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Time and Wavelength Division Multiplexing Passive Optical Network Comparative Analysis: Modulation Formats and Channel Spacings

A. Fayad, Q. Alqhazaly, T. Cinkler

Abstract**—**In light of the substantial increase in end-user requirements and the incessant need of network operators to upgrade the capabilities of access networks, in this paper, the performance of the different modulation formats on eight-channels Time and Wavelength Division Multiplexing Passive Optical Network (TWDM-PON) transmission system has been examined and compared. Limitations and features of modulation formats have been determined to outline the most suitable design to enhance the data rate and transmission reach to obtain the best performance of the network. The considered modulation formats are On-Off Keying Non-Return-to-Zero (NRZ-OOK), Carrier Suppressed Return to Zero (CSRZ), Duo Binary (DB), Modified Duo Binary (MODB), Quadrature Phase Shift Keying (QPSK), and Differential Quadrature Phase Shift Keying (DQPSK). The performance has been analyzed by varying transmission distances and bit rates under different channel spacing. Furthermore, the system is evaluated in terms of minimum Bit Error Rate (BER) and Quality factor (Qf) without applying any dispersion compensation technique, or any optical amplifier. Optisystem software was used for simulation purposes.

Keywords**—**Bit Error Rate, BER, Carrier Suppressed Return to Zero, CSRZ, Duo Binary, DB, Differential Quadrature Phase Shift Keying, DQPSK, Modified Duo Binary, MODB, On-Off Keying Non-Return-to-Zero, NRZ-OOK, Quality factor, Qf, Time and Wavelength Division Multiplexing Passive Optical Network, TWDM-PON.

I. Introduction

NOWADAYS, there is an exponential increase in the traffic demands within communication networks due to the rapid increase in the number of users and their use of smart mobiles with high processing speeds in addition to data-hungry services offered by service providers such as video conferences, distance education, e-commerce, and HDTV. Since copper cables are no longer adequate to satisfy these demands, optical fibers have emerged as one of the driving forces behind the success of the internet [1]. Presently, passive optical networks (PON) are considered the key technology to provide low-cost services, and Fig. 1 illustrates the general structure of PON, which is considered as a point to multipoint (P2MP) fiber optical network with no active elements in the path of the signal, which connects OLT in the Central Office (CO) to several ONUs at the customer sites using 1:N optical splitter [2]. Due to the urgent necessity for increasing the data rates, splitting ratio, and transmission distance, PON has gone through several developments from APON/BPON to GPON (Gigabit-PON) and XG-PON (Next Generation GPON) with data rates progressively increasing from 155 Mbps to 10 Gbps [4]. NG-PON2 was proposed as the next evolution of PON by ITU-T and Full-Service Access Network (FSAN) to increase the transmission speed in PON to more than 10 Gbps to meet users' demands [5]. The requirements of NG-PON2 have been determined in ITU-T G.989 Recommendations [25]. This standard indicates a bandwidth capacity of up to 40 Gbps on both downlink and uplink to service 256 ONU units across a 40 km transmission distance [6]. A number of candidates was proposed for NG-PON2 as TDM-PON, WDM-PON, OFDM-PON, OCDM-PON and TWDM-PON [2], [4]. TWDM-PON which blends the advantage of more wavelengths offered by WDM-PONs and a large number of users per wavelength provided by TDM-PONs is considered to be the best option for meeting the requirements of NG-PON2 as it is a mature technology with the ability to co-exist with legacy PONs without re-engineering the Optical Distribution Unit (ODN) [3]. To provide all forms of data-intensive services to a larger number of users at greater distances, there is a continuous need to increase data rates, split ratios, and transmission reach of the PONs [3], [4]. As a result, other effective solutions to meet these requirements and potential needs must be developed. One of the most critical aspects to remember is the modulation format, which has a major impact on the system performance [7].

