450 Gbps Low-cost Intensity Modulation with Direct Detection (IM/DD) Wave Length Division Multiplexing (WDM-PON) for 5G Fronthaul

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Abstract

This work designs an eighteen-channel bidirectional Intensity Modulation with Direct Detection (IM/DD) Wavelength Division Multiplexing-Passive Optical Network (WDM-PON) system. The proposed system meets the requirement of the ITU-T 5G fronthaul link suggested design in G-series Recommendations-Supplement 66. The newly designed system, with a 25Gb/s/λ data rate (450Gbps as a system capacity), has been tested and simulated using OptiSystem V.19 software. The system has been evaluated by the BER with respect to variable the optical span and CW laser power. Based on the ITU-T recommendations, the simulation results demonstrate that this system might be used as an F1 and as an Fx 5G fronthaul link for functional split choices starting from options 1 to 7a. These options are required under 25Gbps/λ for each upstream and downstream link direction. Furthermore, the proposed system utilized a bidirectional single-mode optical fiber within short optical spans of up to 10 km. The proposed system is characterized by a low-cost, simple, DSP-free and amplifier-free system with a reasonable system capacity.

Keywords: AWG, Bidirectional WDM-PON, Intensity Modulation with Direct Detection (IM/DD)

1. Introduction

The high demand for data rates especially after introducing the 5G cellular network requires constructing a base station (BT) that meets consumer needs while also improving the BTs' flexibility and dependability. Consequently, the BTs are shifting from many technologies to increase their performance in radio functionality and baseband transmission [1]. Cloud-Radio Access Network (C-RAN) is one of these technologies suggested to be a solution for the next mobile generation networks to achieve great benefits by employing this technique such as higher throughput, scalability, energy efficiency and lower CAPEX, OPEX and latency [2]. The fronthaul (FH), as shown in **Fig. 1**, is used to connect the Remote Radio Head (RRH) and Base Band Unit (BBU) is the most important component of the C-RAN architecture since it affects the total capacity, performance, and deployment cost of the system [3]. Generally, three different technologies are used by the researchers to provide a high data rate and low latency links in the fronthaul which they are Microwave Radio Transmission (MRT), Free Space Optics (FSO), and Fiber Optics (FO). Among them, the FO is preferred by ITU-T due to its inherent features such as low latency, large capacity, and scalability [4]. One of the most effective fronthaul access architectures that may offer high optical implementation capacity links and long-reach fiber is the Passive Optical Network (PON); the wavelength Division Multiplexing is one of the many modulations and multiplexing techniques employed by this network [5]. By using several wavelengths of fiber, WDM may support more users, hence increasing the capacity of the optical fiber network [6]. To enable future high bandwidth, residential and backup services, WDM-PON was developed in the late 1980s and is now suggested by many authors to be used as a solution that meets the required fronthaul link networks [7]. The authors in [8] investigates the applicability of WDM-PON for 5G wireless networks, emphasizing the importance of deployment scenarios. While not universally applicable, specific service areas can benefit from WDM-PON. The study presents trial results demonstrating system feasibility and discusses a hybrid PON architecture that combines WDM-PON with 50 Gb/s time-division multiplex PON (TDM-PON) networking .With an Erbium-doped Fiber Amplifier (EDFA), WDM mux-demux splitter, and Avalanche Photodiode (APD) light detector, a straightforward and reasonably priced bidirectional WDM-PON is modelled by the authors in [9] for long-distance transmission. The proposed model provides a cost- and energy-efficient optical fiber network using the spectrum slicing technique over a 170 km long bidirectional optical fiber. The model has been designed for a 3 Gbps non-return to zero (NRZ) transmission system. But the system included 5 channels and the system capacity was significantly low at only 15 Gbps. To increase the system capacity, the authors in [10] proposed (TWDM-PON) Time Wavelength Division Multiplexed-Passive Optical Network with a system capacity of up to 80Gbps. To achieve this capacity, eight optical channels each with eight-time slots and synchronous data rates of 10 Gbps for both upstream and downstream transmission has been proposed. Furthermore, to lower the bit error rate of the system**,** a launched optical power/channel of 5–10 dBm is suggested to sustain a maximum BER of 10^{-13}. Using TWDM-PON is not preferable by the ITU-T in [11] because of the latency issue while WDM-PON shows superior performance with regard to latency and system capacity. An 8-channel with 2-10Gbps/λ WDM-PON 80 Gbps system with a single Erbium-Doped Fiber Amplifier (EDFA) has been reached by the researchers in [6]. The authors in [12] suggested and assessed a centralized light source WDM-PON architecture (CLS). Rayleigh backscattering (RB), which causes optical interferometric noise in the main lobe of each downstream (DS) optical signal, is minimized in this work by using just one 10 GHz band reject filter at the remote node (RN). Moreover, utilizing this filter results in an upstream (US) optical interferometric noise reduction. The advantage of the proposed system in [6] is that it would increase the downstream capacity to 160 Gbps (16 channels at the rate of 10 Gbps) and 40Gbps (16 channels at the rate of 2.5 Gbps) for upstream transmission capacity. All the above works utilized NRZ and MZM as a bit coding and an optical modulation which use low-cost and simple systems to provide a solution for high bandwidth demand link applications. However, to increase the data rate of each channel, an advanced modulation with Digital Signal Processing (DSP) should be used such as Quadrature phase shift keying (QPSK) and Quadrature Amplitude Modulation (QAM) under a penalty on increasing system complexity and cost [13]. The authors in [14] suggested an 800 Gbps Dual Polarization Quadric Phase Shift Keying (DP-QPSK) with a coherent detection to obtain a 100Gbps/Channel (with eight channels) using DSP and two EDFAs for uplink and downlink at the central unit. While the authors in [15] suggested an 8-channel dual polarization 128-QAM DWDM communication system, each channel's data rate is set at 90 Gbits/s, and simulations are run on an 80 km single-mode fiber (SMF). For dispersion compensation, dispersion compensation fiber (DCF) of the proper length is utilized. In addition to the DCF, suitable optical amplifiers are used to control linear imperfections. Finally, Using intensity modulated/direct detection optical orthogonal frequency division multiplexing (IM/DD-OFDM), the researchers in [16] evaluate a proposed system incorporates downstream wavelengths with a high transmission rate of 100 Gbit/s and employs 16 Quadrature Amplitude Modulation (16-QAM). For the upstream wavelengths, a 5 Gbit/s On-Off Keying (OOK) modulation scheme is utilized. The system design takes advantage of non-coherent IM/DD OFDM technology, ensuring efficient signal processing. Additionally, a simple Reflective Semiconductor Optical Amplifier (RSOA) colorless transmitter is employed, eliminating the need for complex Dispersion Compensating Fiber (DCF) components. The proposed WDM-PON system achieves maximum downstream transmission rate of 100Gbps /channel with over all 16 channels and system capacity of 1.6Tbps for 30km using SMF.

