BMBAD BJESR
Mühendislik Bilimleri ve Araştırmaları Dergisi
Journal of Engineering Sciences and Researches

# Performance Investigation of Bidirectional Hybrid Long-Haul Optical IM/DD OFDM WDM-PON Using OOK-RSOA Remodulation

# OOK-RSOA Modülasyonunu Kullanan Çift Yönlü Karma Optik IM/DD OFDM WDM-PON Sisteminin Performansının İncelenmesi

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Araştırma Makalesi/Research Article

ARTICLE INFO

*Article history*

Received : 4 March 2022
Accepted : 1 April 2022

*Keywords:*

Intensity Modulation and Direct Detection, Orthogonal Frequency Division Multiplexing, Wavelength Division Multiplexing, Passive Optical Network, Reflective Semiconductor Optical Amplifier

ABSTRACT

In this paper, we have studied and simulated bidirectional hybrid long reach Intensity Modulated and Direct Detected Optical Orthogonal Frequency Division Multiplexing Wavelength Division Multiplexing Passive Optical Network (IM/DD-OFDM-WDM-PON) with 100 Gbps of various M-Quadrature Amplitude Modulation (M-QAM) in transmitted downstream signal and 2.5 Gbps On-Off keying (OOK) upstream signal using wavelength reused technique by Reflective Semiconductor Optical Amplifier (RSOA) at Optical Network Unit (ONU). The simple, low cost and colorless long-haul IM/DD-OFDM-WDM-PON based on RSOA is designed to support extreme data rate signal by utilizing Dispersion Compensating Fiber (DCF). All results prove that IM/DD-OFDM-WDM-PON can achieve good Bit Error Rate (BER) performance over propagation length of (300 km for 4-QAM), (200 km for 16-QAM) and (50 km for 64-QAM). For comparison, the performance of the network is studied in terms of BER, the effect of the propagation length on the constellation diagram, and the relation of BER versus bit energy and noise density ratio (Eb/No).



MAKALE BİLGİSİ

*Makale Tarihleri*

Gönderim : 4 Mart 2022
Kabul : 1 Nisan 2022

*Anahtar Kelimeler:*

Yoğunluk Modülasyonu ve Doğrudan Algılama, Dikgen Frekans Bölmeli Çoğullama, Dalga Boyu Bölmeli Çoğullama, Pasif Optik Ağ, Yansıtıcı Yarı İletken Optik Amplifikatör

ÖZET

Bu makalede, optik ağ birimindeki Yansıtıcı Yarı İletken Optik Amplifikatör (RSOA) ile 2.5 Gbps'lik Açık-Kapalı anahtarlama yukarı akış sinyali ve 100 Gbps'lik çeşitli M- Karesel Genlik Modülasyonu (QAM) aşağı akış sinyali kullanılarak Çift Yönlü Hibrit Uzun Erişim Yoğunluk Modülasyonlu ve Doğrudan Algılanan Optik Dikgen Frekans Bölmeli Çoğullama Dalga Boyu Bölmeli Çoğullamalı Pasif Optik Ağ (IM/DD-OFDM-WDM-PON) simüle edilip incelenmiştir. RSOA'ya dayalı basit, düşük maliyetli ve renksiz uzun mesafeli IM/DD-OFDM-WDM-PON, Dağılım Dengeleyici Fiber (DCF) kullanılarak yüksek veri hızı sinyalini desteklemek için tasarlanmıştır. Tüm sonuçlar, tasarlanan sisteme ait (4-QAM için 300 km), (16-QAM için 200 km) ve (64-QAM için 50 km)'lik yayılma uzunluğuna karşı düşük Bit Hata Oranı (BER) gerçekleştirilerek gösterilmiştir. Karşılaştırma için, bu sistemin performansı BER, yayılma uzunluğunun takımyıldız diyagramı üzerindeki etkisi ve BER ile bit enerjisi ve gürültü yoğunluğu oranı (Eb/No) arasındaki ilişki açısından incelenmiştir.



