

Design and Implementation of Hybrid Medium DP-DQPSK DWDM ROF Transmission System for Different Weather Conditions

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Abstract—This document Designing system with Free-space optical (FSO) communication can supply high-speed digital data linkages to rural regions where geography, setup costs, and groundwork safety are major obstacles. Transmission impairments and space loss could be considered major challenges for handling the FSO system. This work, it has been designed and analyzed a system based on the combination of Dual Polarization Differential Quadrature Phase Shift Keying (DP-DQPSK) and Dense Wavelength Division Multiplexing (DWDM) using the Direct Detection (DD) technique. The proposed system has been utilized with a hybrid transmission medium of Single-Mode Fiber (SMF) with a fixed length of 60 km and FSO with a varied length of (5, 7, and 9) km. The system was designed with Optisystem software 18 and consist of 64 channels and 14 Gbps of data rate per channel to make the system 5G communication compatible, 3.5 GHz RF electrical signals have been used to modulate the optical carrier. The channels 1, 6, 12, ..., 64 were selected as samples among all channels to be investigated and analyzed along with four different atmospheric weather conditions. Additionally, the proposed system is designed to investigate based on different weather attenuation that affected the parameters of Quality Factor (QF) and Bit Error Rate (BER). The significant advantage of the proposed system by using the DD technique is no reference wave is required. Hence, make the system less complex and possible to be implemented and tested via different weather conditions. Results obtained indicate reverse relation between the QF and both the FSO distance and attenuation. While BER-based parameters showed a direct relation. For light air and haze, the results showed that the system has higher reliability for all the three investigated FSO distances. For the medium haze, the system has shown the capability to transfer as far as 7 km. And for the rain condition, the system capability was set to 5 km.

Keywords—FSO, SMF, radio over fiber, WDM, 5G

1 Introduction

Optical transmission has risen to the top of the priority list for high-capacity, long-distance transportation networks, outperforming all previous technologies in terms

of capacity and transmission quality. Simply said, Optical Wireless Connecting (OWC) tries to transport data between two distant places across free space utilizing optical radiation as a carrier signal. Although the light signal can be spread across a deep area, the atmosphere, or seas, the focus of this research is on terrestrial Free Space Optical (FSO) technology, where the atmosphere becomes the channel of interest. The line of sight (LoS) between the two communication sites is the mainstay of the FSO relationship. The transmitter and receiver-based FSO (Tx-FSO/Rx-FSO) must be in direct LoS with each other without any blockage to enable successful information exchange. This allows OWC communication with the following conditions: Tx-FSO and Rx-FSO have a direct LoS, and the beam power is adequate to reach the other end [1, 2]. FSO technology has been introduced on the market for the first time at 10 Gbps, in response to telecom operators' needs. Most Radio Frequency (RF) technologies, such as LTE (Long Term Evolution), GSM (Global System for Mobile Communications), Wi-Fi (Wireless Fidelity), and Bluetooth. FSO technology, on the other hand, is based on the under-atmospheric optical transmission of a portion of the visible or infrared light spectrum. FSO systems were created to establish an LoS communication between two separate locations at a high data rate. FSO also allows all forms of data to be delivered at a rate comparable to fiber optics while maintaining the flexibility and advantages of a wireless network [3, 4].

FSO technology has several possible uses. These technologies include wireless and wired communications, and Fiber To The x (FTTx) [5]. Initially, the usage of FSO includes supporting a fiber link. Also, to replace a damaged or unavailable primary fiber link, FSO links might be used. The second benefit of FSO is high-speed data transfer between base stations and network equipment. This is to improve wireless mobile networks and base station bandwidth [6]. In contrast to GSM 900 MHz or 1800 MHz wireless communications, the FSO communication method eliminates frequency saturation difficulties. FSO lines have plenty of bandwidth for multimedia [7, 8]. Temporary FSO lines are used for a conference or a dedicated connection if the existing network fails. It is also used to temporarily replace optical fibers in situations such as temporary site installation or disaster recovery [7, 9]. For example, a data bridge spanning a river, busy city, or railway is an intriguing data bridge. Due to the increased demand for HDTV cameras and data, FSO technology is used in broadcasting to transport live HD camera feeds to remote locations [10–12].

Due to the FSO's importance in delivering increased data rates in various conditions, several techniques were developed to address it.

For example, [13] uses Dual Polarization – Differential Quadrature Phase Shift Keying (DP-DQPSK) with SMF cable and FSO channel. The suggested system can handle a 10 Gbps data rate, 50 km SMF distance, 800 m FSO channel, and various weather conditions. The QF findings were in the region of 4.5 dBm, and the BER was in the range of 10^{-6} , indicating lower values that may not be adequate for reliable transmission. So, such a system must be upgraded and optimized.

Also, previous research has investigated Quantum Dash Laser as a laser source for system-based DP-DQPSK over SMF and FSO channels [14, 15]. This study dealt with both self and external injection. The results from transmission distances of 10 km SMF and 4 m FSO show that external injection can boost the system performance to

128 Gbps. For self-injection, it has demonstrated a data transfer capacity of 20 km SMF and 10 m FSO. However, the proposed system has only been tested over small distances and requires considerably longer distances to demonstrate the proposed laser source.

Using the FSO channel and varying weather conditions, the authors developed a QPSK system with a 128 Gbps transmission capacity [16, 17]. The investigation distances were 15, 25, 35, and 50 km with a 0.19 dB attenuation. The results showed that operating the system at a 25 km distance will reduce the received signal and increase the error rate. The proposed technology also failed to transport data in fog with a 15.5 dB attenuation. The system performed well with low attenuation up to 1.5 dB.

A high-speed front haul system based on 128 Gbps DP-QPSK, Digital Signal Processing (DSP), and homodyne detection has been presented previously [18]. The work was tested in good weather and on a 2.65 km FSO channel. The proposed system's findings were compared to the Back-to-Back (B2B) model's results for BER, OSNR, and Beam Divergence. The proposed technology has only been tested for short distances, which may not be sufficient for 5G and beyond communication.

