Design of high throughput 2.7 Tbps DWDM System under MIMO-FSO Channel as Back-up Optical Link for 5G Networks

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Abstract: The present article aims to investigate and evaluate the performances of DWDM (or Dense Wavelength Division Multiplexed) system under MIMO-FSO (or multiple input multiple output-free space optical) channel. However, the proposed system is configured and simulated in the worst-case meteorological conditions, and we base here on the variation of the attenuation coefficient. In this article, the proposed system is devoted to 90 users, every user exploits 30 Gbps. So, the total capacity of system is 90x30 Gbps. In addition, the use of MIMO technique in FSO channel ensures us the stability of the proposed system in the worst-case meteorological conditions and especially when the system exploits a high throughput. To assess the acceptable performance levels of the proposed system, it is necessary to use the following criteria: the minimum bit error rate (or BER) performance, the maximum quality factor (or Q-Factor) and the optical signal to noise ratio (or OSNR) performance. Finally, the proposed system in this paper provides a promising solution for 5G networks as back-up optical link.

Keywords: FSO, MIMO, DWDM, EDFA, BER, Q-Factor, OSNR.

1. INTRODUCTION

Optical transmission has emerged as the essential technology for high-capacity, long-distance transport networks, replacing all previous technologies in terms of capacity and transmission quality.

Simply, the use of optical wireless linking (OWL) aims to transfer the data over free space between two distant points using optical radiation as a carrier signal. The channels in which the light signal is spread can be a deep area, atmosphere or seawater, but the focus of this work is on the terrestrial free space optical (FSO) technology, and the channel of interest, here, is the atmosphere. The FSO link relies primarily on the line of sight (LoS) between two ends of the two communication points. To ensure information successful exchange, the transmitter and receiver of FSO (Tx-FSO /Rx-FSO) must be in direct LoS with each other without any obstruction. This makes the OWL communication theoretically possible with the condition: that there is a direct view between Tx-FSO and Rx-FSO, and that the beam power is at a level sufficient to reach the other end [1,2].

FSO technology has been introduced for the first time on the market at 10 Gbit/s, responding to the needs of telecom operators. It is the future rival of most radio frequency (RF) technologies, such as: LTE (Long Term Evolution), GSM (Global System for Mobile communications), WiFi (Wireless Fidelity), and Bluetooth ... However, the fundamental principle of FSO technology is based on the under-atmospheric optical transmission of part of the visible or infrared light spectrum. FSO systems have been designed to establish a LoS communication between two different regions at a very high data rate. Furthermore, FSO enables all types of data to be transmitted at a rate equal to the fiber optic rate with all the flexibility and advantages of a wireless network. In theory, the FSO link requires an optical transmitter, a propagation channel and an optical receiver. For more details, we also refer to articles [3-7]. The FSO link generally employs a pair of optical transceivers (Tx-FSO/Rx-FSO) which are mounted on poles, behind windows or fixed on roofs, facing each other. For more information about Tx-FSO/Rx-FSO, Light Pointe provides those [8-12].

The wavelength in which the FSO technology works is the first parameter to consider. Specifically, Tx-FSO emits infrared radiation that is often in the wavelength range of about 1550 nm, as the sensitivity of the photodiodes employed in Rx-FSO is much better at 1550 nm than that of the visible or near infrared spectrum. In addition, laser radiation presents a risk to eye safety in the visible range only at wavelengths of about 1550 nm. Indeed, the cornea and the crystalline lens absorb light at 1550 nm and do not focus on the retinal part of the eyes, unlike visible and near infrared lasers, which can cause irreversible retinal damage. This is an essential factor for OWL under FSO channel where the light energy is high and the beam is within reach of the user. Simply choosing a laser at 1550 nm guarantees the safety of the FSO system even if the strength of the laser beam is higher [11-16].

