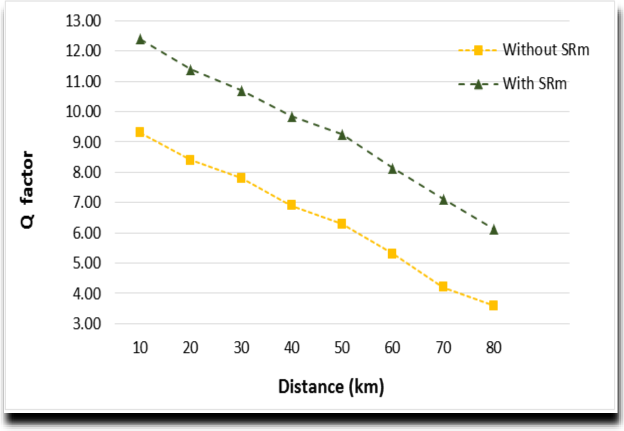


FIGURE 10. Q-factor versus fibre length with and without SRM.

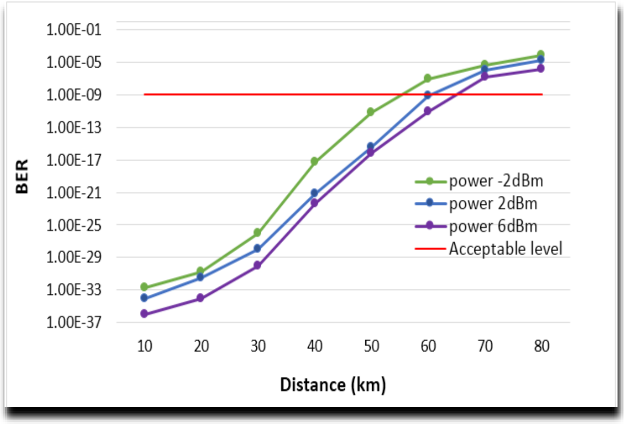


FIGURE 11. Variation of BER as a function of fibre length for different input powers.

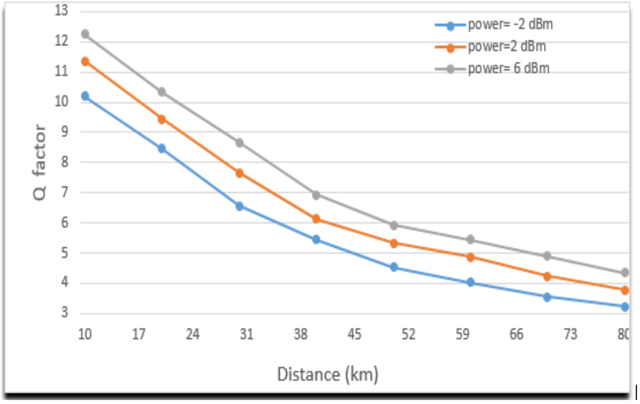


FIGURE 12. Variation of Q-factor as a function of fibre length for different input powers.

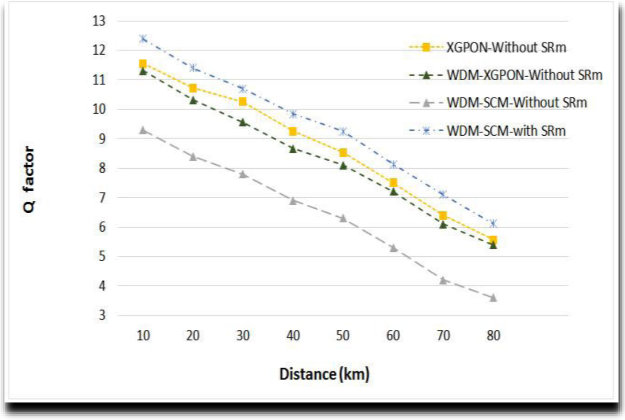


FIGURE 13. Q-factor versus fibre length for different systems with and without SRM.

both 2 dBm and -2 dBm, respectively. When the fibre length is set to 50 km, the Q-factor value increases from 4.53 to both 5.34 and 5.93 when the input power increases from -2 dBm to both 2 dBm and 6 dBm, respectively. These results indicate that there is significant improvement if the received 6 dB power is used in the transmission link compared to other values. As a result, we can conclude that the BER mainly depends on the power, therefore, decreasing the BER is the direct consequence of increasing the power since the SNR is increasing. The BER performance increases if the input power is below -2 dBm, and it decreases if the input power is above 6 dBm. It should be mentioned that when the input power is above 6 dBm, nonlinearity effects will also appear, however, these effects are not addressed in this work.

The Q-factor, according to the fibre length, is shown in Figure 13. The results indicate that the performance of the WDM/SCM-XGPON-RoF system with SRM is the best compared to the other systems. However, for the fibre length of 50 km, the Q-factor is 9.25, exhibiting better performance compared to the other systems when using the same modulation and input power. The Q-factors for the XGPON, XGPON-WDM and WDM-SCM-XGPON systems without SRM are 8.54, 8.10 and 6.30, respectively. Generally, for the 50 km fibre length, the improvement of system performance (WDM/SCM-XGPON) using SRM compared to XGPON is 8%, while it is 14% compared to WDM-XGPON and 46% compared to the proposed WDM/SCM-XGPON system.