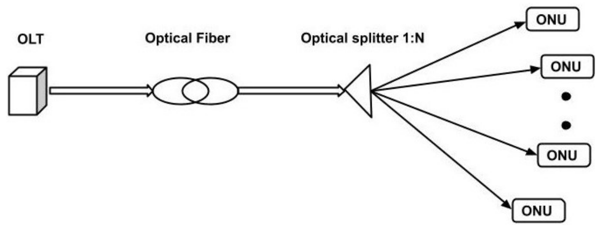

Fig. 1 General Architecture of PON

The authors in [8] evaluated the performance of eight wavelengths-based TWDM-PON employing three modulation formats (NRZ, RZ, CSZ) varying input power, transmission distance, and bit rate in terms of minimum BER, Qf.

In [9], the authors analyzed the effect of the DQPSK line technique in comparison to the usual On-Off Keying (OOK)

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technique with and without Erbium-Doped Fiber Amplifier (EDFA) in Hybrid Passive Optical Network (Hybrid PON). Rajalakshmi and Shankar [10] proposed a design for 80 Gbps symmetrical TWDM-PON bit rate using eight pairs of wavelengths for a 100 km transmission distance with 1:8 splitting ratio employing a reflective semiconductor optical amplifier (RSOA). The result was analyzed in terms of BER and Qf for different photodetectors (PIN.ABD) based on different modulation formats (NRZ, RZ, RZ-DPSK, CSRZ-DPSK, NRZ-DPSK, DB. In [11], the authors designed a TWDM-PON with a capacity of 80 Gbps. Eight optical channels have been used, each with eight-time slots, and 10 Gbps per channel bit rate are realized using NRZ modulation. A distance of 50 km was achieved with a splitting ratio of 1:64. In [12], the authors analyzed the performance of different modulation techniques, Manchester, Differential Phase Shift Keying (DPSK), and DQPSK in terms of min(BER) and Q-factor. In [13], the authors investigated an 80/10 Gbps downstream/upstream TWDM-PON for NGPON2 with a split ratio of 1:8. The simulation was carried out using two data formats, RZ and NRZ, at different input power and optical fiber lengths of up to 50 km. The authors of [14] evaluated the performance of WDM/TDM PON to serve 128 ONUs for a distance of up to 28 km. Using different modulation formats like NRZ, RZ, and Manchester encoding for different distances were evaluated at a data rate of 1.25 Gbps in terms of BER and Qf. In [15], the authors investigated the performance of different optical modulation formats NRZ-OOK, NRZ differential phase-shift keying (NRZ DPSK), return-to-zero DPSK (RZ-DPSK, carrier-suppressed RZ DPSK (CSRZ-DPSK), and DB in WDM-PON transmission system.

According to the literature survey and our knowledge, we have not found any paper dealing with the performance of TWDM-PON with different modulation formats under different channel spacings which are essential when designing and modeling the network. This article compares the performance of various modulation formats, NRZ-OOK, CSRZ, DB, MODB, QPSK, and DQPSK in eight wavelengths TWDM-PON under different channel spacing for different bit rates and varying transmission distances. As seen in the following section, our article focuses on the transmission distance between the multiplexer and the demultiplexer. There are other advanced formats, for instance, Quadrature Amplitude Modulation (QAM), and Pulse Amplitude Modulation (PAM) [16]. However, in this paper, we focus on modulation formats with less complexity in transceivers design and simpler to investigate. The limitations and features for the considered modulation formats are determined, as a way of determining the best modulation format aiming at enhancing the performance of NG-PON2.

This paper is structured as follows: The proposed architecture of the TWDM-PON system with used modulation formats is explained in Section II. In Section III, the simulation results have been evaluated and discussed. While, conclusion of the results and observations is in Section IV.