FSO technology has very interesting capabilities for a wide range of applications. It can easily be complemented with other technologies, such as wireless and wired communications and Fibre To The-x (FTTx) technologies. FSO applications include the following: (1) Fiber link support: FSO links can be used to provide back-up links in the event of data loss or connection failure, if the primary fiber link is damaged or unavailable. (2) Backhaul communications for mobile telephony: FSO links enable intensive data transfer of communication links between base stations and the network infrastructure. This improves mobile wireless networks and extends the bandwidth between base stations. The FSO communication system is an interesting solution because it eliminates the wireless links widely used for the GSM 900 MHz or 1800 MHz which already pose frequency saturation problems. In addition, FSO links have a large bandwidth suitable for multimedia applications. (3) Temporary FSO links: FSO technology is employed to find applications where a temporary link is needed, either for a conference or for a dedicated connection in case of a failure of the current network. It is also exploited for temporary replacement of optical fibers, and various applications where optical fibers cannot be deployed for one reason or another, and deployment in the event of a temporary site installation or for any other disastrous reason. (4) Difficult terrain: FSO links provide an exciting data bridge when there is a connection between two points separated by a river, busy street or railway, or when traffic is not available or is too expensive to continue. (5) High Definition Television (HDTV): Due to the enormous need for spectrum for HDTV cameras and signals, FSO technology is increasingly being used in the broadcasting industry to transmit live signals from HD cameras to locations remote from the central office. (6) Military communications: FSO is an interesting communication method for military applications because of the security. The use of conventional radio frequencies (RF) may intercept the communication, which is not the case with FSO technology, where RF waves are emitted over a wide area allowing reception of the signal close to the system, although it is still necessary to demodulate and decode. On the other hand, the FSO link has a very narrow beam divergence, usually in millimeter-radians, so that the only way to intercept the signal is in the transmission path. Laser transmission equipment is inexpensive, easy to install and use, not subject to restrictive regulations, suitable for almost any network configuration and covering a wide range of applications [11,12,17-20].

In FSO technology, there are some main advantages; we will mention the following: it is easy and fast to deploy its network with small and simple equipment; it is characterized by the speed of moving the network and the reuse of links; the license is not required to install it; it is inexpensive with a higher data rate compared to other technologies; the power of the light beam under the FSO channel is transmitted at the speed of light; it has greater security than RF technology. On another hand, it has its own limits. Since this technology requires a direct LoS between transmitter and receiver, the link is therefore subject to a number of factors: (1) Distance-dependent availability and (2) LoS condition. In addition, in order to transmit the light waves over the FSO channel, it is necessary to overcome certain propagation problems, such as signal attenuation at reception, which leads to an increase in the bit error rate (or BER) and a decrease in the quality factor (or Q-Factor) and optical signal-to-noise ratio (or OSNR) [11,12].

In the present paper, the proposed DWDM system under FSO link is suitable for the needs of 5G mobile networks. The 5G is the 5th Generation of wireless technology. It is engineered to increase throughput, decrease latency and enhance the flexibility of mobile services. In addition, the 5G technology has a nominal maximum throughput of 20 Gbps, while the 4G technology has a nominal maximum throughput of 1 Gbps. 5G also offers lower latency, which can enhance the business applications capabilities as well as other digital experiences, such as: videoconferencing [21]. Consequently, the ability to install FSO links in 5G networks ensures the constant increase in the required throughput by fixed, mobile, Internet and video subscribers; with providing a greater number of users.

2. RELATED WORK

A lot of researches on FSO technology have been investigated and suggested in order to improve the data transmission in our everyday lives. In the present section, we present some related works on FSO technology.