Figure 14 presents the received BER at 10 Gbps versus the optical fibre length when the distance changes from 10 km to 80 km using XGPON, WDM-XGPON and WDM-SCM-XGPON, with and without SRM, respectively. The results of the proposed system with SRM were compared with other systems. We analysed the patterns of BER and the outcome showed an enhanced performance with the use of SRM. From the simulation results, we can see that the BER for the proposed system with SRM is less than 1.00E-9 at 80 km, exhibiting an enhanced performance compared to other systems when using the same modulation and input power. The systems without SRM, such as XGPON, XGPON-WDM and WDM-SCM-XGPON, presented less than acceptable levels at 50 km, 48 km and 43 km, respectively. For the system utilizing only XGPON and WDM-XGPON the BER is 1.4 × 1.00E-5. For the system using WDM-SCM-XGPON without SRM, the BER is 1.65 × 1.00E-5. For the system employing WDM-SCM-XGPON with SRM and at a 70 km distance, an improved BER of 1 × 1.00E-15 is acquired.

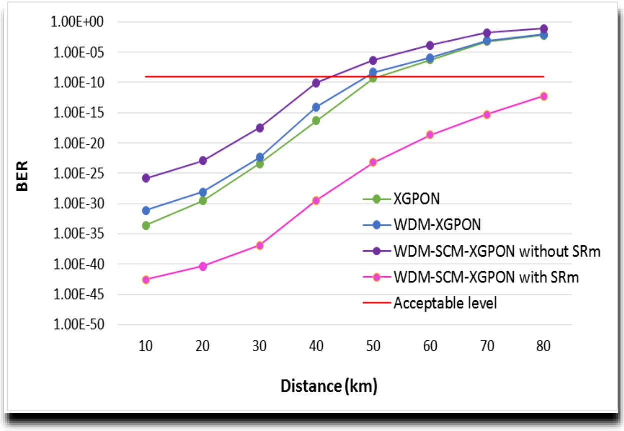


FIGURE 14. BER versus optical fibre length for different systems with and without SRM.

Generally, a comparison of the eye diagrams regarding the BER and Q-factors of the receivers, with and without SRM, reveals that SRM is a key component for improving the execution of the proposed system.

VI. CONCLUSION

Increasing demands for higher bandwidths have initiated the use of 10-GPON. This work presented the SCM/WDM-10GPON-RoF bidirectional system with a split ratio of 1:32 using SRM at 1577 nm for downlink transmission and 1270 nm for uplink transmission, respectively. The proposed system is adequate for various applications. To enhance system performance, SRM on the receiver side has been suggested and designed using MATLAB, which played a key role for improving the proposed system's execution with RoF technology. The results of the proposed link for various input powers and fibre lengths have been compared on the receiver side, with and without SRM, for different systems. Thus, it has been concluded that the proposed system yields better results compared to systems without SRM. The performance exhibited double the enhancements in terms of BER and Q-factor values using SRM for successful transmission with 80 km fibre length. This was the highest level in the SRM case for the proposed system. At 70 km distance, the results revealed an improvement in the proposed system with SRM (BER of 1 × 1.00E-15) compared to without (BER of 1.65 × 1.00E-5). The Q-factor also improved from 6.30 without SRM to 9.25 with SRM, respectively. The proposed system verifies that the requirements of different customer applications can be met. Customers can be given priority services. It has become easier for different end-users to obtain high data rates and attempt to use the bandwidth simultaneously. This simulation allows us to determine the appropriate design and decide how to deploy this technology based on the needs of the service. Thus, due to the request for higher bandwidth, the XGPON can be upgraded to NGPON2 in future works.

ABBREVIATIONS

The following abbreviations are used in this manuscript:

Abbreviations	**Definition**
AWG	Arbitrary Waveform Generator
BER	Bit Error Rate
BSs	Base Stations
BW	Bandwidth
CE	Coexistence Component
CW	Continuous Wave
DWDM	Dense Wavelength-Division-Multiplexing
EE	Electronic Equalizer
EPON	Ethernet Passive Optical Network
FTTH	Fibre To The Home
GPON	Gigabit Passive Optical Network
IF	Intermediate Frequency
LBF	Low-Pass Filter
MUX	Multiplexer
MZ	Mach-Zehnder
NRZ	Non Return Zero
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPL	Optical Path Losses
OSNR	Optical Signal to Noise Ratio
PMD	Polarisation Mode Dispersion
PON	Passive Optical Network
PRBS	Pseudorandom Sequence
QAM	Quadratic Amplitude Modulation
Q-factor	Quality Factor
RA	Raman Amplification
RF	Radio Frequency
RoF	Radio over Fibre
SCM	Sub-Carrier Multiplexing
SMF	Single-Mode Fibre
SNR	Signal to Noise Ratio
SRM	Square Root Module
TSOA	Traveling-Wave Semiconductor Optical Amplifier
TWDM	Time Wavelength Division Multiplexed
WDM	Wavelength Division Multiplexing
XGPON	10-Gigabit Passive Optical Network

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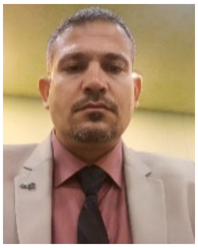

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