The proposed design offers a system capacity of 450 Gbps and can serve 18 Optical Network Units (ONUs) over Bidirectional Single Mode Optical Fiber (BD-SMF), making it suitable for providing fronthaul links to multiple 5G base stations in urban areas. By adopting a simpler modulation technique, the design reduces infrastructure costs and increases system channels, aligning with ITU-T standards for 5G fronthaul links. This minimizes capital expenditures (CAPEX) and improves the feasibility of deploying fronthaul systems in 5G networks. In comparison to previous works, the proposed design utilizes simple Mach-Zehnder Modulator (MZM) and Non-Return-to-Zero (NRZ) modulation techniques, achieving a maximum bit rate of 25 Gb/s per channel. This outperforms previous works that employed similar simple modulation techniques without digital signal processing or dispersion compensator fiber. Other studies employed more complex and expensive modulation schemes, such as Dual Polarized-Quadrature Phase Shift Key (DP-QPSK) and Dual Polarized-Quadrature Amplitude Modulation (DP-QAM), to achieve higher data rates. However, the proposed design demonstrates practicality and cost-effectiveness by achieving high data rates while utilizing simpler modulation techniques. The novelty of the proposed work lies in its ability to achieve a high data rate per channel using simple modulation techniques, while also increasing the number of system channels over a single BD-SMF and reducing infrastructure costs. This approach aligns with ITU-T standards for 5G fronthaul links, providing a significant advancement in the field.

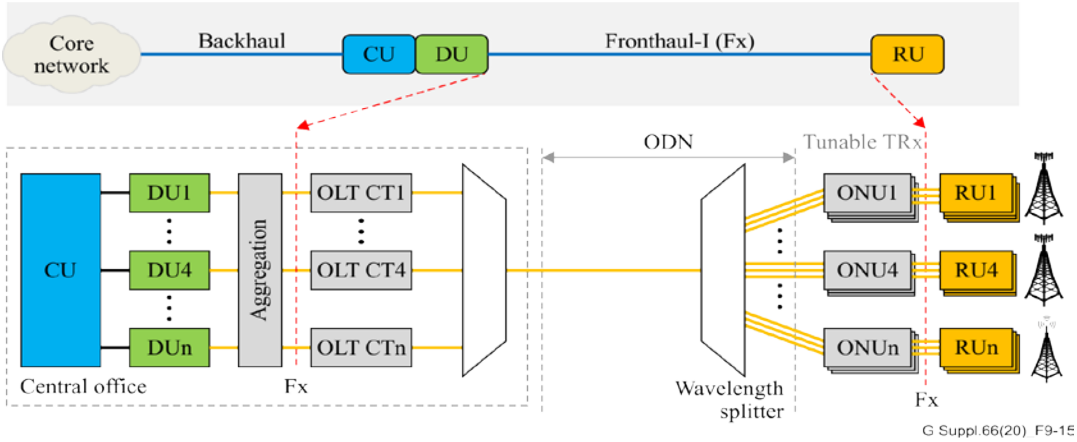


Fig. 1. WDM-PON fronthaul Architecture [11]

2. Technical Background

The rise in the data speeds of 5G makes using the traditional Common Public Radio Interface (CPRI) fronthaul solution problematic. Moving to a higher layer split would reduce latency and bandwidth needs and allow for the centralization of fewer processing tasks. Thus, the suggested fronthaul link design must consider technological and cost-effective trade-offs between throughput, latency, and functional centralization [11]. The 3rd Generation Partnership Project (3GPP) has discovered many break points in the radio processing chain where significant reductions in transport capabilities may be achieved. Option 2 was chosen as the high-layer breakpoint by the 3GPP in April 2017 and is known as the F1 interface, while Fx is the general shorthand for the two low-layer split points (options 6 and 7) [11]. Other organizations, such as the CPRI, O-RAN Alliance, and Small Cell Forum, have varied the Option 7 split point [17]. Layered network architecture is a concept that is described by both 3GPP and IEEE [17]. As illustrated in **Fig. 2**, the radio network layer includes Central Unit (CU)/ Distributed Unit (DU)/Remote Unit (RU), whereas the transport network layer includes Optical Line Terminal (OLT)/ Optical Network Unit (ONU). PON and WDM-PON are excellent choices supported by The ITU-T in [11] for supporting 5G New Radio (NR) transmission at the F1 and Fx interfaces because of their efficient fiber infrastructure and low latency.

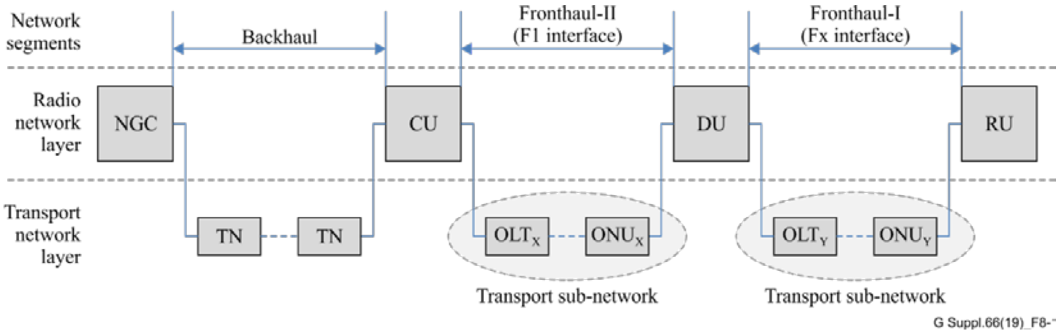


Fig. 2. The radio network layer (CU, DU, RU) and the transport network layer (OLT, ONU) structure concept [11].

As a promising option, WDM-PON can enhance performance in terms of bandwidth, security and latency. A passive wavelength de-multiplexer, such as an Arrayed Waveguide Grating (AWG), is used in the distant node of a typical WDM-PON system. The de-multiplexer codes signal on various wavelength channels are before routing them to various ONUs. The power budget of the entire system is significantly improved by the use of a de-multiplexer since it prevents the significant insertion loss provided by an optical splitter. With this method, a dedicated wavelength channel is set aside between the OLT and each ONU to build a point-to-point link where each ONU can utilize the full bit rate of its wavelength channel [18].

A crucial component of many WDM-PON designs is the Arrayed Waveguide Grating (AWG) router which is shown in **Fig. 3**. It has numerous inputs and multiple outputs. A standard AWG router consists of two-star couplers connected by waveguide arms of different lengths. Each arm has a fixed length relationship with its neighbour. By acting as an optical grating, these waveguides spread out signals of various wavelengths. ΔL is the difference in the optical path length between the consecutive array waveguides which could be found as,

$$\Delta L = \frac{m\,\lambda_o}{n_{eff}} \qquad (1)$$

Here, n_{eff} is the effective refractive index of each single mode waveguide, λ_o is the center wavelength, and m is an integer number [19].

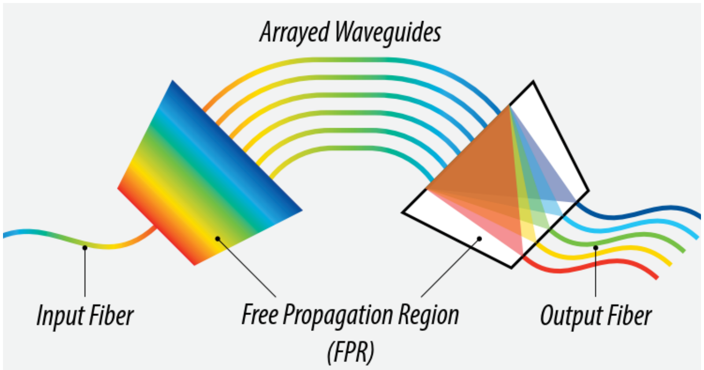


Fig. 3. Arrayed Waveguide Grating[20]

3. Model Design

The schematic diagram of the suggested system is shown in **Fig. 4**. Basically, the system is designed to be used as a bidirectional 5G fronthaul link among the BBUs' pool in the distribution center and the RRH at each base station sector. The system comprises eighteen individual channels. On the downstream side (from BBU to each sector), all the channels from each optical line terminal (OLT) are multiplexed via the AWG into a single channel to be transmitted over a bidirectional single-mode optical fiber cable. On the optical distribution network (ODN) side, the combined channels are demultiplexed using an AWG demultiplexer. Finally, each received channel is redirected to an individual optical network unit (ONU) of each sector at 5G base stations. The proposed bidirectional WDM-PON system model includes non-return to zero (NRZ) pulse generators, Mach-Zehnder Modulators (MZM), optical circulators, two AWGs, a bidirectional single-mode optical fiber (BD_SMF) link, BPFs, LPFs and Photo Detectors (PDs) as shown in **Fig. 5**. The suggested system is set up, simulated and tested using Optisystem V.19.