II. Simulation Model of TWDM-PON Transmission System

Fig. 2 shows the block diagram of the simulated TWDM-PON. The proposed architecture consists of three segments: Optical Line Terminal (OLT), ODN, and Optical Network Terminal (ONT). TWDM-PONs use hybrid aggregation technology TDM/WDM. Only the downlink has been simulated in this work. OLT is located in the CO of the provider and includes eight transmitters to transmit the signals toward Optical Network Unit (ONU). The ODN consists of 8:1 optical Multiplexer (MUX), Single-Mode Fiber (SMF), 1:8 De-multiplexer (DEMUX), 1:4, and 1:64 power splitters taking into account that the DEMUX and power splitter are aggregated at the same geographical place with zero km length of fiber between them. The ONT side consists of 512 ONUs, where each ONU includes receiver. The design of the transmitter and receiver depends on the type of applied modulation, as will be explained later. Table I determines the parameters of the proposed architecture. We evaluate the Units performance of the proposed system in terms of Qf and minimum BER using Optisystem software.

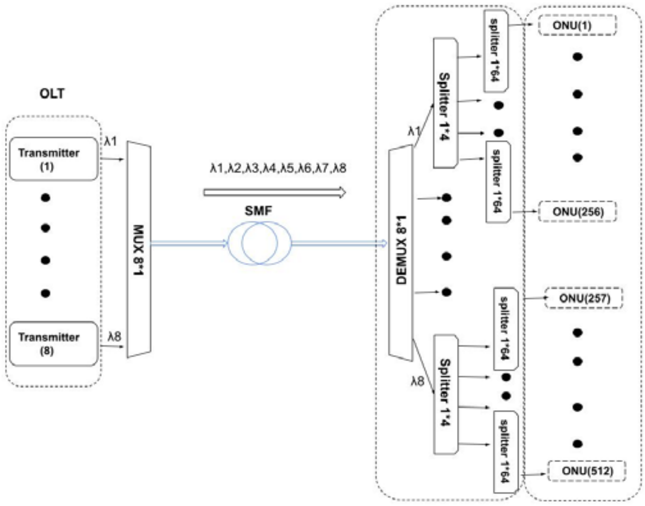

Fig. 2 Block diagram of the simulated TWDM_PON system

TABLE I
Parameters of the Simulated System

Parameter	Value
Bit Rate per wavelength	(10-40) Gb/s
Laser Power	10 dBm
Channels	8
First Wavelength	1596 nm
Channel spacing	(0.8-0.4) nm (100 -50) GHz
Optical fiber type	Single Mode
Optical fiber length	15-140 km
Optical fiber Attenuation	0.2d B/km
Number of ONUs	512 ONU

A. Modulation Formats and Transmitter Design

In this section, we demonstrate the design of the transceiver with the different studied modulation formats as follows:

NRZ-OOK Modulation

NRZ OOK is the dominant modulation format in optical communication systems [16]. Fig. 3 shows the transmitter diagram for NRZ-OOK format which consists of a Pseudo-Random Bit Sequence Generator (PRBS) connected to NRZ signal-generator. The output signal is used to modulate the optical source (Continuous Wave laser) using Mach-Zehnder modulator (MZM).

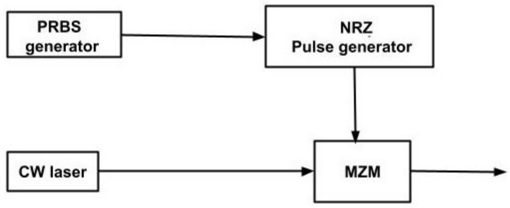

Fig. 3 Block diagram for NRZ-OOK transmitter

CSRZ Modulation

CSRZ is a multilevel modulation format, in which the information is encoded on the intensity levels (0 and 1) with changing the phase by π every bit. There is no DC component for CSRZ. Consequently, there is no carrier component for CSRZ in the spectrum and CSRZ signal bandwidth is smaller if compared to the conventional RZ format. The CSRZ format is intended to reduce the nonlinear impairments in the optical channel [17]. Fig. 4 presents the transmitter block diagram for CSRZ modulation.