A DP-QPSK system with hybrid modulation was recently constructed and tested at 340 Gbps at distances ranging from (1.6–50) km in various weather conditions [19]. The results demonstrated a successful transmission procedure in various situations. Several characteristics, such as the data rate of 300 Gbps and the Tx laser source of 10 dBm, need to be evaluated.

Finally, Chen. X et al. has offered an analytical strategy for Binary PSK (BPSK) employing the FSO channel for distances between (1–4) km [20]. They employed (G-G) fading type and FSO channel in their study. There was a negative correlation between system performance and distance. By employing this technology, a 10 Gbps data rate was successfully reached.

In line with these contributions, integration of the DWDM technique and DP-DQPSK Radio over Fiber (RoF) system is proposed in this paper to achieve a hybrid system that consists of 64 channels and a capacity of 1.79 Tbps. Additionally, the proposed system will investigate the hybrid transmission system of SMF of 60 km and varied FSO with a distance of (5–9) km with considering different weather conditions based on different attenuation values and frequency of 3.5 GHz to support a high data rate 5G based applications.

2 Technical content

This section will include the most relevant technical topics related to the subject of the proposed work and as clarified below:

2.1 DQPSK technique

Phase-Shift Keying (PSK) is a digital modulation technique that sends data by shifting the phase of a constant frequency reference signal. The modulation is achieved by changing the sine and cosine inputs at a specific time interval. Differential Phase Shift Keying (DPSK) is a common type of phase modulation that transmits data by altering the carrier wave's phase. When the constellation is rotated by some influence

in the communications channel over which the signal goes, as with BPSK and QPSK, there is phase ambiguity. This problem can be solved by changing the phase rather than setting it. The phase-shifts in Differential QPSK (DQPSK) are 0° , 90° , 180° , and 90° , respectively, corresponding to data “00”, “01”, “11”, and “10”. The general diagram for the DQPSK transmitter and receiver can be seen in Figure 1 [21].

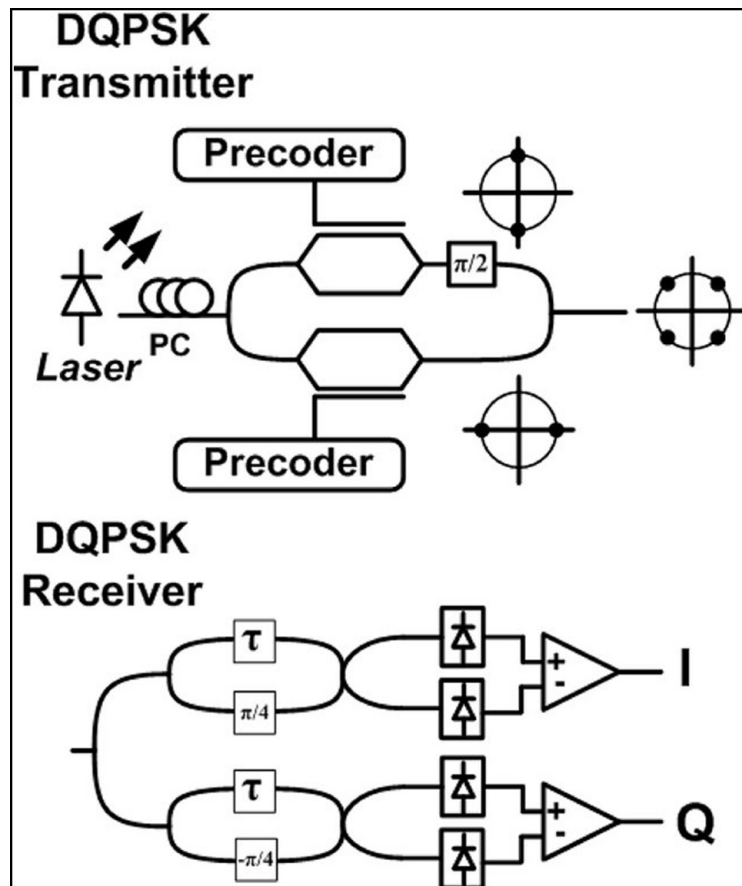


Fig. 1. General diagram for DQPSK system [16]

2.2 Free Space Optic (FSO) channel model

FSO communication has gained popularity in various wireless communication applications due to its low cost, fast data speed, and excellent security [22, 23]. Because of this, FSO communication is seen as a promising technology that will play a significant role in future communication research [24, 25]. However, as an optical wave propagates through turbulence, it encounters obstructions [26]. Because the refractive index of the atmosphere turbulence varies randomly with temperature and pressure,

the optical signal strength swings throughout this period, this phenomenon is known as scintillation [27, 28].

FSO has several benefits of simple and quick network deployment with low-cost equipment, no license required for installation, high data rate compared to other technologies, power of the light beam delivered via the FSO channel is faster than RF and more secure than RF. However, it has its limitations. Several factors affect the link, including (1) distance-dependent availability and (2) LoS condition. To transmit light via the FSO channel, various propagation concerns must be resolved, such as signal attenuation during the reception, which raises BER and lowers QF and OSNR [29, 30]. As a result, four distinct attenuation values are explored in this research (Table 1). Figure 2 shows a general idea of transmission over FSO channel [31].