In the downstream, at each channel the pseudo-random bit sequence (PRBS) generator produces random binary sequences with the required data rate of 25 Gbps. Next, the NRZ pulse generator element produces rectangular non-return to zero (NRZ) electrical pulses with exponential edge shapes, given by (2) [21].

$$E(t) = \begin{cases} 1 - e^{-\left(\frac{t}{c_r}\right)}, & 0 \le t < t_1 \\ 1, & t_1 \le t < t_2 \\ e^{-\left(\frac{t}{c_f}\right)}, & t_2 \le t < T \end{cases} \quad (2)$$

Here, c_r and c_f are the rise-time and fall-time coefficients, respectively. T represents the bit duration that is qual to the reciprocal of the bit rate of the message. The two time points t_1 and t_2 together with c_r and c_f are numerically set to generate pulses that align with the values of the parameters Rise time and Fall time. The Mach-Zehnder modulator modulates the coded bits from the PRBS and NRZ with Continuous Wave (CW) lasers. The MZM is an interferometric-based intensity modulator. It is made up of two 3 dB couplers coupled by two equal lengths waveguides. An externally applied voltage can be utilized to alter the refractive indices in the waveguide branches via an electro-optic effect. Depending on the applied voltage, the separate channel can cause destructive and constructive interference at the output. Next, the output intensity can be varied based on the voltage. The output optical signal $E_{out}(t)$ is related to the input optical signal $E_{in}(t)$ by (3) [22].

$$E_{out}(t) = E_{in}(t).e^{j\phi_{PM}(t)} \quad (3)$$

Where $\phi_{PM}(t)$ is the phase modulation, can be expressed by (4) [22].

$$\phi_{PM}(t) = \frac{u(t)}{V_\pi}\pi \quad (4)$$

Where $u(t)$ is the applied external electrical voltage, and V_π is the required driving voltage to obtain a required phase shift of π. The generated optical signals from all the eighteens different OLTs are sent to the first AWG at Central Office (CO) which multiplexes them after that they are sent over the bidirectional optical fiber cable. Then, the multiplexed signal is passed to the second AWG at ODN which de-multiplexes the incoming signal. The de-multiplexed signals are sent to each of the eighteens ONUs. At each ONU, the combined downstream and upstream signals are separated using an optical circulator. After that, the downstream signal is passed to a BPF before getting to the photo detector (PD) to eliminate the unwanted leaked frequency components. The PD converts the fluctuations in optical power level back to the original electrical signal format. Intensity modulation with direct detection (IM/DD) is the name of this receiving technique. Systems that use IM/DD techniques are straightforward and reasonably priced [13].

At the upstream side (from each 5G base station sector to the BBU pool), the same downstream technique is applied in a reverse direction using the same frequency band used in the downstream. It is worth saying that by using a one-unit optical delay, the interference between the upstream and downstream has been avoided.

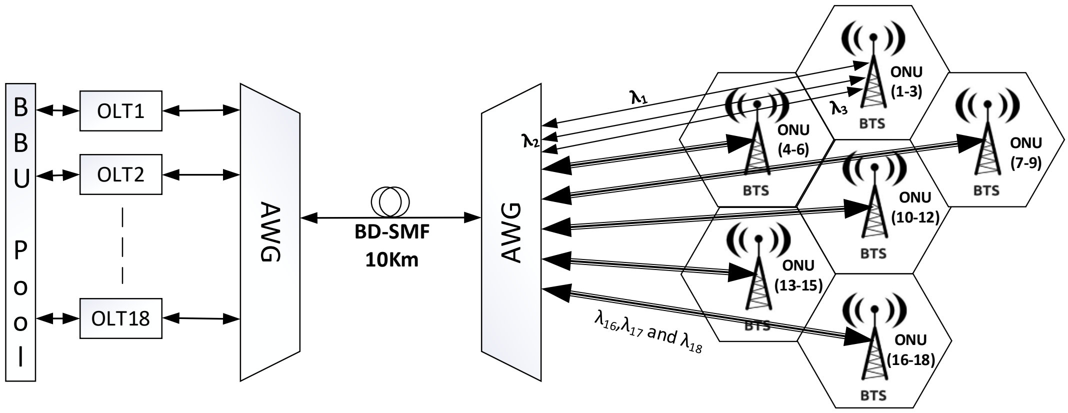


Fig. 4. Schematic Diagram of the Proposed Design.

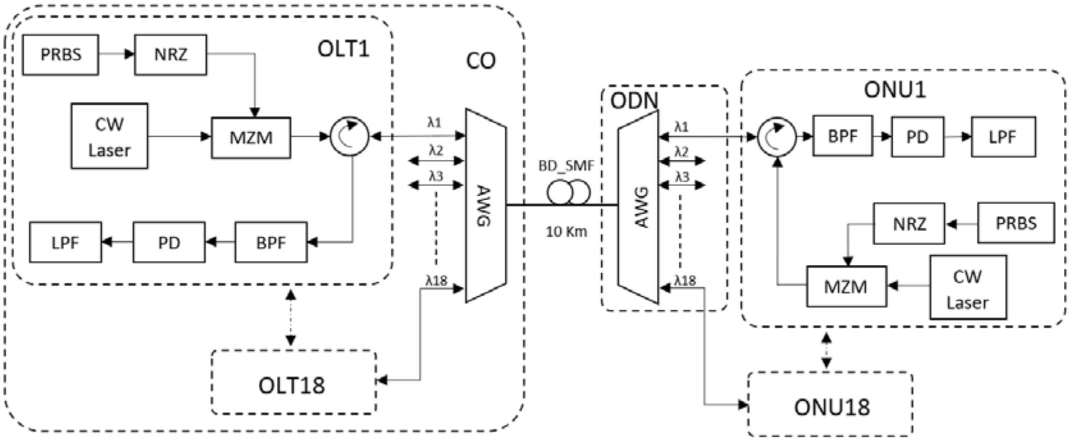


Fig. 5. The proposed bidirectional WDM-PON design.

The WDM-PON design parameters are given in **Table 1**. The downstream and upstream data rates for the system are chosen to be 25 Gbps based on the requirements for passive optical networks that are declared by the ITU-T recommendations in [11]. Moreover, the prerequisite bidirectional optical fiber parameters, where are presented in **Table 2**, are also declared in the same ITU-T recommendation. Meeting these requirements is the main objective of this proposed design. The optical transmitter parameters including the wavelengths for both the upstream and downstream channels are also explained in **Table 1** [23]. Likewise, the optical receiver parameters are also presented in **Table 1**. The responsivity of Indium Gallium Arsenide (InGaAs) at 1550nm must be 0.7A/W [24]. Finally, the AWG parameters at the optical network distribution side are selected to suit the system requirements according to the ITU-T recommendations, which are given in **Table 3**.