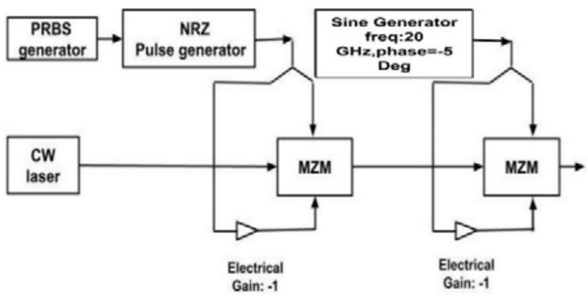

Fig. 4 Block diagram for CSRZ transmitter

Duobinary (DB) Modulation

DB is a format of modulation for information encoding, there are two intensity levels, and the phase is modified by π similarly to CSRZ, with phase changes occurring only for 1-bits separated by an odd number of 0 bits. Its key advantage is its narrower spectral width, which allows it to be more resistant to chromatic dispersion and narrowband optical filtering. Nonlinear effects, on the other hand, have a greater influence on DB [18]. The DB transmitter diagram is shown in Fig. 5.

MODB Modulation Format

It was built on the basis of DB, and in MODB, the spectral width is narrower than in DB, which leads to greater resistance to chromatic dispersion and nonlinear effects in the fibers [19]. The transmitter diagram is shown in Fig. 6.

QPSK Modulation

QPSK [24] is a modulation technique that uses one symbol to transmit two bits of data. In total, and (00,01,10,11) are the results of combining two data sets. As a result, four separate phases must be completed. The four offsets with a difference of 90-degrees are 45°, 135°, 225° and 315° and Fig. 7 shows the transmitter diagram for QPSK modulation

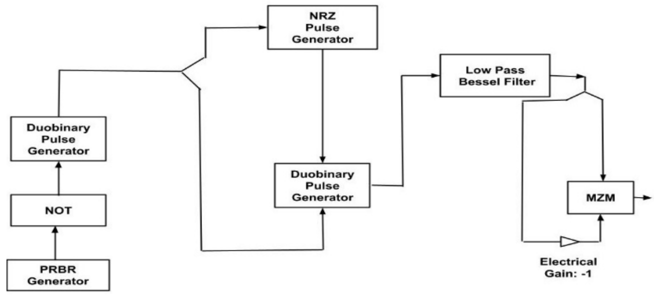

Fig. 5 Block diagram for DB transmitter

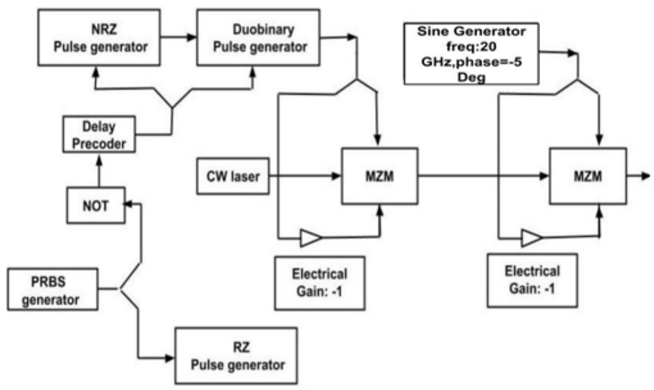

Fig. 6 Block diagram for MODB modulation format

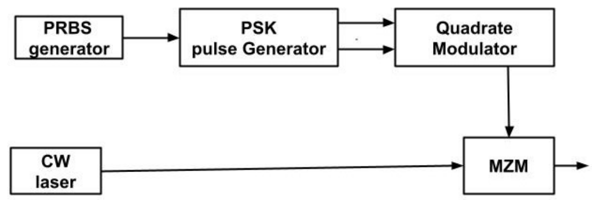

Fig. 7 Block diagram for QPSK transmitter

DQPSK Modulation

DQPSK [20]-[22] is a modulation format that transmits data by determining a certain phase of one symbol concerning the previous symbol. The DQPSK phase options are 0°, 90°, –90°, and 180° (or, equivalently, –180°) if we use the usual four QPSK phase values of 45°, 135°, 225°, and 315°. Fig. 8 shows the transmitter diagram of the DQPSK modulated system.