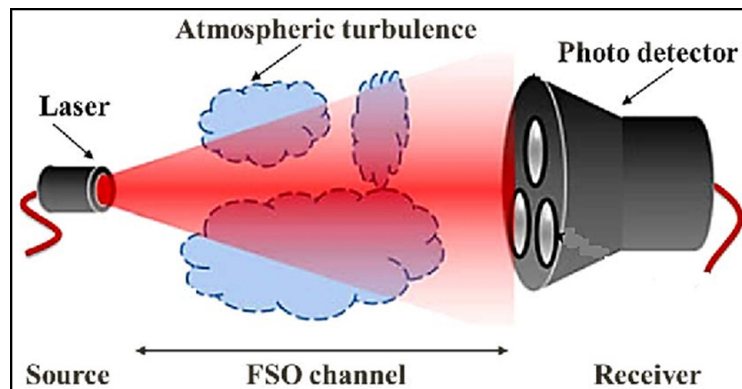


Fig. 2. Transmission over FSO channel [26]

2.3 Single-Mode Fiber (SMF) channel model

SMF is a long-distance optical fiber. It is one of two optical fiber types, the other being multimode. SMF is a single glass fiber strand used to transmit a single-mode or beam of light. SMF has a faster transmission rate and a nearly 50-fold longer range than MMF. SMF, on the other hand, is more expensive. The most fundamental distinction between SMF and MMF is the core size, loss or attenuation, and fiber bandwidth.

3 System design

To go over the technical features of the integrated DP-DQPSK DWDM system that includes hybrid SMF and FSO medium with 64 channels and a data rate of 1.79 Tbps, three categories will be used. The transmitter, transmission medium, and receiver components in this system are classed into three subcategories that will be described in detail. When taking a look at Figure 5, you can see what the general view is for the proposed system.

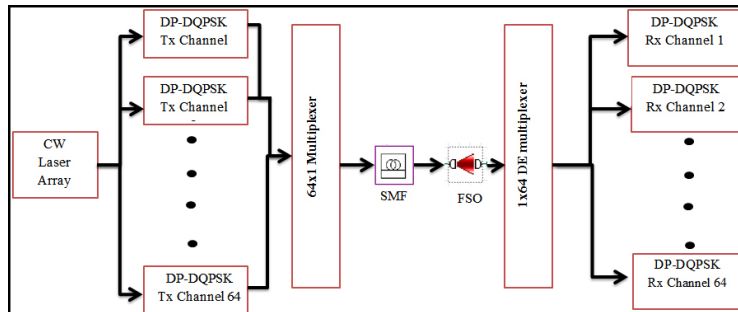


Fig. 3. A general view of the proposed system

Our current Optisystem implementation of the first part of our system uses a CW laser array element and sets the number of ports to 64. We then used two Pseudo Random Bit Sequence (PRBS) generators with bit rates selected to develop the DP-DQPSK transmitter system. At this point, each PRBS would be connected to a precoder, which would then be used to configure either a serial or parallel transmitter. The latter would be fed to a pulse generator of type Non-Return to Zero (NRZ). One final detail worth mentioning is that the LiNb Mach Zander Modulator (MZM) was used as a modulator. In this design, the incoming light is divided into two arms by the input optical branch, then these two arms are recombined by the output optical branch. One or both of the optical arms control the degree of interference at the output by applying an electrical signal to it. After that, the outputs of the first two MZM would be split apart by a 1×2 power splitter, which is then connected to another four modulators of the same type, whose inputs are fed by the outputs of the first two MZM. The final step in this system would be to connect all of the output lines from the four modulators to a polarization combiner. For each of the lines from the latter, there would be a connection to the 64×1 multiplexer device's input port. Table 1 contains the parameters that have been selected for each transmitter component. As seen in Figure 4, the transmitter design which uses the optisystem has also been made clearer.

Table 1. Selected parameters for the proposed DP-DQPSK DWDM transmitter part

Parameter	Value	Unit
CW laser array		
Number of output ports	64	
Line width	0.1	MHz
Initial phase	0	deg
Power	-10	dBm
Frequency	190.3–196.6	THz
Frequency spacing	0.1	THz
PRBS Generator		
Bit rate	14	Gbit/s
LiNb MZ Modulator		
Extinction ratio	30	dB
Switching bias voltage	4	V
Switching RF voltage	4	V
Insertion loss	0	dB