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## 1. INTRODUCTION

Wavelength Division Multiplexing Passive Optical Network (WDM-PON) is considered to be a cost-effective solution in optical communication since it provides several advantages such as better performance, higher capacity and long reach of optical fiber [1-2]. Additionally, an Orthogonal Frequency Division Multiplexing (OFDM) technique adds more advantages to WDM-PONs due to the fact that it provides a higher data rate and more flexible bandwidth allocation for Optical Network Units (ONUs) [3]. OFDM is a preferred solution for WDM-PON because it can provide high spectral efficiency, high tolerance to chromatic dispersion and extend the transmission distance. For reducing implementation cost of PONs, colorless optical sources at ONU are used to re-modulate downstream signal with lower upstream bit rate like Reflective Semiconductor Optical Amplifier (RSOA) and injection-locked Fabry–Perot laser diode (FP-LD) [4]. M-QAM in each subcarrier of OFDM signal is used to increase the capacity and efficiency of optical OFDM systems to provide low Bit Error Rate (BER) and high data rate transmission. Intensity modulated/direct detected (IM/DD) optical OFDM system is considered as simple and low cost optical OFDM communication system which can be found in a lot of optical applications [5-9]. Wavelength reused WDM-PONs do not need any extra and external light source in ONU but downstream signal is required. Wavelength reuse technique can improve and provide low cost and wavelength control functionalities of WDM-PONs. Dispersion Compensating Fiber (DCF) is one of the first dispersion compensation approaches to produce negative chromatic dispersion, which helps to improve the system's transmission performance [10].

### 1.1. Related Works

According to previous published articles that are related to the system, in [11], a bidirectional OFDM-WDM-PON system based on OFDM signal for 40 Gbps downstream transmission and wavelength reused RSOA with OFDM signal for 10 Gbps upstream transmission with direct detection was demonstrated. In [12], bidirectional long reach WDM-PON system delivering 20 Gbps downstream signal and 10 Gbps upstream signal on a same wavelength using locked laser and RSOA was presented and implemented over 45 km optical fiber. In [13], for the next-generation free space optics (FSO) network, a cost-effective RSOA-based bidirectional WDM-Ro-FSO-PON was established. Over a 500 m FSO-link, 10 Gbps downstream, 1.25 Gbps upstream, and 1.49 Gbps video signals were successfully sent. In [14], using Differential Phase Shift Keying (DPSK) downstream signals and OFDM modulated upstream signals, a 10 Gbps bidirectional WDM-PON with RSOA based colorless ONU was studied for Gigabit PON (GPON) up to 25 km fiber transmission. In [15], the utilization of incoherent light to illustrate a wavelength reuse WDM-PON technology was demonstrated. RSOA was employed as a colorless, low-cost optical source that could be reused. Bidirectional communication across 30 km was established at 1.25 Gbps with a BER of 10-9 using 100-GHz channel spacing and BER of 10-5 using 50-GHz channel spacing. In [16], over a 20-kilometer optical range, a bidirectional RSOA-based WDM-PON with high extinction ratio in both directions was demonstrated using a 10 Gbps DPSK signal for downstream and a 5 Gbps re-modulated OOK signal for upstream. In [17], EDFA-based 40 Gbps downstream and 10 Gbps upstream transmissions long-haul WDM-PON scheme was achieved by using QPSK downstream and fiber brag grating (FBG) optical equalizer-based RSOA IM-DD for upstream signal over 40 km fiber transmission. In [18], a novel architecture of WDM OFDM-PON was demonstrated for sending 10 Gbps data in two directions over 50 km. Direct detected OFDM signal was used for downstream signal and simple OOK data was used for upstream transmission. In [19], on a single wavelength, a long-haul OFDM WDM–PON with 100 Gbps downstream and 2 Gbps upstream traffic was simulated. At the central office, a CW laser was used for downstream signal, and at each optical network unit, an RSOA was utilized for upstream signal. In [20], Optisystem software was used to simulate a 100 Gbps long haul IM/DD optical OFDM system with various M-QAM modulation schemes. Using dispersion compensation fiber (DCF) inside a fiber channel, simulated system was investigated to provide high data rate transmission for downstream signals. For long reach propagation length, 4-QAM OFDM system had the best BER performance when compared to other simulated systems.