Table 1. WDM PON Parameters

Parameters	Values
Layout Parameters	
Bit rate (downstream)	25 Gbps
Bit rate (upstream)	25 Gbps
Sequence length	64 bits
Samples per bit	64
Number of Samples	4096
Optical Transmitter (CW laser)	
Laser Power input, Pin	1mW (0 dBm)
Wavelength (Downlink)	(1550.12, 1549.32, 1548.52, 1547.72, 1546.92, 1546.12, 1545.32, 1544.53, 1543.73, 1542.94, 1542.14, 1541.35, 1540.56, 1536.77, 1538.98, 1538.19, 1537.4, 1536.61) nm
Wavelength (Uplink)	(1550.12, 1549.32, 1548.52, 1547.72, 1546.92, 1546.12, 1545.32, 1544.53, 1543.73, 1542.94, 1542.14, 1541.35, 1540.56, 1536.77, 1538.98, 1538.19, 1537.4, 1536.61) nm
Laser lineWidth	10 MHz
Optical Receiver (PIN PD)	
Responsivity (InGaAs)	0.7 A/W
Dark Current	10 nA

Table 2. Bidirectional optical fiber parameters

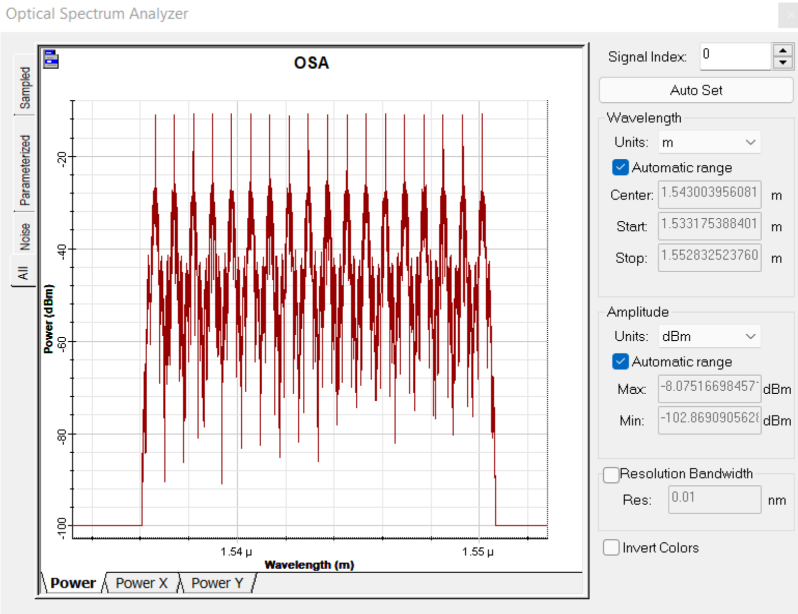
Parameter	Value
Reference wavelength	1550 nm
Length	10 km
Attenuation	0.35 dB/km
Dispersion	16.75 ps/nm/km

Table 3. AWG parameters at OND

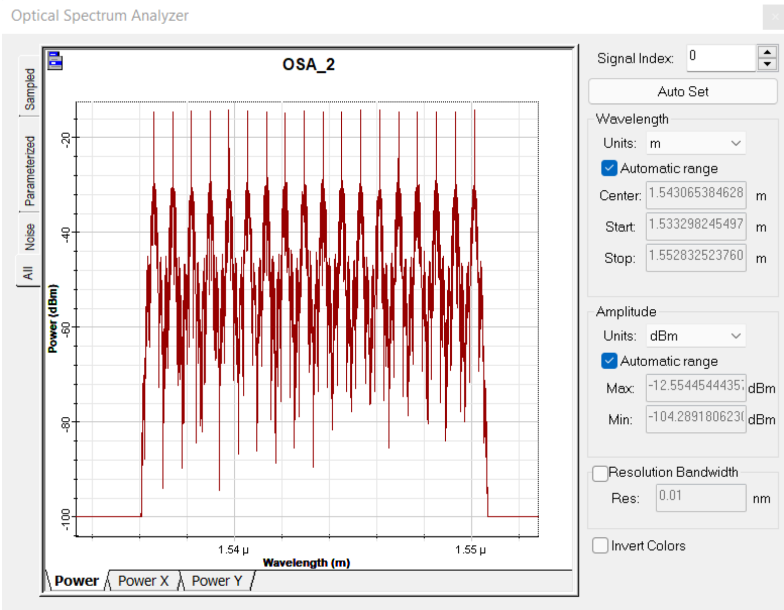
Parameter	Values
Size	18 (input ports and output ports)
Frequency	193.399 THz
Bandwidth	70 GHz
Frequency spacing	100 GHz
Insertion loss	3 dB
Return loss	65 dB
Depth	100 dB
Filter type	Gaussian
Filter order	2

4. Results and Discussion

The spectrum diagrams in **Fig. 6** show the features of the Downlink (Downstream) and Uplink (Upstream) channels. A total of eighteen channels, all in the C-Band range, were used in this analysis. The measurement's reference wavelength was set to 1550 nm, and the channels were kept at a power level of -11 dBm. These specifications and spectral representations provide important details about the frequency composition and power levels of the investigated channels.



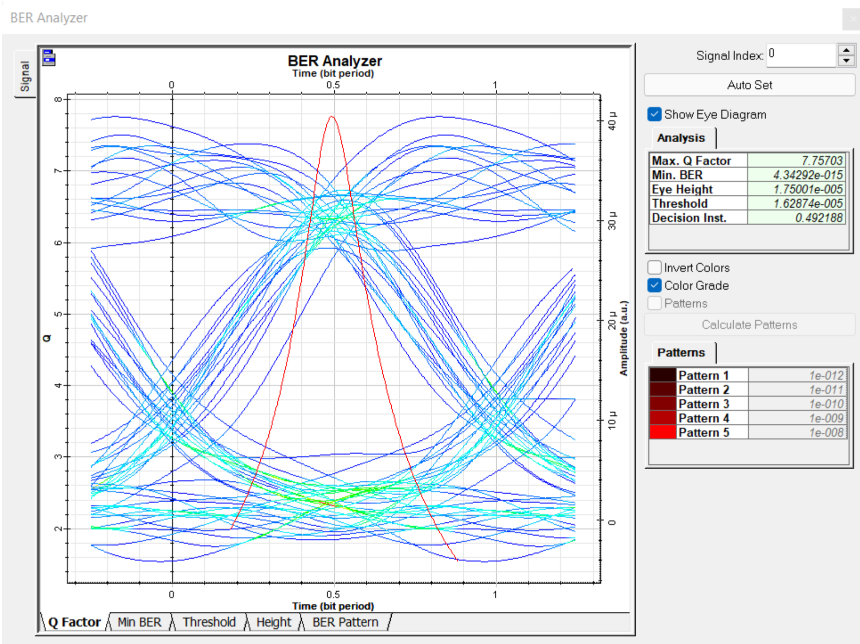
A. Downlink



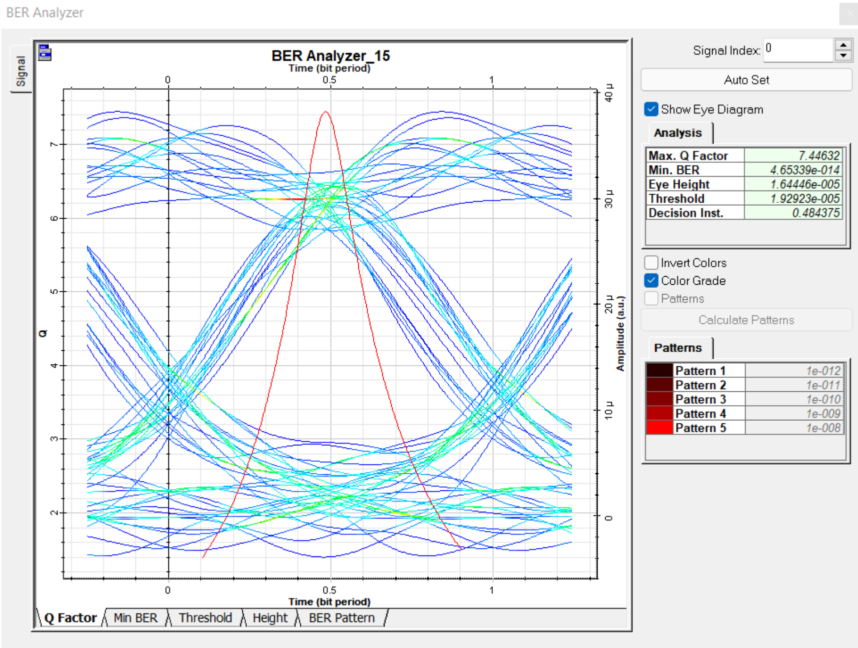
B. Uplink

Fig. 6. Channels Optical Spectrum.