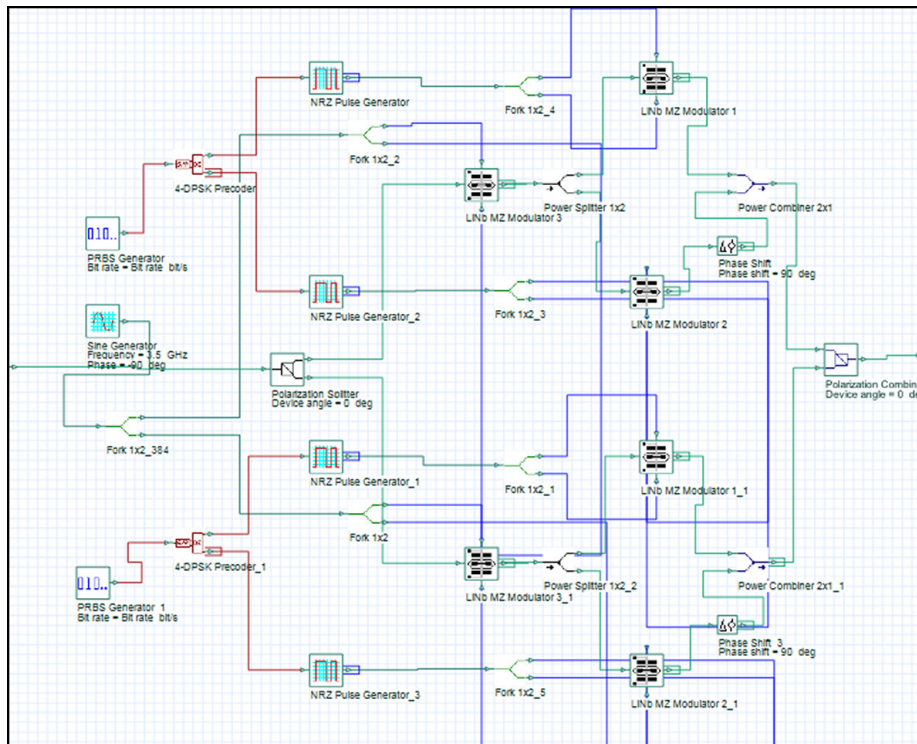


Fig. 4. The design of the proposed DP-DQPSK DWDM transmitter part

The optically modulated signal from the multiplexer line is transferred through the SMF for predetermined distances of 60 km (fixed distance) in the second part. Our proposed systems' attenuation and dispersion effects are taken into account in the proposed design and performance analysis by setting them to 0.2 dBm/Km and 16.75 ps/nm/Km, respectively. The problem of chromatic dispersion would arise due to the long-distance transmission. As a result, for longer transmission lengths, dispersion adjustment must be used. Therefore, a Dispersion Compensation Fiber (DCF) has been developed. The optical amplifier was chosen for this element to ensure transmission dependability over extended distances. After that, the FSO medium is used to handle distances of 5, 7, and 9 kilometers under various atmospheric conditions. In order to test the proposed system's reliability using a hybrid transmission medium, Figure 5 depicts the design of this part, and Table 2 lists the selected parameters for the component. It should be mentioned that the suggested system's end would be connected to a 1×64 DE multiplexer in order to recombine the optical signal transmitted in this section. Finally, Table 3 lists the atmospheric conditions that would be tested for the proposed system as indicated by attenuation in dB/km.

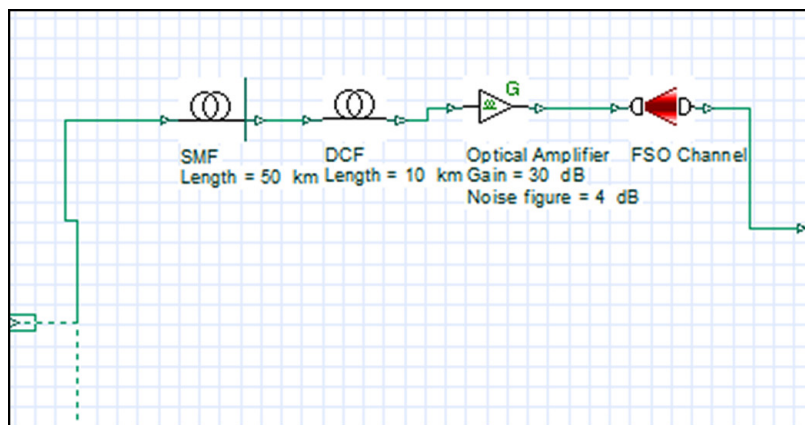


Fig. 5. The design of the proposed DP-DQPSK DWDM hybrid medium part

Table 2. Selected parameters for the proposed DP-DQPSK DWDM transmission medium part

Parameters	Value	Unit
SMF		
Length	50	km
Attenuation	0.2	dB/km
Dispersion	17	ps/nm/km
Differential group delay	0.2	ps/km
DCF		
Length	10	km
Attenuation effect	included	
Attenuation data type	Constant	
Attenuation	0.5	dB/km
Dispersion	-85	ps/nm/km
Optical Amplifier		
Operation mode	Gain Control	
Gain	20	dB
Power	10	dBm
Noise figure	4	dB
FSO		
Range	5, 7, 9	km
Attenuation	varied	dB/km
Scintillation model	Gamma-Gamma	

Table 3. The studied four cases of atmospheric attenuations for FSO channel

Atmospheric	Attenuation (dB-Km)
Clear Air	0.43
Light Haze	1.537
Medium Haze	4.2
Rain	5.8

The third part begins by recombining 64 channels from the DE multiplexer, where each channel is handled by an EDFA amplifier and a rectangular frequency transfer function optical filter. The received signal would then be handled by the power splitter, which is used to split an optical input signal into two output signals and is supported by the x coupler. After that, the optical signal input is given a time delay, and the input optical signal is given a time phase. Finally, using the PIN photodetector, the optical signal will be transformed into an electrical signal, and data 1 and 2 of the transmitted data would be examined using the BER analyzer tool offered by Optisystem software. Figure 6 depicts the whole connection for the proposed receiver component of the DP-DQPSK DWDM hybrid system, with the characteristics chosen for this part indicated in Table 4.

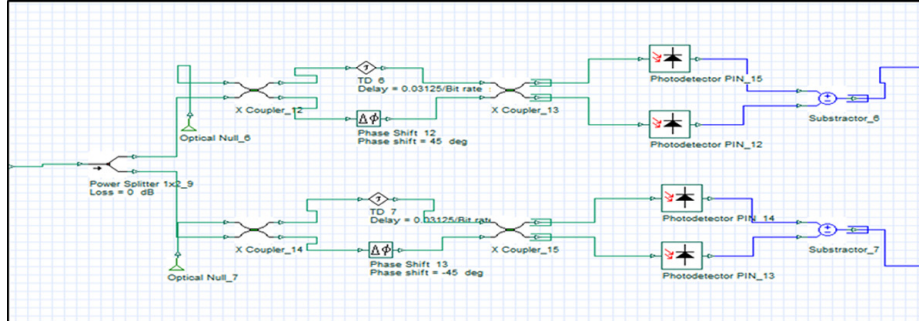


Fig. 6. The design of the proposed DP-DQPSK DWDM receiver part

Table 4. Selected parameters for the proposed DP-DQPSK DWDM receiver

Parameter	Value	Unit
EDFA		
Operation mode	Gain Control	
Gain	22	dB
Power	10	dBm
Noise figure	4	dB
Rectangle Optical Filter		
Bandwidth	60	GHz
Power Splitter 1×2		
Power ratio array	1 1	
Loss	0	dB
Photodetector		
Responsively type	Constant	
Responsively	1	A/W
Dark current	10	nA
Noise calculation type	Numerical	
Noise bandwidth source	Use sample rate	

4 Result and discussion

The results of the proposed system with hybrid transmission medium would be analyzed based on the parameters obtained from Optisystem software and as listed below:

4.1 QF results

The parameter of QF is studied by considering the four selected weather conditions and fixed SMF distance of 60 km attached with varied FSO three distances of

(5, 7 and 9) km. For FSO distance of 5 km it has been analyzed as seen in Figure 7 and for both data 1 and data 2. It can be seen a higher quality for the received signal achieved under the conditions of light air and both light and medium haze. Meanwhile, for the rain condition it can be seen higher effect on the signal quality and this effect varied based on the utilized channel wavelength.