### 1.2. The Paper's Contributions

The list of contributions confirmed by this paper are given below:

- Simulated system provides 100 Gbps OFDM downstream data rate and 2.5 Gbps OOK upstream data rate, additionally this system with using various M-QAM is designed and simulated by Optisystem software [21] and analyzed to achieve the lowest BER value.
- Transmission length is increased to study its effect on Q factor, BER, constellation diagram and signal spectrums.
- DCF method is provided to improve the system performance of simulated systems.
- RSOA is used as low cost, simple and colorless source in ONU to re-modulate downstream signal and achieve bidirectional optical network.
- As a result, 4 QAM system achieved the lowest BER value for long reach optical communication system.

Paper Organization: In Section 2, system model and description are given. In Section 3, the simulation results and discussion are given. Finally, the paper is completed with the conclusions in Section 4.

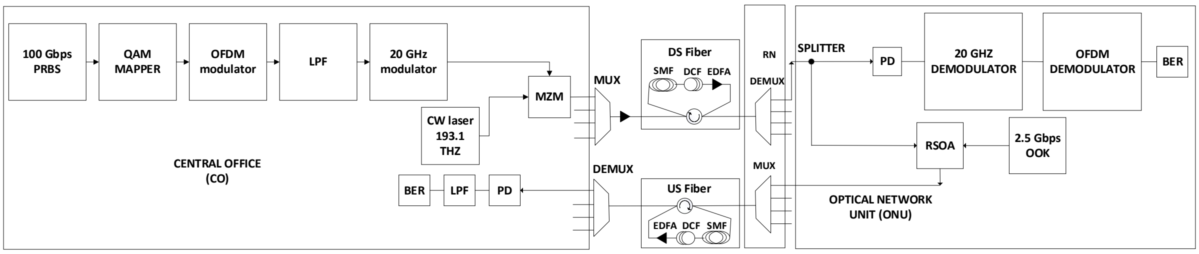



**Figure 1.** Bidirectional IM/DD OFDM WDM-PON based RSOA scheme.

## 2. SYSTEM MODEL AND DESCRIPTION

The scheme of our simulated bidirectional WDM-PON is illustrated in Figure 1. Scheme of simulated WDM-PON and simulation results were designed and explained by using OptiSystem. At CO, BER set test is used to both generate 100 Gbps downstream bits and obtain BER value. The transmitted bit rate is equal to 50 Gbps because the number of subcarriers and Fast Fourier Transform (FFT) points are equal to 512 and 1024, respectively. OFDM modulator values and global simulation parameters are given in Table 1. Cyclic prefix (CP) is chosen to be 100 due to Inter Symbol Interference (ISI) between OFDM symbols.

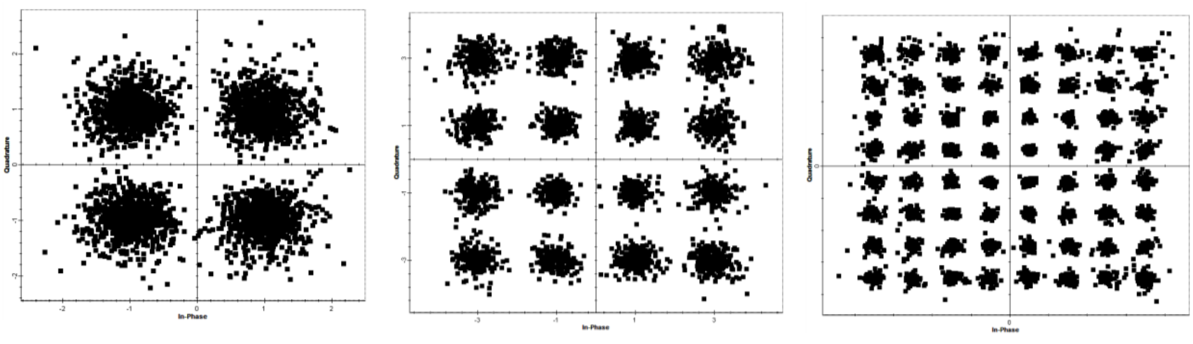
**Table 1.** Main parameters of simulation.