However, the authors of the proposed paper [22]: "*Performance Evaluation of an Adaptive Hybrid FSO/RF Communication System: Impact of Weather Attenuation*", have investigated on the performances of an adaptive hybrid system (or AHS) between FSO and RF links under the effect attenuation such as: fog, humidity and rain, at different wavelengths, which are as follows: 850 nm, 950 nm and 1550 nm. According to the authors, the RF link has been used as a rescue link in order to ensure the continued high availability of the adaptive hybrid FSO-RF system, at different frequencies, which are as follows: 10 GHz, 50 GHz and 100 GHz. As results of simulation, the authors of [22] have concluded that the attenuation coefficient due to fog has a significant effect on the performances of proposed system [22]. As example, for FSO link at 1550 nm wavelength and with a visibility of 1 km, the attenuation can reach 50 dB/km. In contrast, the attenuation of RF link at 10 GHz frequency can reach $8 * 10^{-9}$ dB/km. In addition, the authors of [22] have also noted that the attenuations for FSO link have higher values than the RF link, but the 1550 nm wavelength of FSO link has a priority among the other wavelengths, such as: 850 nm and 950 nm. Consequently, they have concluded that when the RF link is exploited as a rescue link at low frequencies, the proposed adaptive hybrid FSO-RF system can provide them with better performance. In addition to the above, the authors have evaluated the proposed hybrid system by two metrics, are as follows: the received signal power (or RSP) and the minimum BER performance. In this context, the authors have mentioned that, in order to reach a minimum BER and a detectable RSP, an appropriate wavelength for FSO link and a low frequency for RF link have to be chosen, so that both have a strong effect on the attenuation coefficient, which results to a greater transmission distances. In terms of the RSP, the authors of [22] concluded that the RF link has a better performance, it is lower than the FSO link by approximately 50%, but the RSP in RF link can be detected, this means that the receiver sensitivity of RF link is better than the sensitivity of FSO link. As example, for RF link, the RSP at link distance 1 km is equal to -56.59 dBm (3 cm wavelength or 10 GHz frequency), than for FSO link and with the same link distance, the RSP is equal to -28.52 dBm (1550 nm wavelength or 193.55 THz frequency). In terms of the minimum BER performance, the authors of [22] note that the minimum BER at link distance 1 km for RF system is worth to $1.23 * 10^{-6}$ (3 cm wavelength or 10 GHz frequency), than for FSO system and with the same link distance, the minimum BER is worth to $1.96 * 10^{-6}$ (1550 nm wavelength or 193.55 THz frequency). As noted, the obtained minimum BER performance from RF system is approximately the same as that obtained for the FSO system.

In paper [23]: "*Outage Performance Analysis of Hybrid FSO/RF System Using Rayleigh and K-Distribution*", the authors have investigated and determined the outage probability performance of an adaptive hybrid FSO-RF system employing the decoding process and the forward (DF) relaying. However, the proposed channel that has been considered by the authors for the adaptive hybrid FSO-RF system is modeled through Rayleigh distribution and K-distribution for both RF and FSO links, respectively [23]. In addition, the expressions given in [23], such as: the function of probability density, the function of cumulative distributive, and the outage probability for proposed system, are obtained from the Meijer G-function. In addition to the above, the authors also indicated that the Meijer G-function is simple to use for determining the above-mentioned expressions, due to their availability in the software MATLAB. Moreover, the authors have evaluated the proposed system through the curve characteristic of outage probability versus average received signal-to-noise ratio (or SNR) under varying values for the preset threshold of SNR (the pre-set SNR per the proposed system) and different values for alpha (or α, which is the discrete number of scatters in the environment). As remarks, the authors have concluded that, the outage probability performance increases as the number of scatters in the environment increases and to decline the outage probability performance of the proposed system, the average received SNR must outperforms than the pre-set SNR per the system. So, the pre-set SNR value for the proposed adaptive hybrid FSO-RF system by the authors is significant to longer transmission distances [23].

From the paper [24]: "*The Effect of Weak Atmospheric Turbulence and Fog on OOK-FSO Communication System*", the authors studied and evaluated the minimum BER performance for FSO link using the On-Off keying (or OOK) modulation format under conditions of weak turbulence and atmospheric attenuation. However, the purpose of paper [24] focuses on the data transmission over longer distances with lower BER through increasing the transmitted power. Here, the communication channel of proposed FSO link is modeled by log-normal atmospheric turbulence and for the presence of fog, they used Kim's attenuation model. Based on the obtained results of paper [24], they concluded that the reduction of the fog induced loss effect and increasing the link distance for data transmission with lower BER are achieved by increasing the input power of the FSO transmitter. Further, the authors have also presented the effect of scintillation index on the minimum BER performance under conditions of weak turbulence and atmospheric attenuation. In this context, they have noted that the minimum BER performance increases when the scintillation index increases and vise-versa, and the minimum BER performance tends to lower values for higher transmitted power of the FSO transmitter [24].