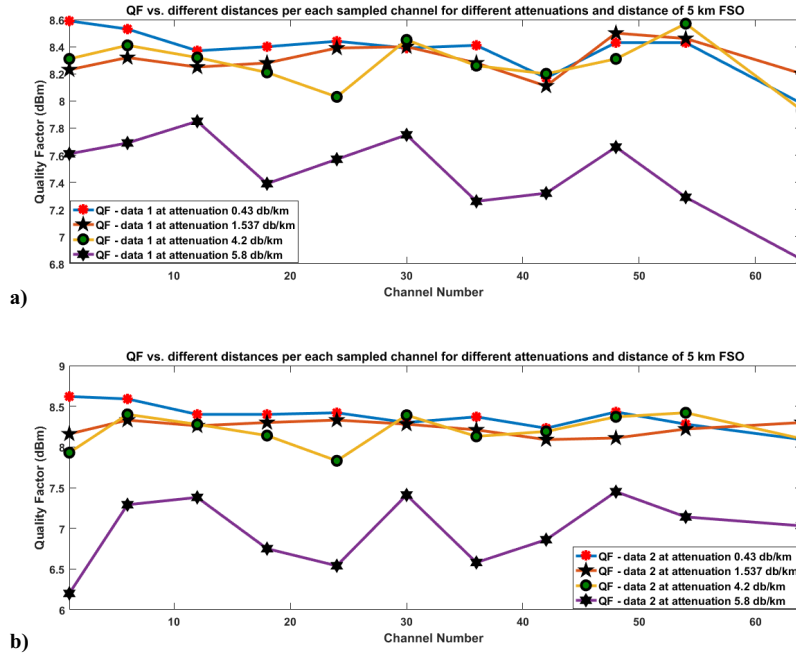


Fig. 7. QF vs. different distances per each sampled channel for different attenuation and distance of 5 km for (a) data 1 and (b) data 2

For the distance of 7 km as seen in Figure 11, it can be noticed a reverse relation as increasing the distance of FSO channel would reduce the value of QF obtained from different received stations. Furthermore, it can be noticed that under rain condition the proposed DP DQPSK DWDM system has failed to perform the transmission. Due to the higher attenuation effects related with rain condition. Keep in mind that the system is transmitting data for fixed distance by using SMF cable for 60 km. Additionally, for distance of 9 km, which represent the last case as seen in Figure 8, it can be seen that the system performance was only achieved for the case of light air and haze. Due to the series effects of weather conditions that increased when the distance is increase. Hence, it can conclude a reverse relation between the raising of attention and the FSO channel distance. Finally, the QF based results is obtained from the three investigated distances and per each channel has been listed as seen in Table 5. The averaged QF values were calculated from previous data as listed in Table 6, where it can be observed the reversal relation between the distance and both the QF and attenuation.

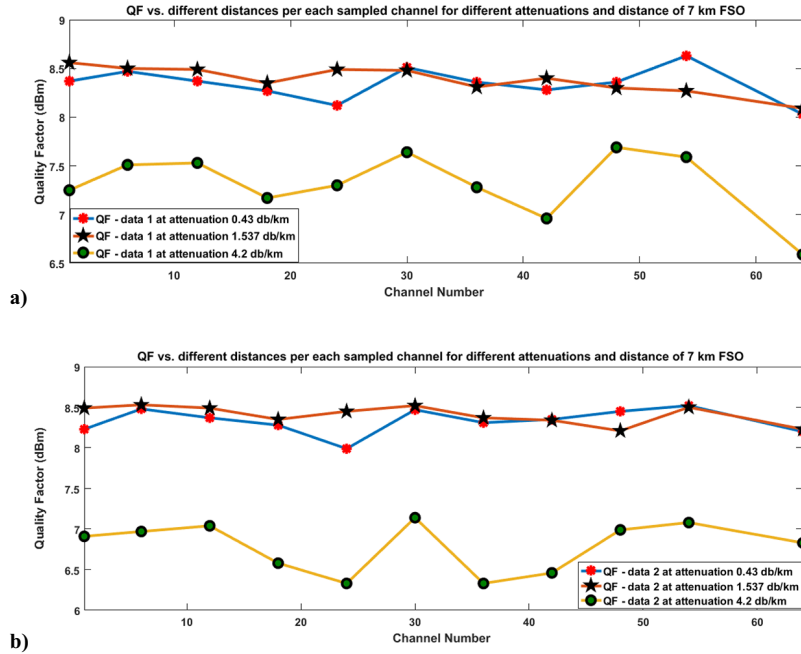


Fig. 8. QF vs. different distances per each sampled channel for different attenuation and distance of 7 km for (a) data 1 and (b) data 2