| | |
|---|---|
| **Global simulation layout parameters** | |
| Bit rate | 100 Gbps |
| Number of samples | 65536 to 1048576 |
| Sequence length | 16384 to 65536 |
| Samples per bit | 4 to 16 |
| **OFDM modulator** | |
| Number of subcarriers | 512 |
| FFT points | 1024 |
| Cyclic prefix | 100 |
| Training OFDM symbols | 2 |
| **CW laser** | |
| Center frequency | 193.1 THz |
| Linewidth | 0.1 MHz |
| Power | 2 dBm |
| **PIN Photodetector** | |
| Dark current | 10 nm |
| Responsitivity type | InGaAs |
| **RSOA** | |
| Input Facet Reflectivity | $50x10^{-6}$ |
| Output Facet Reflectivity | $50x10^{-6}$ |
| Active Length | 0.0006 m |
| Taper Length | 0.0001 m |
| Width | 0.4e-006 |
| Height | 0.4e-006 |

At CO, QAM sequence generator converts bit streams into different level value of symbols depending on number of bits per symbol. The transmitted symbols are converted to multilevel electrical pulses by M-ary sequence generator. OFDM modulator is used to modulate transmitted QAM symbols into multiple orthogonal subcarriers. However, FFT points should be doubled according to number of subcarriers. Frequency values are assigned to lower data rate subcarriers from 0 to 12.5 GHz. Modulated OFDM signals are transmitted to low pass filter which has a cutoff frequency equal to (symbol rate*0.65). Then, these signals are transmitted to quadrature modulator which increases their frequency up to 20 GHz. Transmitted optical signal is generated by applying Continues Wave (CW) laser at 193.1 THz to Mach-Zehnder Modulator (MZM) which modulates and converts transmitted RF electrical signal. CW laser and PIN photodetector parameters are summarized in Table 1. After MZM, the optical signal is multiplexed by WDM multiplexer which multiplexes a different wavelength downstream signal then the multiplexed signals are amplified by utilizing optical amplifier that has noise floor of 4 dB and gain of 10 dB as basic parameters. The multiplexed optical signal is delivered across (10*loops no. + 50) km SMF with a 0.2 dB/km attenuation, 16 ps/nm/km dispersion, 0.08 ps/nm$^2$/km dispersion slope, and 2.610$^{-20}$ nonlinearity coefficient. DCF is used to overcome generated dispersion caused by the main optical fiber and to improve transmission performance. The DCF value is calculated at the channel based on the main fiber length. To compensate for channel loss and boost the optical signal, another optical amplifier is utilized. The amplified optical signal is demultiplexed at the Remote Node (RN) using a WDM demultiplexer with an 80 GHz bandwidth. At the ONU side, optical splitter which is considered as a passive component is used to split optical downstream signal into two parts. Part of the incoming optical signal is received by PIN photodetector that converts it to an electrical signal. Parameters of PIN photodetector are assigned as center frequency and dark current equal to 193.1 THz and 10 nA, respectively. Received electrical signal is amplified by passing through electrical amplifier. Amplified signal is down converted and recovered by applying to Quadrature demodulator. OFDM demodulator parameters are same to OFDM modulator for recovering QAM symbols to achieve low errors. The received QAM symbols are detected and converted to bit streams by QAM sequence detector. The portion of the optical signal is sent to RSOA for re-demodulation using the 2.5 Gbps OOK upstream signal. Main parameters of RSOA are mentioned in Table 1. RSOA re-modulate and amplifies incoming downstream signal to generate amplified and modulated upstream signal that will be sent to CO. Then modulated upstream signals which are generated by RSOAs are combined again by WDM multiplexer at RN as illustrated in Figure 1. These combined signals are sent back to upstream optical fiber (US fiber) that has the same parameters of downstream optical fiber (DS fiber). At CO, upstream signals are demultiplexed then they are detected by PD. Received upstream signal is transmitted through a low pass filter to convert it to baseband electrical signal. BER of upstream signals is observed and calculated after passing through low pass filter.