Fig. 7 and **Fig. 8** show the eye diagrams for the downlink and uplink of some of the eighteen channels that were examined. The eye diagram serves as a comprehensive tool for assessing the performance of a communication system, enabling the identification of signal quality, timing variations, presence of ISI, and the impact of noise and dispersion. It facilitates a visual representation that aids in understanding the behavior of the transmitted signal, helping researchers and practitioners optimize system performance and diagnose potential issues. As can be observed by examining the eye diagrams, the figures demonstrate that the Max Q-Factor of all channels surpasses 6, and in some channels, it even approaches 8, which is regarded as an acceptable result[6]. Interim of signal quality, the eye diagrams demonstrate the high quality of the transmitted signal where a well-defined and open eye pattern indicates good signal integrity. Regarding the timing variations, the figures show feasible responses concerning timing variations, including rise time, fall time, and jitter (Jitter refers to the timing fluctuations or deviations in the signal). Eventually, observing the shape, width, and closure of the eye-opening in Fig7 and Fig 8 will verify the high performance of the proposed system against ISI, noise, and dispersion. To further prove the system's performance especially with respect to the Min BER, two different system evaluations have been discussed in sections 4.1 and 4.2.

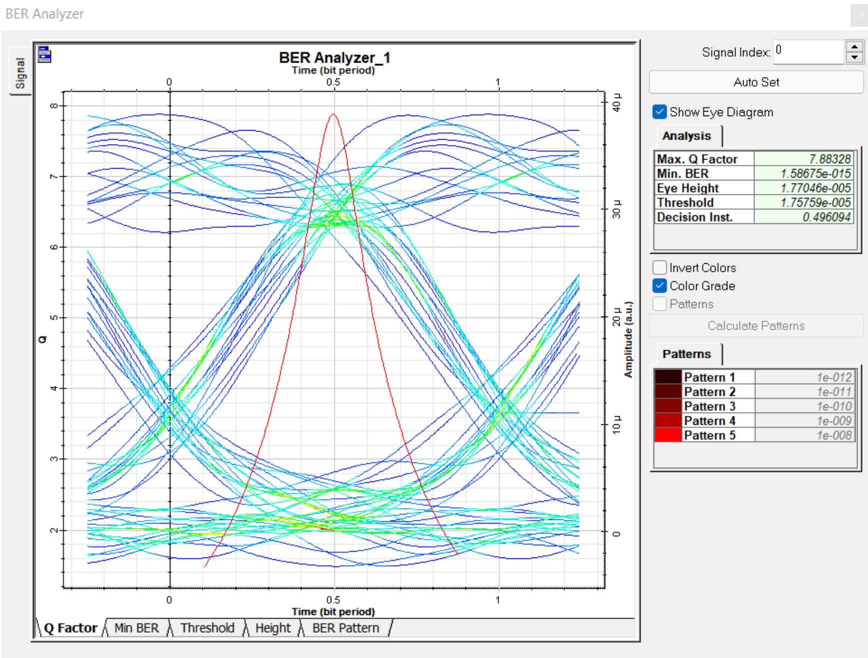


A. CH1 DL (1550.12 nm)

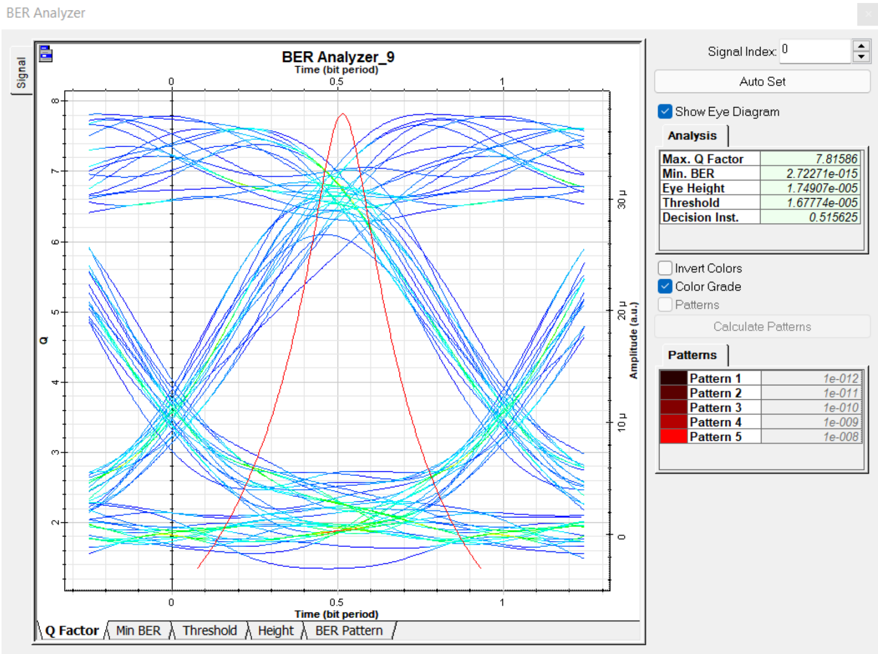


B. CH8 DL (1544.53 nm)

Fig. 7. Downlink Channel 1 and Channel 8 Eye Diagrams.



A. CH1 UL (1550.12 nm)

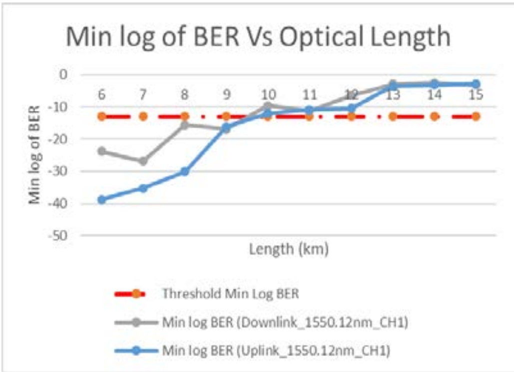


B. CH8 UL (1544.53 nm)

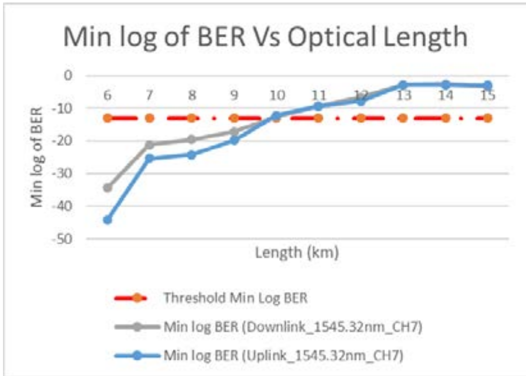
Fig. 8. Uplink Channel 1 and Channel 8 Eye Diagrams.