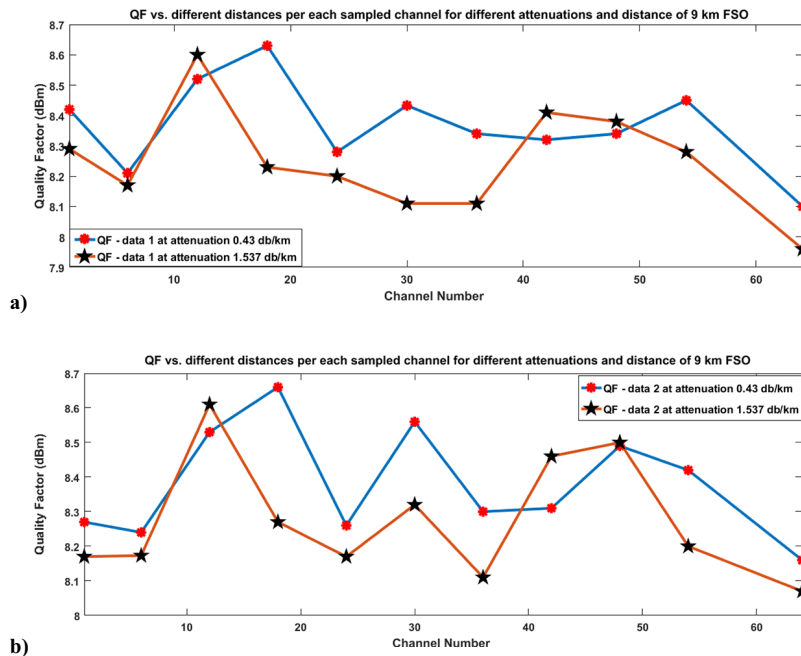


Fig. 9. QF vs. different distances per each sampled channel for different attenuation and distance of 9 km for (a) data 1 and (b) data 2

Table 5. The QF values obtained from each atmospheric attenuation per each investigated FSO distances

Channel/QF Value	5 Km		7 Km		9 Km	
	Data 1	Data 2	Data 1	Data 2	Data 1	Data 2
	Attenuation = 0.43 dB/km					
1	8.59	8.62	8.37	8.23	8.42	8.27
6	8.53	8.59	8.47	8.48	8.21	8.24
12	8.37	8.4	8.37	8.37	8.52	8.53
18	8.4	8.4	8.27	8.28	8.63	8.66
24	8.44	8.42	8.12	7.99	8.28	8.26
30	8.39	8.3	8.51	8.47	8.433	8.56
36	8.41	8.37	8.36	8.31	8.34	8.3
42	8.17	8.23	8.28	8.35	8.32	8.31
48	8.43	8.43	8.36	8.45	8.34	8.49
54	8.43	8.28	8.63	8.52	8.45	8.42
64	7.98	8.09	8.03	8.2	8.1	8.16
	Attenuation = 1.537 dB/km					
1	8.23	8.16	8.56	8.49	8.29	8.17
6	8.32	8.33	8.5	8.53	8.17	8.173
12	8.25	8.26	8.49	8.49	8.6	8.61
18	8.28	8.3	8.35	8.35	8.23	8.27
24	8.39	8.33	8.49	8.45	8.2	8.17
30	8.4	8.28	8.48	8.52	8.11	8.32
36	8.28	8.21	8.31	8.37	8.11	8.11
42	8.11	8.09	8.4	8.34	8.41	8.46
48	8.5	8.11	8.3	8.21	8.38	8.5
54	8.46	8.22	8.27	8.5	8.28	8.2
64	8.2	8.3	8.09	8.23	7.96	8.07
	Attenuation = 4.2 dB/km					
1	8.31	7.93	7.25	6.91	–	–
6	8.41	8.4	7.51	6.97	–	–
12	8.32	8.277	7.53	7.04	–	–
18	8.21	8.14	7.17	6.58	–	–
24	8.03	7.83	7.3	6.33	–	–
30	8.45	8.39	7.64	7.14	–	–
36	8.26	8.13	7.28	6.33	–	–
42	8.2	8.19	6.96	6.46	–	–
48	8.31	8.37	7.69	6.99	–	–
54	8.57	8.42	7.59	7.08	–	–
64	7.93	8.1	6.59	6.83	–	–

(Continued)

Table 5. The QF values obtained from each atmospheric attenuation per each investigated FSO distances (*Continued*)

Channel/QF Value	5 Km		7 Km		9 Km	
	Data 1	Data 2	Data 1	Data 2	Data 1	Data 2
	Attenuation = 5.8 dB/km					
1	7.61	6.2	–	–	–	–
6	7.69	7.29	–	–	–	–
12	7.85	7.38	–	–	–	–
18	7.39	6.75	–	–	–	–
24	7.57	6.54	–	–	–	–
30	7.75	7.41	–	–	–	–
36	7.26	6.58	–	–	–	–
42	7.32	6.86	–	–	–	–
48	7.66	7.45	–	–	–	–
54	7.29	7.14	–	–	–	–
64	6.83	7.03	–	–	–	–

Table 6. Averaged QF values obtained from the three distances and per each attenuation case

Distance	Averaged QF Obtained from each Case of Attenuation for all Sampled Channels							
	0.43 dB/km		1.537 dB/km		4.2 dB/km		5.8 dB/km	
5 km	8.37636	8.37545	8.31091	8.23545	8.27273	8.19791	7.47455	6.96636
7 km	8.34273	8.33182	8.38545	8.40727	7.31909	6.78727	–	–
9 km	8.36755	8.38182	8.24909	8.27755	–	–	–	–

4.2 BER results

The BER parameter is investigated using four different weather situations, a set SMF distance of 60 km, and three different FSO lengths of (5, 7, and 9) km. It has been examined for an FSO distance of 5 km, as shown in Figure 10, and for both data 1 and data 2. Under the conditions of light air and both light and medium haze, the error in the received bits has a reduced impact. Meanwhile, the effect of rain grew, resulting in greater BER values, and this effect varied depending on the channel wavelength used.