## 3. SIMULATION RESULTS

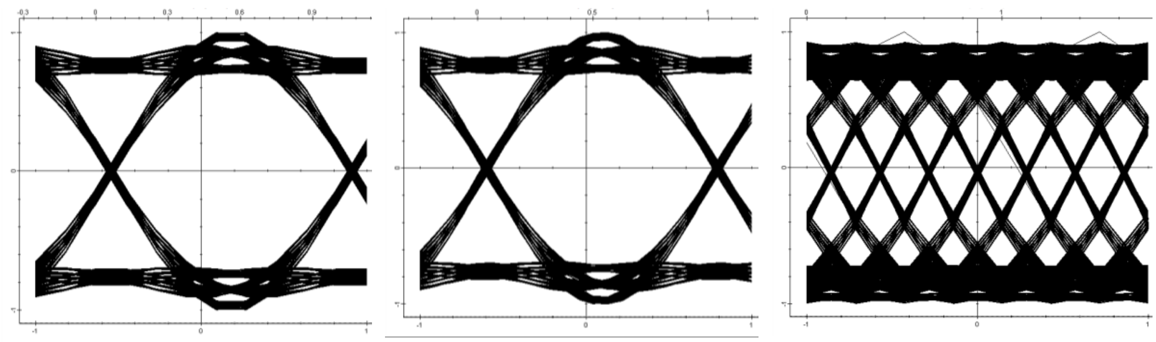
The network is designed and simulated for various M-QAM against optical fiber length by utilizing Optisystem as illustrated in Figure 1. QAM is considered as the best coding compared to others and it is used to convert bit streams into symbols. Different M-QAM's are used in IM/DD OFDM WDM-PON to study the BER performance and enhance transmission performance and it is used to compare the obtained results for simulated systems. For minimizing the effect of fiber nonlinearity, laser linewidth and power are chosen to be 0.1 MHz and 2 dBm, respectively. Firstly, simulation results of downstream OFDM signal are discussed and explained in this section. Figure 2 illustrates constellation diagram of received electrical OFDM signal for different M-QAM's at optical fiber length of 300 km, 200 km and 50 km, respectively. As long as optical fiber length increases, M-QAM order decreases to find both the lowest BER value and the constellation diagram as illustrated in Figure 2.



(a) (b) (c)

**Figure 2.** Constellation diagram of received downstream signal at ONU for a) 4-QAM, b) 16-QAM and c) 64-QAM, respectively.

Additionally, eye diagram is utilized to measure both ISI and noise of channel in optical communications. For minimum propagation length, Figure 3 illustrates the eye diagram of different M-QAM of downstream OFDM signal.



(a) (b) (c)

**Figure 3.** Eye diagram of received downstream OFDM signal for a) 4-QAM, b) 16-QAM and c) 64-QAM, respectively.

Figure 4 shows propagation length against Log of BER for making comparison between simulated systems. Using various M-QAM and at BER of $10^{-3}$, maximum optical fiber length of each simulated system can be found as 300, 200 and 50 km as shown in Fig. 4. Fig. 4 illustrates that 4-QAM network has the lowest BER for long reach optical communication.