Similar to [23], the authors of research work [25]: "*Hybrid RF/MIMO-FSO Relaying Systems Over Gamma–Gamma Fading Channels* ", have proposed an adaptive hybrid RF/MIMO-FSO system to combat the fading of signal due to atmospheric turbulence. However, the proposed cooperative RF/MIMO-FSO system by the authors has the capability to improve the data transmission better as compared to the RF system or FSO system. In addition, the proposed channel that has been considered for the RF link (RF source node to amplify-and-forward (or AF) relay node) is modeled through Nakagami-m distribution, whereas the fluctuation of irradiance under the MIMO-FSO link (AF relay node to optical destination node) is modeled through Gamma–Gamma scintillation model. In addition to the above, the proposed system is carried out with a variable gain relaying MIMO system on the FSO link part. Moreover, the authors of [25] have evaluated the proposed system by means of two metrics, are as follows: the outage probability performance and the minimum BER performance. According to the obtained results of [25], the authors have concluded that increasing of the diversity order gain of MIMO-FSO link causes an improvement in the overall reliability of the proposed system.

In paper [26]: "*Design of high-speed 10-Gb/s wired/FSO systems for local area communication networks for maximum reach* ", the authors have proposed a hybrid upgrade wired/wireless (or SMF/FSO) system under high-speed (10 Gb/s) employing various all optical amplifiers (or OAs) and modulation techniques. However, from the title of [26], it is clear that the design of the proposed system aims to achieve a maximum reach of distance in local area communication networks with transmission data rate, which is worth 10 Gb/s. In addition, the authors have evaluated the proposed system by these factors: the minimum BER performance, the maximum quality factor (or Q-Factor) and the optical signal-to-noise ratio (or OSNR). From the obtained results, the authors have observed that the high-speed of continuous-phase frequency-shift keying (or CPFSK) modulation technique based on SMF/FSO link produces the maximum Q-Factor and the minimum BER performance than the other techniques under various OAs conditions. In the end of paper [26], the authors have cited that the trade-off between the proposed CPFSK modulation technique and various OAs has been chosen to improve the proposed system stability. In another paper [27]: "*Effects of atmospheric weather and turbulence in MSK based FSO communication system for last mile users* ", the authors have proposed a rescue link based on the minimum shift keying (or MSK) modulation over FSO link. However, the authors have successfully studied and evaluated the effects of atmospheric turbulence and different weather conditions on the performance of proposed MSK-FSO link at 10Gbps downlink, between base station (or BS) at central station (or CS) and the end user.