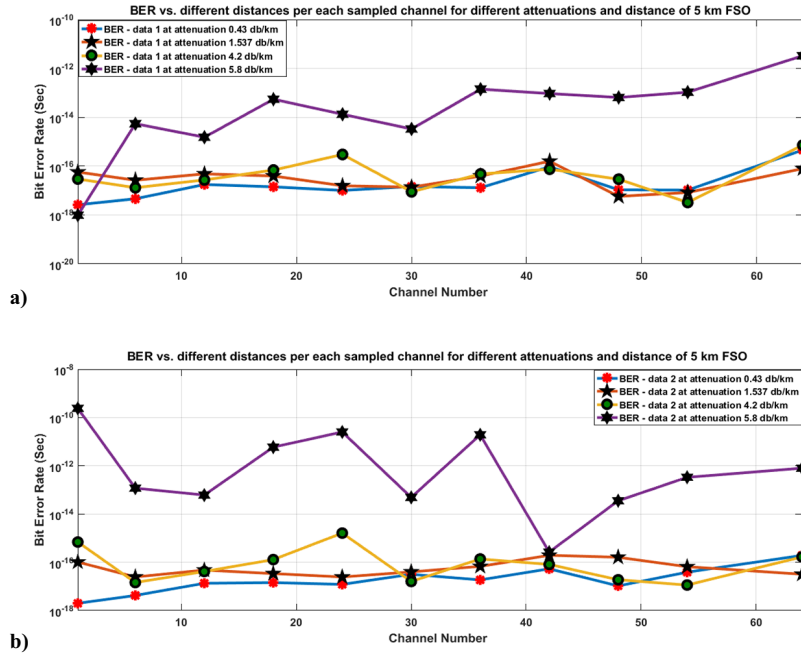


Fig. 10. BER vs. different distances per each sampled channel for different attenuation and distance of 5 km for (a) data 1 and (b) data 2

Figure 11 shows a direct relationship between increasing the distance of the FSO channel and increasing the value of BER acquired from different received stations at a distance of 7 km. Furthermore, the planned DP DQPSK DWDM system failed to transmit during rainy conditions because of the increased attenuation effects caused by rain. Meanwhile, the 9 km distance shown in Figure 12 indicates that the system’s performance was only reached when light air and haze were present. Due to a succession of weather conditions that worsened as the distance between them grew. As a result, it is possible to draw a direct link between the increase in attention and the FSO channel distance. Finally, as shown in Table 7, the BER-based obtained results from the three analyzed distances and per each channel have been listed. The averaged BER values were obtained using data from the previous table, as shown in Table 8, where the reverse relationship between distance and both BER and attenuation can be seen. It can be noticed from the previous table that all averaged values obtained were above the minimum threshold of (E-12) and thus confirm the reliability for the proposed system under different investigated weather conditions especially for the distance of 5 km.

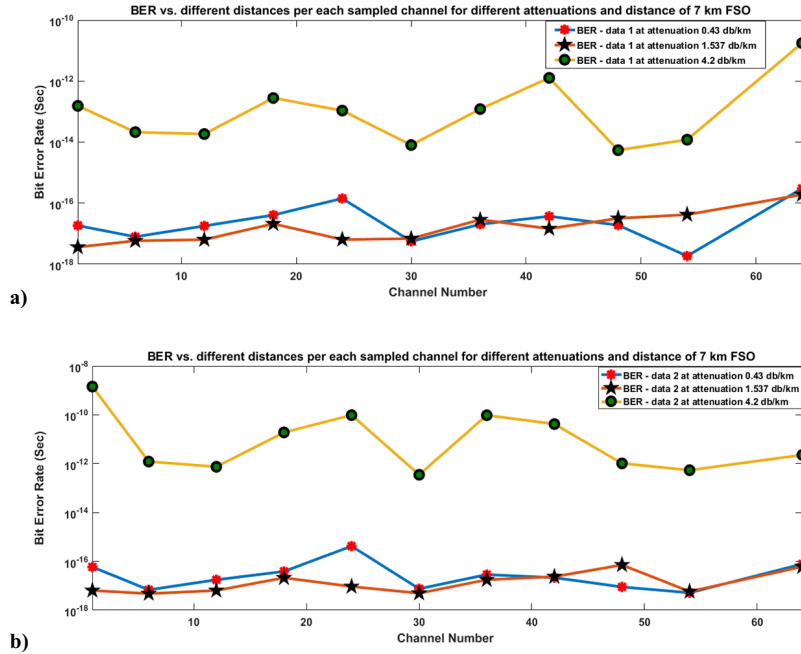


Fig. 11. BER vs. different distances per each sampled channel for different attenuation and distance of 7 km for (a) data 1 and (b) data 2

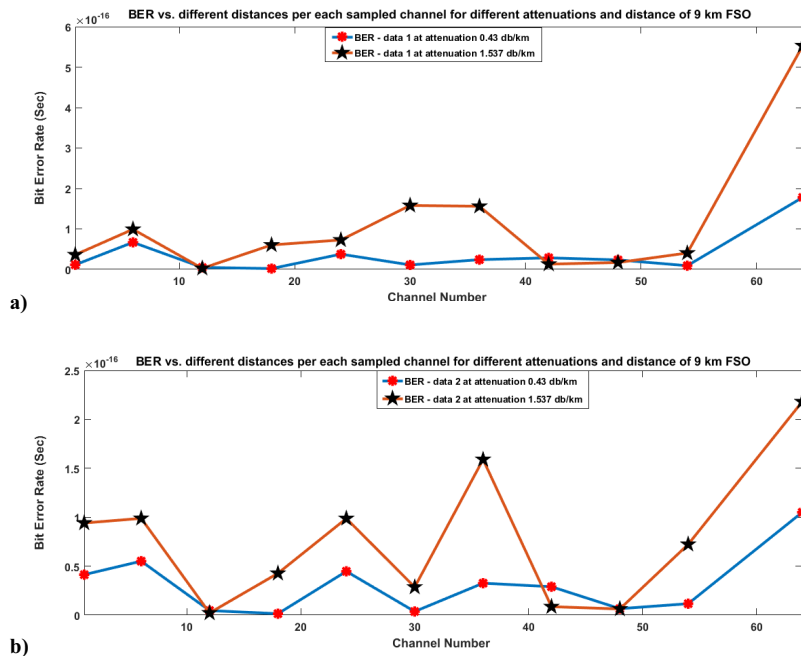


Fig. 12. BER vs. different distances per each sampled channel for different attenuation and distance of 9 km for (a) data 1 and (b) data 2

Table 7. The BER values were obtained from each atmospheric attenuation per each investigated distance