B. Receiver Design

In this section, we focus on the design of the receiver for the studied modulation formats. It is observed that NRZ-OOK, CSRZ, DB, MODB have the same receiver architecture as shown in Fig. 9, and the other modulation formats QPSK and DQPSK also use the same receiver architecture as clarified in

Fig. 10.

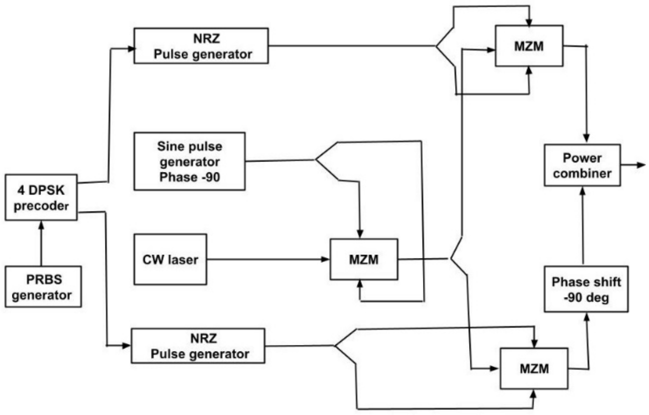

Fig. 8 Block diagram for DQPSK transmitter

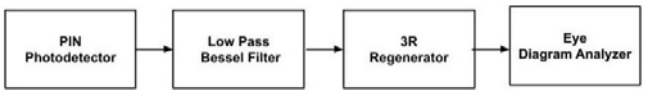

Fig. 9 Block diagram for NRZ-OOK, CSRZ, DB and MODB modulation formats receiver

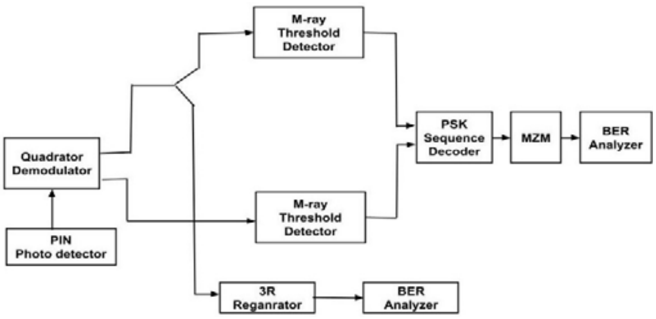

Fig. 10 Block diagram for QPSK and DQPSK modulation formats receiver

C. Qf and BER Calculation

Qf is a dimensionless parameter [23] that measures the quality of a transmission signal in terms of signal-to-noise ratio (SNR). The higher the Qf value, the better the SNR and, therefore, the lower the probability of bit errors. The formula for calculating Qf is:

$$Q = \frac{\mu 1 - \mu 0}{\sigma 1 + \sigma 0} \quad (1)$$

where $\mu 0$, $\mu 1$, $\sigma 0$ and $\sigma 1$ are average values and standard deviations of the sampled values, respectively.

The minimum BER can be obtained depending on Q-factor as:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \quad (2)$$

III. Results and Discussion

In this paper, we compare the effect of various different modulation formats NRZ-OOK, CSRZ, DB, MODB, QPSK, DQPSK for variant transmission distances and different bit rates under two-channel spacing 100 GHz and 50 GHz or 0.8 nm and 0.4 nm on the performance of simulated TWDM_PON in terms of minimum BER and maximum Qf, in order to find the best modulation to increase the bit rate and transmission distance of TWDM_PON with different conditions, considering the acceptable value for minimum BER is 10^{-9} and Qf~6. In Tables II and III, we summarize the comparison results.