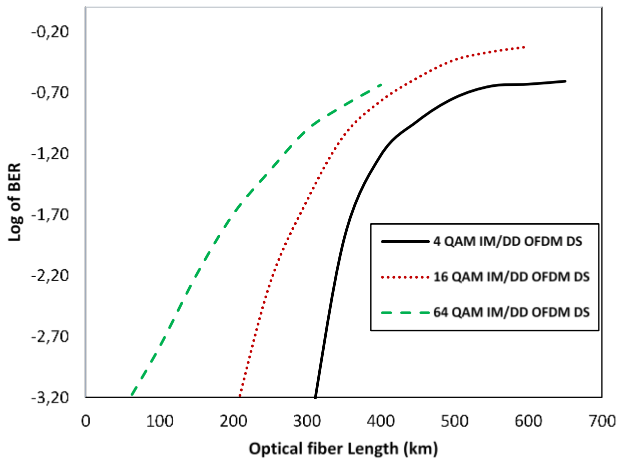



**Figure 4.** BER curves of various M-QAM OFDM DS.

Q factor curves versus optical fiber length for three different simulated networks are shown in Figure 5. At maximum optical fiber length, Q factor is obtained as 10.42, 10.81 and 11 dB at BER of $10^{-3}$. Figure 5 shows that for long-range optical communication networks, the 4-QAM network has the highest Q factor value.

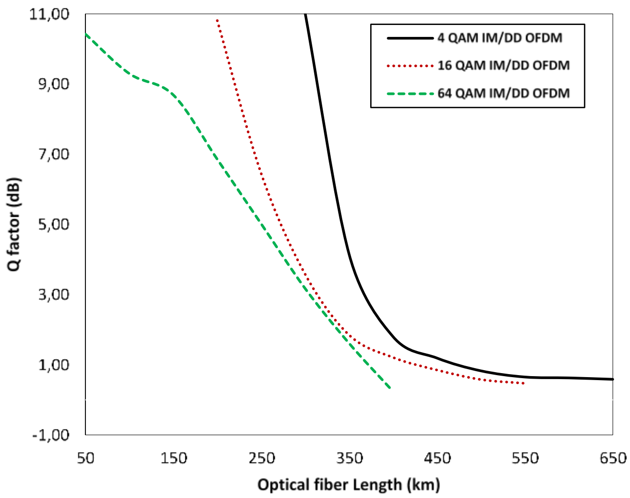



**Figure 5.** For simulated systems, the Q factor values are plotted against the length of the optical fiber.

BER values in terms of Eb/No are provided in Figure 6 for all simulated networks. Eb/No values for varied M-QAM rise by 18, 23, and 31 dB at BER of $10^{-3}$, as seen in Figure 6.

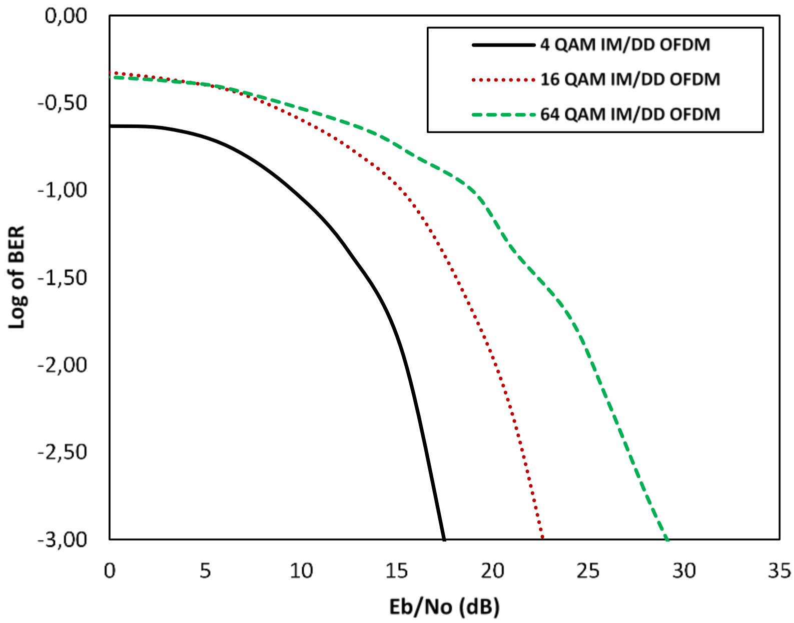



**Figure 6.** BER versus Eb/No.

The results of simulation are explained in Table 2.