4.1 System Evaluation for Variable Optical Fiber Lengths

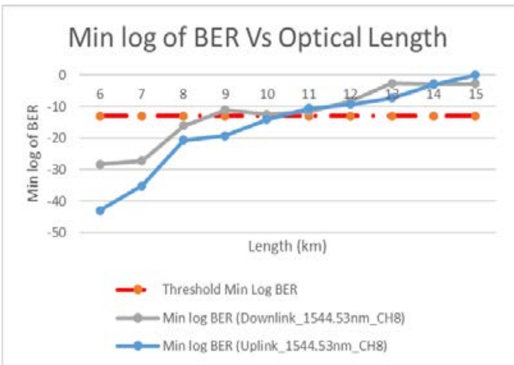
To check the proposed designed validity, the minimum log of the bit error rate for various optical lengths has been compared with the reference threshold values that are a minimum log of BER = -9 and -13 according to [6] and [10] respectively. The evaluation results of selected channels 1,7,8 and 18 on both system sides (Downlink and Uplinks) are shown in **Fig. 9**. It is noticeable from the figures that most of the channels are under Min log of BER of -13 at 10 km except channel 1 on the downlink side with a Min log of BER of -10 which is also acceptable [6]. Several variables, including crosstalk interference and nonlinear effects, can contribute to the fluctuation in BER in a Wavelength Division Multiplexing-Passive Optical Network (WDM-PON) system as shown in **Fig. 9** when the same wavelength is used on both the uplink and downlink sides. In a bidirectional WDM-PON system, signals from the uplink and downlink share the same wavelength, which can cause crosstalk and interference. Crosstalk and interference between the signals might emerge from this cohabitation, which would lower the BER and lower the quality of the transmitted data. On the other hand, Optical nonlinear effects, including self-phase modulation and four-wave mixing, can happen in bidirectional transmission system. These influences can modify the signal's properties and result in signal deterioration, which can alter the BER. However, as the system channels have accepted BER values, this means that this system is valid for serving as a 5G fronthaul link for link lengths less than 10 Km, because after this length the obtained BER results exceed the accepted values.



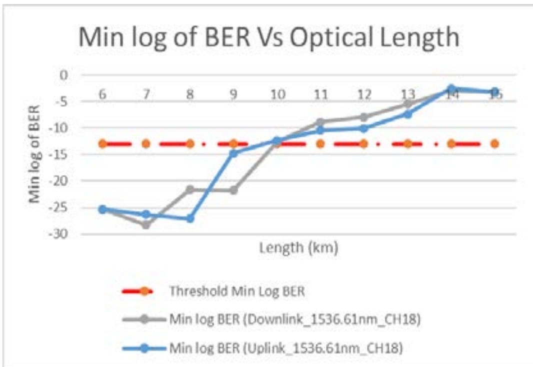
A. CH 1 DL and UL (1550.12 nm)



B. CH 7 DL and UL (1545.32 nm)



C. CH 8 DL and UL (1544.53 nm)



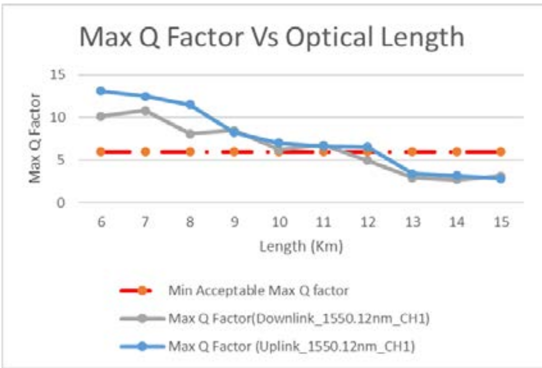
D. CH 18 DL and UL (1536.61 nm)

Fig. 9. Min log of BER versus Optical Length

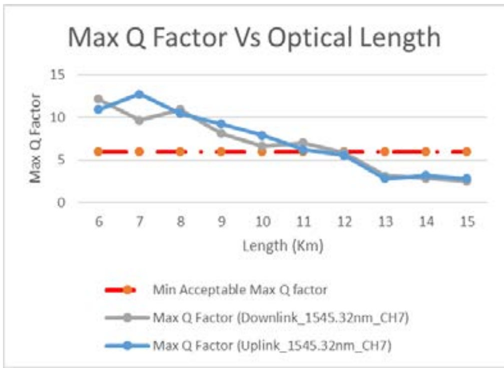
Furthermore, **Fig. 10** shows that Max Q-Factors for the same mentioned channels are over 6 until 10 km of optical cable length and they will start to decay below 6 when the optical span exceeds 10 km due to the optical fiber nonlinearity, chromatic dispersion and attenuation. The **Fig. 10** furthermore, illustrates the variations in the values of the Max Q-Factor. The same fundamental reasons that were examined in Section 4.1 are responsible for these variances. These fluctuations in the Q-Factor values are specifically caused by the impact of crosstalk and optical nonlinearity on the signal quality. Crosstalk and optical nonlinearity are two factors that can degrade the quality of received signals and cause changes in the Q-Factor by adding noise and distortion to transmitted signals.

The overall results shows that this proposed design is well suited for short distance applications, within areas covering a range of up to 10 km. It serves as an affordable fiber connection with a data transmission speed of 25 Gbps/channel. The system can accommodate split options outlined in the ITU T G Series Recommendations–Supplement 66 [11] ranging from option 1 to option 7a.

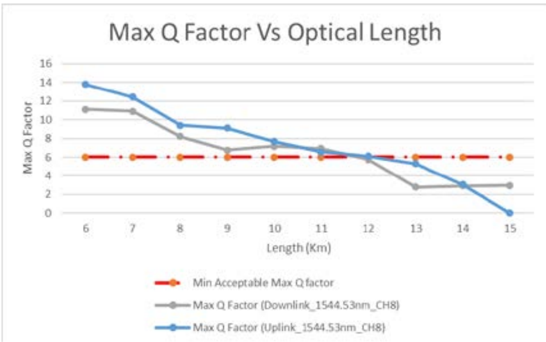
In particular option 7a requires data rates of 22.2 Gbps for the downlink and 21.6 Gbps for the uplink, which can be efficiently supported by this system configuration. The recommended setup includes eighteen channels of 25Gbps each resulting in a system throughput of 450 Gbps for both the downlink and uplink. This achievement of throughput is beneficial for a low-cost wavelength division multiplexing (WDM) system especially during the initial implementation phase of 5G when utilizing existing LTE infrastructure, with the Non-Stand Alone (NSA) plan.