A. Performance Comparison for 100 GHz Channel Spacing

It is considered that the bit rate equals to 10 Gbps per channel, the input power equals 10 dBm and fiber length varies from 20 km to 140 km. Figs. 11 and 12 show the minimum BER and maximum Qf evaluation of the compared modulation formats considering the acceptable minimum BER <= 10^{-9} and maximum Qf~6. The learned lessons from this comparison show that if we want to achieve a high transmission distance, this means that the linear impairments will increase. Thus, we observe that DB format is the best selection of the mentioned modulation formats for rural areas where there is a need to send signals to long distances of more than 120 km without using amplifiers as it has a high resistance for linear impairments. QPSK also has a good resistance for linear impairments as it serves up to 100 km. MODB and NRZ_OOK formats can achieve a transmission distance up to 85 km and 60 km. The worst cases are when we use DQPSK and CSRZ formats which can serve at most up to 50 km and 45 km, respectively. To compare the maximum achievable bit rate of different modulation formats, we set up the fiber length at 40 km, input power at 10 dBm depending on ITU_T G.989 Recommendations and we change the bit rate value from 5 Gbps to 40 Gbps per channel. We can observe from Figs. 13 and 14 that when the bit rate increases, the nonlinear impairments increase directly. The best selection for urban areas where there is a need for a high bit rate with no need for long distances is the DQPSK format as it has a high resistance for nonlinear aspects. It can serve up to 36 Gbps per channel. DB format supports up to 25 Gbps per channel. In this comparison case, there is no difference when we use QPSK or MODB formats as both of them can serve up to 20 Gbps. As for NRZ_OOK and CSRZ, also they can support a maximum 15 Gbps.

B. Performance Comparison for 50 GHz Channel Spacing

The nonlinear impairments will be higher when we reduce the channel from 100 GHz to 50 GHz. As can be seen in Figs. 15 and 16, there is a big deterioration in DB modulation performance compared to the 100 GHz channel spacing case, which means that DB is not suitable for dense channels systems. It can serve just a 52 km distance. The best choice in this case for long-distance systems is QPSK modulation as it can support up to 73 km of transmission distance. For MODB, NRZ-OOK, and CSRZ, their performance was not affected much when reducing channel spacing from 100 GHz to 50 GHz. They can serve up to 60 km, 55 km, and 40 km respectively while the most resistant format for nonlinear impairments caused by dense channel spacing is DQPSK, where we can observe that the transmission distance increased from 50 km when using 100 GHz channel spacing to 60 km when using 50 GHz.

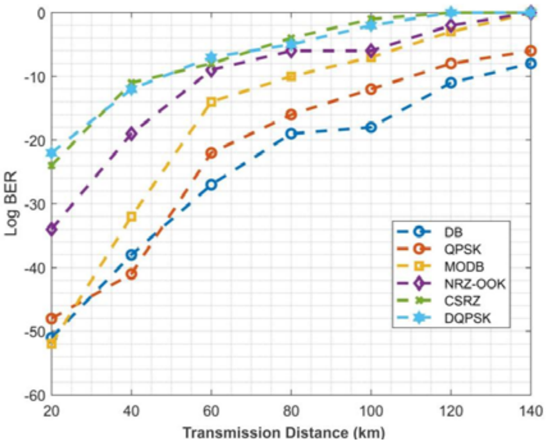

Fig. 11 BER vs. Transmission distance (km)