Channel/BER Values	5 Km		7 Km		9 Km	
	Data 1	Data 2	Data 1	Data 2	Data 1	Data 2
Attenuation = 0.43 dB/km						
1	2.61E-18	2.00E-18	1.84E-17	5.87E-17	1.13E-17	4.13E-17
6	4.58E-18	4.22E-18	7.88E-18	6.81E-18	6.68E-17	5.51E-17
12	1.76E-17	1.35E-17	1.79E-17	1.75E-17	4.84E-18	4.62E-18
18	1.41E-17	1.44E-17	4.07E-17	3.86E-17	1.99E-18	1.43E-18
24	1.01E-17	1.22E-17	1.42E-16	4.19E-16	3.76E-17	4.47E-17
30	1.46E-17	3.17E-17	5.58E-18	7.50E-18	1.10E-17	3.65E-18
36	1.30E-17	1.86E-17	2.02E-17	2.87E-17	2.40E-17	3.26E-17
42	9.39E-17	5.37E-17	3.71E-17	2.14E-17	2.85E-17	2.90E-17
48	1.07E-17	1.05E-17	1.90E-17	8.95E-18	2.34E-17	6.56E-18
54	1.04E-17	3.90E-17	1.85E-18	5.17E-18	9.07E-18	1.16E-17
64	4.55E-16	1.93E-16	3.02E-16	7.74E-17	1.78E-16	1.05E-16
Attenuation = 1.537 dB/km						
1	5.68E-17	1.02E-16	3.62E-18	6.42E-18	3.61E-17	9.41E-17
6	2.64E-17	2.47E-17	5.84E-18	4.74E-18	9.91E-17	9.88E-17
12	4.80E-17	4.75E-17	6.37E-18	6.42E-18	2.53E-18	2.20E-18
18	3.94E-17	3.41E-17	2.11E-17	2.11E-17	6.04E-17	4.27E-17
24	1.56E-17	2.46E-17	6.39E-18	9.30E-18	7.27E-17	9.87E-17
30	1.37E-17	4.01E-17	6.88E-18	4.94E-18	1.58E-16	2.86E-17
36	3.91E-17	6.76E-17	2.87E-17	1.76E-17	1.56E-16	1.59E-16
42	1.58E-16	1.94E-16	1.46E-17	2.36E-17	1.29E-17	8.63E-18
48	5.72E-18	1.62E-16	3.17E-17	7.15E-17	1.69E-17	6.24E-18
54	8.31E-18	6.55E-17	4.20E-17	5.82E-18	4.04E-17	7.23E-17
64	7.84E-17	3.21E-17	1.90E-16	6.07E-17	5.53E-16	2.18E-16
Attenuation = 4.2 dB/km						
1	2.96E-17	6.91E-16	1.54E-13	1.44E-09	–	–
6	1.30E-17	1.45E-17	2.12E-14	1.22E-12	–	–
12	2.71E-17	4.15E-17	1.84E-14	7.47E-13	–	–
18	6.86E-17	1.29E-16	2.79E-13	1.91E-11	–	–
24	2.98E-16	1.62E-15	1.08E-13	9.75E-11	–	–
30	8.86E-18	1.60E-17	8.01E-15	3.52E-13	–	–
36	4.75E-17	1.37E-16	1.21E-13	9.67E-11	–	–
42	7.46E-17	8.17E-17	1.27E-12	4.20E-11	–	–
48	2.90E-17	1.89E-17	5.44E-15	1.03E-12	–	–
54	3.24E-18	1.14E-17	1.20E-14	5.41E-13	–	–
64	7.20E-16	1.67E-16	1.76E-11	2.29E-12	–	–

(Continued)

Table 7. The BER values were obtained from each atmospheric attenuation per each investigated distance (*Continued*)

Channel/BER Values	5 Km		7 Km		9 Km	
	Data 1	Data 2	Data 1	Data 2	Data 1	Data 2
	Attenuation = 5.8 dB/km					
1	9.72E-19	2.39E-10	–	–	–	–
6	5.41E-15	1.18E-13	–	–	–	–
12	1.52E-15	6.10E-14	–	–	–	–
18	5.46E-14	5.91E-12	–	–	–	–
24	1.32E-14	2.51-e11	–	–	–	–
30	3.30E-15	4.88E-14	–	–	–	–
36	1.41E-13	1.92E-11	–	–	–	–
42	9.32E-14	2.64E-16	–	–	–	–
48	6.44E-14	3.54E-14	–	–	–	–
54	1.06E-13	3.33E-13	–	–	–	–
64	3.28-e12	7.93E-13	–	–	–	–

Table 8. Averaged BER values obtained from the three distances and per each attenuation case

Distance	Averaged QF Obtained from each Case of Attenuation for all Sampled Channels							
	0.43 dB/km		1.537 dB/km		4.2 dB/km		5.8 dB/km	
5 km	5.88E-17	3.57E-17	4.45E-17	7.22E-17	1.20E-16	2.66E-16	4.83E-14	2.65E-11
7 km	5.57E-17	6.27E-17	3.25E-17	2.11E-17	1.78E-12	1.55E-10	–	–
9 km	3.60E-17	3.05E-17	1.10E-16	7.54E-17	–	–	–	–

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6 Conclusion

This paper proposed DP-DQPSK based DWDM system that supports 1.79 Tbps of data rate and with using the DD technique for handling the recovery of the optical intensity. The system was designed using Optisystem and investigated for hybrid transmission medium of both SMF with a fixed distance of 60 km and FSO with varied distances of (5,7 and 9) km. For FSO channel investigated, it has been analyzed via studying the effect of four different weather conditions on the performance of the proposed system based on the parameters of QF and BER. Results obtained for the

parameter of QF indicate reverse relation between the QF and both the FSO distance and attenuation. Meanwhile, BER parameters showed a direct relation. For light air and haze the system showed higher reliability in the obtained results and for all the three investigated FSO distances. While for the medium haze the system has shown the capability to transfer for 7 km. In rainy weather, the system capability was set to 5 km. For the future, the rain condition would be further handle to support higher FSO distance via using different amplification techniques.

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