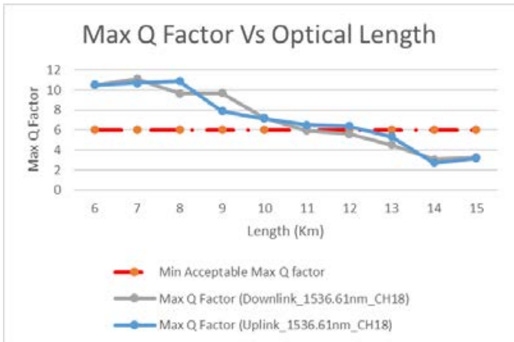
A. CH 1 DL and UL (1550.12 nm)



B. CH 7 DL and UL (1545.32 nm)



C. CH 8 DL and UL (1544.53 nm)



D. CH 18 DL and UL (1536.61 nm)

Fig. 10. Max Q Factor versus Optical Length

4.2 System Evaluation for Variable Transmitting Power (Tx).

In order to keep the system under acceptable bit error rate (BER) and Q-factor criteria, the second assessment of the suggested design tries to identify the minimal launching power necessary for the continuous wave (CW) laser. **Fig. 11** and **Fig. 12** show the results for the highest possible Q-Factor and minimal logarithm of BER as functions of the transmitting power at the downlink side of channels 1, 8, and 18. It is clear from examining the data in the figures that the system has impressive resilience in reaching a sufficient Q-Factor of 6 and minimal logarithm of BER values of -9 and -13 at a transmitting power level starting from 0 dBm. This suggests that even at relatively low transmitting power levels, the system can maintain a high-quality, stable and reliable transmission. The study also shows a positive trend toward performance improvement with rising CW laser transmission power. This finding is in line with the behaviour that optical communication systems are predicted to exhibit, in which more signal power results in better signal-to-noise ratios and, as a result, better BER and Q-Factor performance.

The results also suggest that by appropriately adjusting the transmitting power, the proposed design may be able to support greater communication distances. This is a significant benefit, particularly in long-haul optical communication scenarios where signal attenuation can be a significant issue. The system can efficiently reduce signal loss and increase the range of communication links by optimizing the transmitting power. The trade-offs related to increasing the transmitting power must be taken into account, though. Higher power levels may lead to an increase in nonlinear effects like self-phase modulation and four-wave mixing, which can deteriorate the quality of the signal and reduce the range of communication that is possible. To balance performance improvement and the potential introduction of nonlinear impairments, careful consideration and optimization of the transmitting power are therefore required.

A fascinating method for improving system performance is introduced by the mention of using a passive optical fiber amplifier, such as an Erbium-Doped Fiber Amplifier (EDFA). It can increase signal power without the need for an electrical-to-optical conversion. By incorporating EDFA, the system could be made suitable for long-distance applications by effectively compensating for signal attenuation and extending the communication range. However, it's crucial to consider that the addition of extra parts, like EDFA, will increase the cost of the design as a whole. Therefore, a thorough cost-benefit analysis should be carried out to determine whether such improvements are economically feasible and to make sure that the performance benefits outweigh the associated costs.

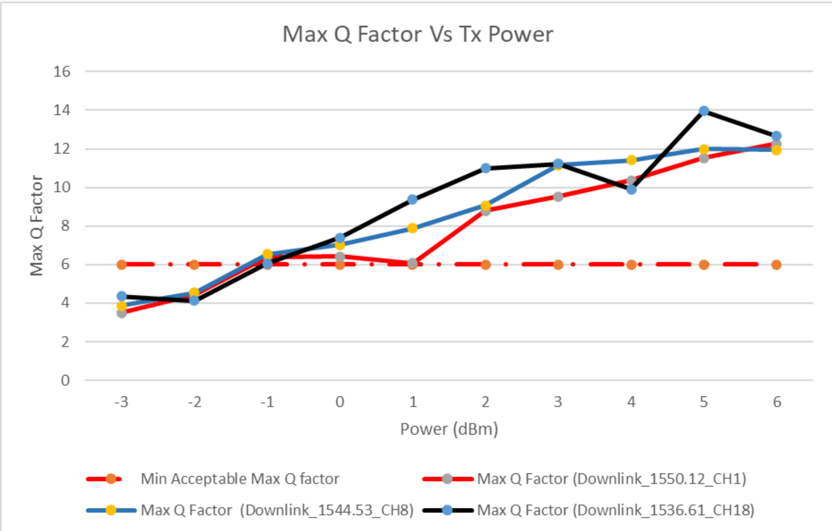


Fig. 11. Max Q Factor versus Tx Power for (Downlink)

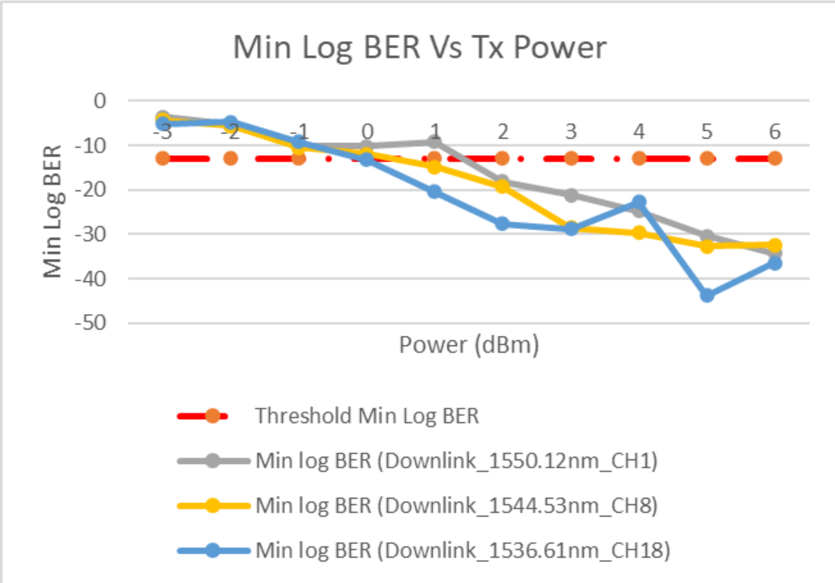


Fig. 12. Min log BER versus Tx Power for (Downlink)

To assess the performance of the system across all eighteen channels, it is necessary to consider the results of each channel. If any channel exceeds the threshold values of BER and Q-Factor (the red dashed lines in **Fig. 13** and **Fig. 14**), the entire system is deemed to have failed. Looking at **Fig. 13**, we can see that the maximum Q-Factor against optical length is displayed, taking into account channels with different wavelengths. Each data series corresponds to a particular wavelength. The figure evident that the with respect the optical span, the highest Q-Factor initially remains above the permissible limit (the red dashed line) for all channels, indicating excellent system performance. As the optical length increases, the maximum Q-Factor for each channel may vary somewhat, but some channels, such as channels 17 represented by the blue line and 14 represented by the yellow line shown in **Fig. 13**, begin to experience a reduction in the maximum Q-Factor after 10km of optical length where they cross the red dashed line leading to entire system failure although the other channels such as channel 16 and 12 illustrated by the green and orange line respectively still above the threshold. This decline may be caused by chromatic dispersion, noise, or other flaws that amplify with increasing optical length.

In **Fig. 14**, we can see the overall system performance of all channels at the downlink side concerning optical fiber span, illustrated by the Min log of BER. All channels exhibit a suitable response up to 10 km, where they're under max Log BER (-13) represented by the red dashed line. However, after 10 km of cable length, some channels such as channels 17 and 14 depicted by the blue and the yellow line respectively exceed the acceptable values of bit error rate, leading to the failure of the entire system. Nevertheless, some channels remain within the satisfactory ranges of BER like channel 10 represented by dark green line and channel 9 depicted by the dark blue line.