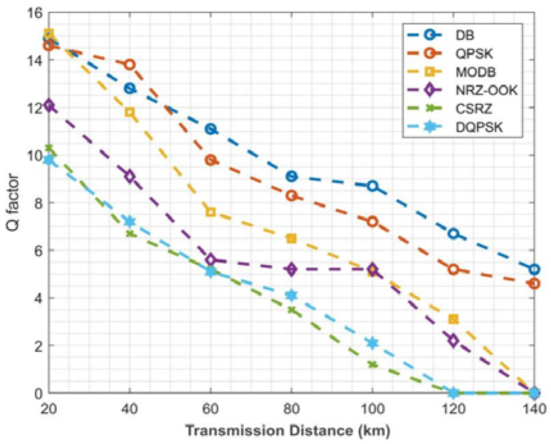

Fig. 12 Q factor vs. Transmission distance (km) for 100 GHz channel spacing

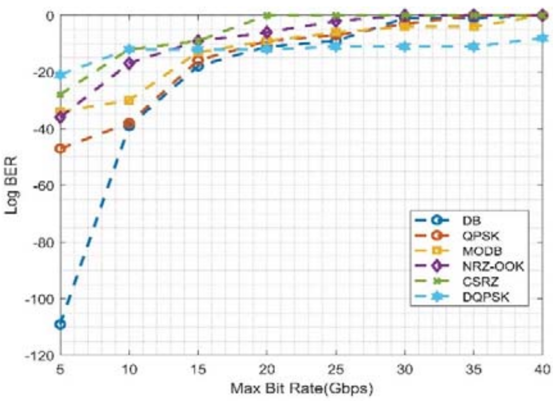

Fig. 13 BER vs. Bit Rate (Gbps) for 100 GHz channel spacing

We set the fiber length to 40 km, the input power to 10 dBm, and change the bitrate per channel from 5 Gbps to 40 Gbps in steps of 5 Gbps to compare the maximum achievable bitrate of different modulation formats. From Figs. 17 and 18, we can observe that the max bitrate has been obtained by using DQPSK format, which equals 38 Gbps per channel so that it is the best selection for urban areas with a high need for high bitrate with 50 GHz channel spacing. The second-best result (max bitrate up to Gbps) is demonstrated by MODB. The third best results are shown by QPSK and CSRZ where they can provide a bitrate up to 15 Gbps. NRZ-OOK demonstrated the fourth best result with 10 Gbps. The lowest Bit rate was by DB. For anomalies in results, we do not have an appropriate explanation at this time as we note similar cases in [8], [9], and [13] where they use OptiSystem software for simulation, in addition to [7] and [16] using OptiSim software.

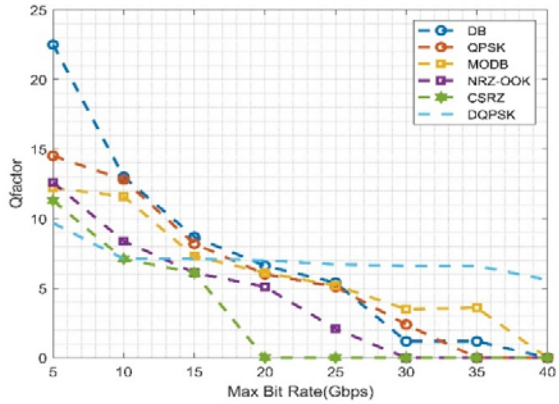

Fig. 14 Qf vs. Bit Rate (Gbps) for 100 GHz channel spacing

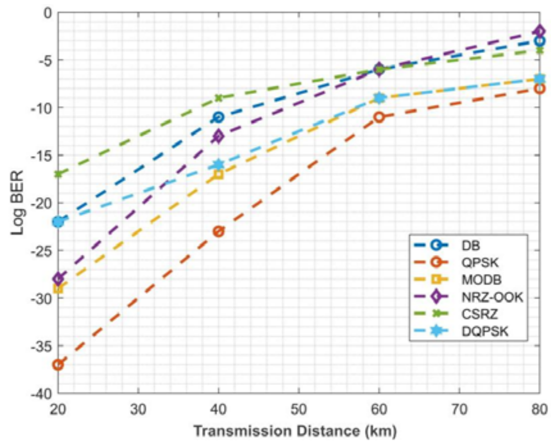

Fig. 15 BER vs. fiber length (km) for 50 GHz channel spacing

TABLE II
MAXIMUM TRANSMISSION DISTANCE COMPARISON FOR DIFFERENT MODULATION FORMATS

Modulation Format	Channel spacing 100 GHz Bit Rate 10 Gbps per channel	Channel spacing 50 GHz Bit Rate 10 Gbps per channel
	Maximum Transmission Distance(km)	
DB	130	52
QPSK	115	73
MODB	85	60
NRZ-OOK	60	56
CSRZ	45	40
DQPSK	50	60