**Table 2.** Optical fiber length, Q factor, and Eb/No for various M-QAM in 100-Gbps WDM-PON at BER = $10^{-3}$.

| M-QAM | Optical fiber length (km) | Q factor | *Eb/No* (dB) |
|---|---|---|---|
| 4-QAM | 300 | 11 | 18 |
| 16-QAM | 200 | 10.81 | 23 |
| 64-QAM | 50 | 10.41 | 31 |

Secondly, simulation results for upstream RSOA signal are discussed as below. Figure 7 shows optical fiber length in term with log of BER values and eye diagram for every simulated system. Depending on Figure 7, 4-QAM proved to have the lowest BER for long reach optical communication compared to others.

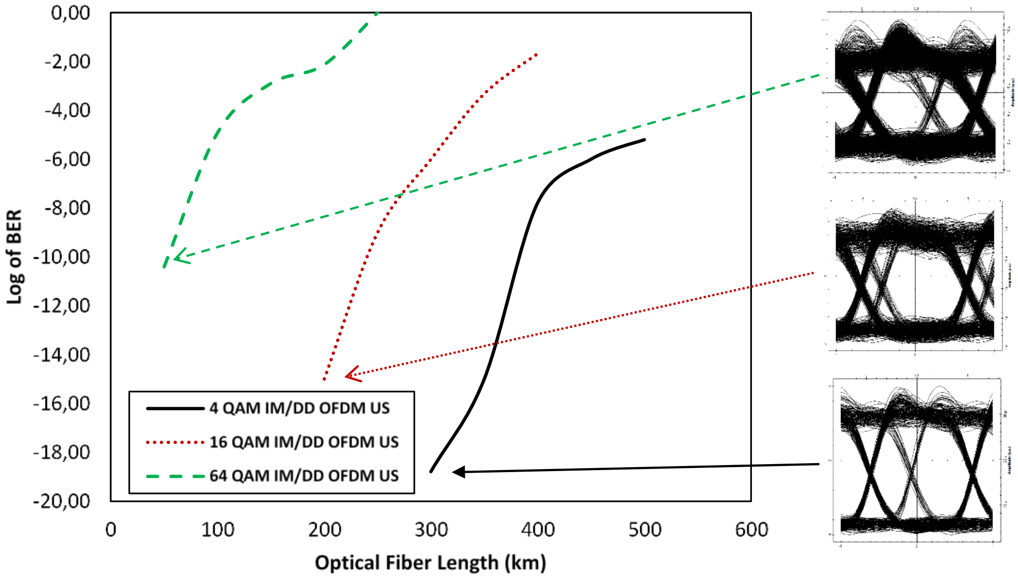



**Figure 7.** BER results for various M-QAM at different optical fiber length.

In Table 2, the ideal optical fiber length for obtaining BER of $10^{-3}$ for all of the networks is determined. The best simulation results for long-range transmission were achieved by 100 Gbps 4-QAM-WDM-PON. DCF is used to improve system performance, adjust for fiber channel dispersion, and enhance transmission bit rate. As a result, the simulation results in optical communication are generally reliable and acceptable.

## 4. CONCLUSION

We have simulated and studied bidirectional low-cost IM/DD OFDM WDM-PON based on RSOA by using different M-QAM's for 100 Gbps downstream signal and 2.5 Gbps upstream signal. IM/DD OFDM WDM-PONs do not need to another laser at ONU as CO-OFDM. A 100 Gbps 4-QAM IM/DD OFDM WDM-PON has been transmitted over 300 km. 16 and 64-QAM WDM-PONs satisfied the best results at optical fiber length of 200 and 50 km, respectively. DCF is considered to be a useful method to increase transmission performance. Eb/No results, Eye diagram and Q factor are obtained in term with optical fiber length for WDM-PON. Those WDM-PONs are simulated to achieve low BER and low cost long-reach 100-Gbps IM/DD-OFDM-WDM-PON.

### Author Contributions

Mahmoud Alhalabi contributed to the design, implementation and simulation of the research and to the analysis of the results.
Mahmoud Alhalabi wrote the manuscript with support from Necmi Taşpınar who supervised the project.

### Conflict of Interest

The authors of the article declare that there is no conflict of interest between them.

### Acknowledgements

This work was supported by the Erciyes University Scientific Research Projects Coordination Unit (Project No: FDK-2019-8750).

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