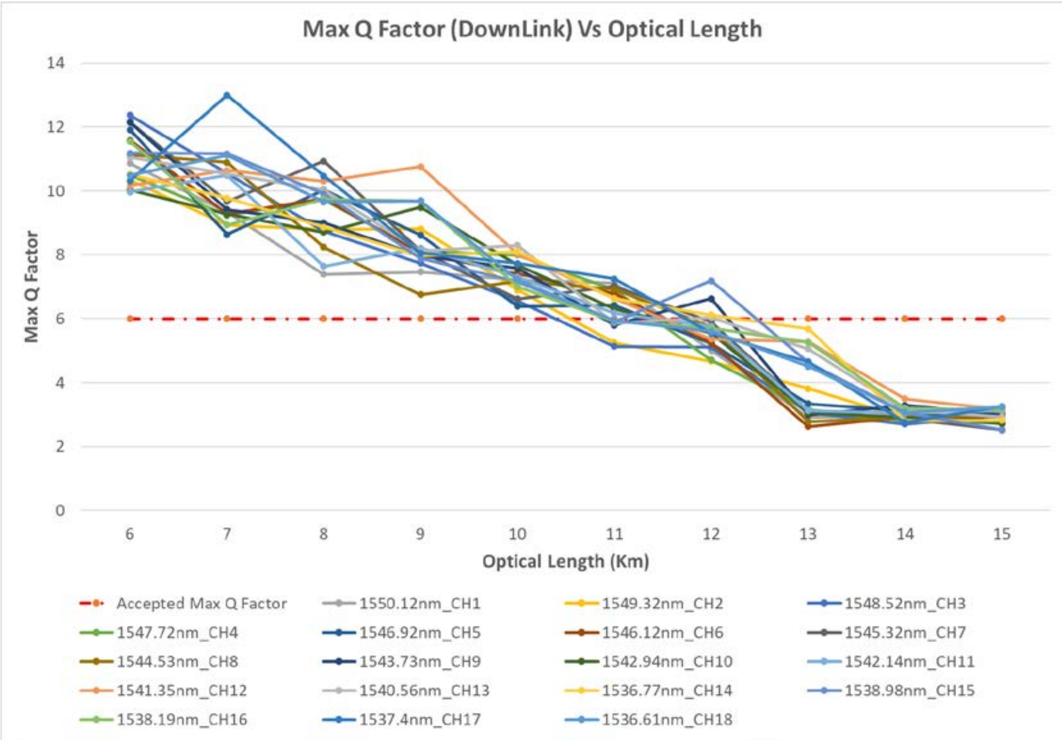


Fig. 13. Max Q Factor versus Optical Length for (Downlink)

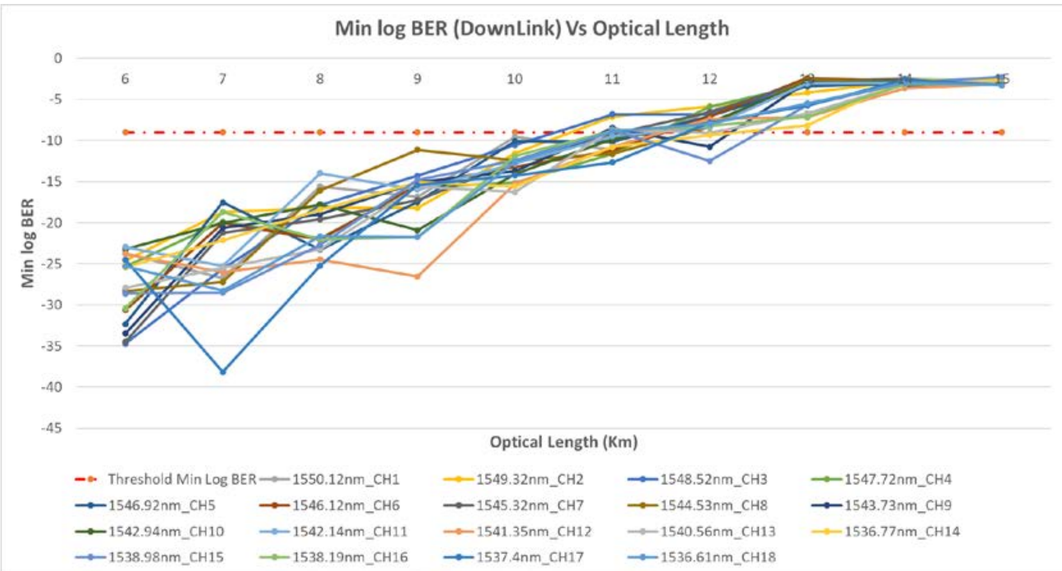


Fig. 14. Min log BER versus Optical Length for (Downlink)

4.3 Comparison of this work with other related works.

Table 4 compares this proposed design with other works in terms of each channel's maximum bit rate, the modulation technology that is used, the overall system capacity and the number of channels for each system. In this work, simple MZM and NRZ modulation and coding techniques are utilized to achieve 25 Gb/s per channel. This by far exceeds the data rate of the systems in [6, 9, 10, 12] where they used the same simple modulation technique without using digital signal processing and dispersion compensator fiber. To reach a higher data rate, this modulation technique could not be exploited. Thus, the authors [14, 15] used a complex and expensive Dual Polarized-Quadrature Phase Shift Key modulation to obtain 100 Gbps/channel and Dual Polarized-Quadrature Amplitude Modulation to achieve 90 Gbps/channel. The authors [15] further increased their system complexity by means of DCF. Consequently, both systems could not be considered simple low-cost systems. Moreover, the work in [15] and [13] indeed provides a better system capacity with 720 and 800 Gbps respectively. However, they could serve only 8 ONUs (base station sectors as one channel could provide a fronthaul link for one sector) in only a single direction (Downlink or Uplink) in [15] and bidirectional SMF (Downstream and Upstream) in [14]. On the other hand, the proposed work in this article could serve 18 ONUs with a reasonable system capacity of 450 Gbps that could provide fronthaul links for six 5G base stations with 3 sections for each base station in an urban area. This will reduce the infrastructure cost and thus minimize the CAPX by reducing the system cost and increasing the system channels that are suitable for 5G fronthaul links according to the ITU-T standards.

Table 4. Comparison of this work with other published works.

Paper	Bit rate per channel	Modulation and coding	No. of Channels	Downlink Tx Power	Distance (Km)	Amplifier	System capacity	Using DSP	Using DCF	Optical fiber type
[9]	3Gbps	NRZ	5	0dBm/1mW	170	EDFA	15 Gbps	No	No	SD_SMF
[10]	10Gbps	MZM and NRZ	8	10dBm/10mW	50	No	80 Gbps	No	No	BD_SMF
[14]	100Gbps	DP-QPSK	8	2dBm/1.6mW	80	2 EDFA	800 Gbps	Yes	No	BD_SMF
[6]	10 Gbps	NRZ	8	6dBm/3.98mW	5-80	EDFA	80 Gbps	No	No	BD_SMF
[12]	10Gbps_DS and 2.5 Gbps_US	MZM and NRZ	16	5dBm/3.16mW	45	No	160 Gbps_DS And 40 Gbps_US	No	No	BD_SMF
[15]	90 Gbps	dual polarized 128-QAM	8	10dBm/10mW	80	EDFA	720 Gbps	Yes	Yes	SD_SMF
This Work	25 Gbps	MZM and NRZ	18	0dBm/1mW	10	No	450Gbps	No	No	BD_SMF

5. Conclusion

A proposed design of an eighteen-channel bidirectional low-cost IM/DD WDM-PON with 25Gb/s/λ in both upstream and downstream sides has been simulated and evaluated. The system is evaluated with the BER versus variable CW launched power and different optical lengths to meet the ITU-T 5G fronthaul proposed design in G-series Recommendations–Supplement 66. The suggested system is characterized by a cheap, straightforward, amplifier-free, and a DSP-free system with a respectable system capacity of 450 Gbps. The simulation results show that it could be utilized as an F1 and as an Fx 5G fronthaul link for functional split options 1 up to 7a introduced by the ITU-T recommendation. Furthermore, the system is recommended to be used in urban cities with a short reached optical span of up to 10 km. However, a further distance could be reached with the same system by increasing the CW laser power up to 6 dBm.

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