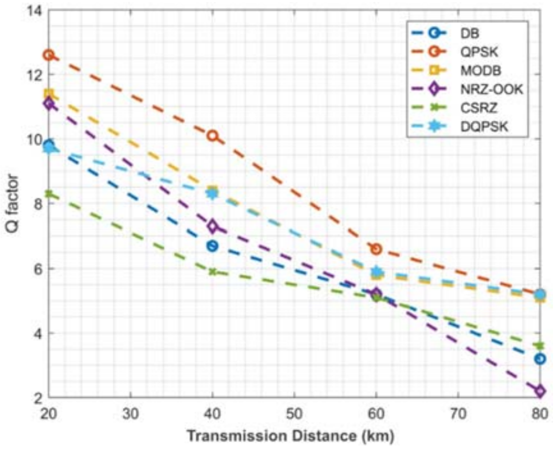

Fig. 16 Qf vs. fiber length (km) for 50 GHz channel spacing

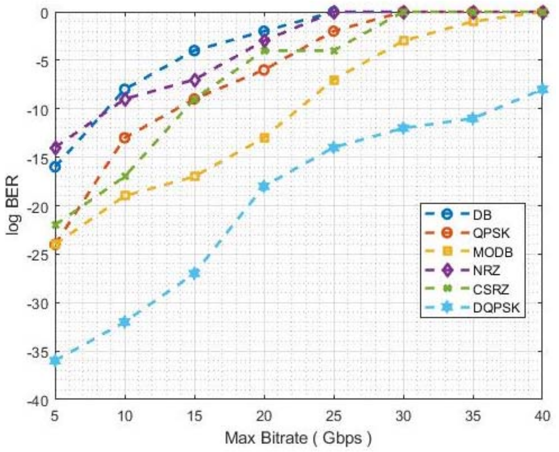

Fig. 17 BER vs. Bit Rate (Gbps)

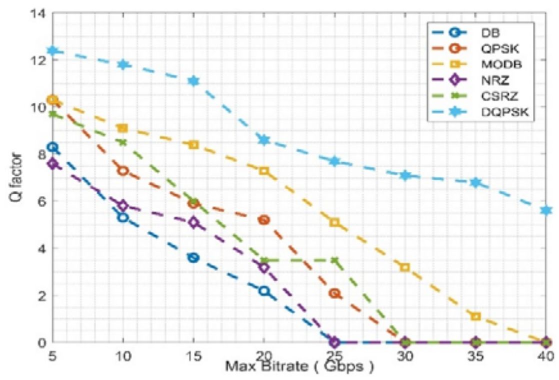

Fig. 18 Qf vs. Bit Rate (Gbps) for 50 GHz channel spacing

IV. Conclusion

In this paper, a TWDM-PON for different modulation formats (NRZ-OOK, CSRZ, DB, MODB, QPSK, DQPSK) has been analyzed and compared for varying transmission distances and bit rates using two-channel spacings, of 100 GHz and 50 GHz. The performance was evaluated in terms of minimum BER and maximum Qf. According to simulation results, when using a channel spacing of 100 GHz, bit rate of 10 Gbps per channel, and input power of 10 dBm, the maximum transmission distance of 130 km could be achieved by using DB modulation. While for a channel spacing of 50 GHz it was observed that the maximum distance was 73 km when using QPSK modulation, under the same simulation conditions. As for the transmission rate, the highest values were achieved by DQPSK modulation across all channel spacings, where bit rates were 36 Gbps and 38 Gbps for channel spacing of 100 GHz and of 50 GHz, respectively. It will be more interesting to compare the higher modulation formats on TWDM_PON with different channel spacings, for instance, 75 GHz and 25 GHz in a way to increase the number of used wavelengths in the system, as we focused in our study on 100 and 50 GHz channel spacing relying on ITU-T recommendation.

TABLE III
Maximum Achievable Bite Rate Comparison for Different Modulation Formats

Modulation Format	Channel spacing 100 GHz Fiber length 40 km	Channel spacing 50 GHz Fiber length 40 km
	Maximum Bit Rate per channel (Gbps)	
DB	25	9
QPSK	20	15
MODB	20	24
NRZ-OOK	15	10
CSRZ	15	15
DQPSK	36	38

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