The paper presented in [28]: "*Analysis of FSO Systems with SISO and MIMO Techniques*", analyses and compares the minimum BER performance of single input single output (or SISO) and multiple input multiple output (or MIMO) over FSO link. The authors of [28] have considered that the proposed system must suffer from much atmospheric turbulence, namely: haze, rain, snow and storms, in order to evaluate the better performance of SISO/MIMO-FSO system in terms of minimum BER. In addition, they have also set the maximum BER value of 10^{-9} as a pre-set BER to ensure the proper functioning of the proposed system. As noted by the authors, as the link distance and attenuation coefficient increases [9 to 12 dB/km], the minimum BER performance also increases and it is close to up the pre-set BER value for the link distance of 1100 m, on the other hand, for the better performance of SISO-FSO system in terms of minimum BER, the link distance should be around to 900 m. In addition, as the data rate of the proposed SISO-FSO system increases within [1.25 to 4.25 Gbit/s] at 1550 nm wavelength and 10 dB/km, the minimum BER performance also increases with longer link distance. Further, they have also tested the proposed SISO-FSO system at 1550 nm wavelength and 1.25 Gbps for various weather conditions, which are as follows: haze, rain and fog. As the authors have observed, the light haze and heavy rain have a significant impact on the minimum BER performance for the proposed SISO-FSO system. In the end of first part [28], the analysis of proposed SISO-FSO system by the authors is summarized by the following points : (1) For a lower attenuation coefficient and shorter link distance, the minimum BER performance is better and can reach a well lower value than the pre-set BER value. As example, if the link distance of the proposed SISO-FSO system is fixed at 1000 m, the optical signal propagating under SISO-FSO channel can degrades when the attenuation coefficient increases by 9 dB/km, and at 12 dB/km, the optical signal is completely degraded. (2) The optical signal propagating under SISO-FSO channel can also degrades when the data rate is changed from [1.25 to 4.25 Gbit/s]. As example, if the data rate of 4.25 Gbit/s is reached, the attenuation of the optical signal starts at a link distance of 1600 m. (3) When the different weather conditions are taken into account in the proposed SISO-FSO system; it shows strong attenuation and degradation in terms of the minimum BER performance.

In the second part of paper [28], the authors have proposed the optimal solution to improve the performance SISO-FSO system. The method is very simple, they have substituted the SISO-FSO link by the MIMO-FSO link and they have also retained the same Tx-FSO/Rx-FSO configuration parameters. However, the authors proposed the following two types of links: 2×2-FSO link and 4×4-FSO link. For these links, they have analyzed the minimum BER performance as function of the attenuation coefficient under various link distances. As expected by the authors, the minimum BER performance reaches lower values, although the attenuation coefficient and link distances increase. In addition, the authors have also noticed that as the data rate and link distance increase, the minimum BER performance is at a higher level and the target value of minimum BER performance is reached at a link distance of 1500 m using 4x4-FSO link (this is better performance compared to the SISO-FSO link). Furthermore, when they have achieved the best performance with the 4x4-FSO link, they have thought to analyze the performance of 4x4-FSO link under several weather conditions. As the authors have observed, the moderate rain and heavy rain have a significant impact on the minimum BER performance for the proposed 4x4-FSO link. But, when the light haze and heavy haze are taken into account, the proposed 4x4-FSO link offers the best performance. As example, compared to the proposed SISO-FSO link, the minimum BER performance for 4x4-FSO link with light haze and heavy haze from [4800 m to 6000 m] is better and reach a well lower value than the pre-set BER value.

In the end of paper [28], the authors have concluded that the proposed MIMO-FSO system outperforms than the SISO-FSO system in terms of the minimum BER performance. It is also cited that the SISO-FSO link can offers a longer transmission distance, which is equal to 2 km, while a 4x4-FSO link can reach up to 5 km under medium weather conditions.

The paper published in [29]: "*Optimization of MDM-FSO system with different encoding schemes*", analyses and compares the performance of linear polarization (or LP) channels by mode division multiplexing (or MDM) under FSO link. The types of channels proposed are as follows: LP01 and LP11. However, the authors have considered that each channel can carries the data at 10 Gbit/s and are then transmitted at a link distance of 8 km using NRZ/RZ modulation schemes. In addition, the performance of the proposed system (or MDM-FSO system) by the authors [29] has been assessed under atmospheric turbulence. In addition to the above, the performance assessment indicators of MDM-FSO system are as follows: the minimum BER performance, the acceptable level of OSNR performance, the maximum Q-Factor performance and the eye diagram. With the results achieved, the authors have noted that the proposed MDM-FSO system under channel LP01 has better performance than when using the channel LP11 for both RZ and NRZ modulation schemes.

It is worth noting that several techniques have been suggested to address the impact of environmental attenuation on FSO link. However, the present paper presents a study and evaluation of a DWDM system under various links, namely: (1) SISO-FSO link, (2) EDFA-SISO-FSO link (here, EDFA (or erbium-doped fiber amplifier) is configured as booster amplifier and pre-amplifier), (3) MIMO-FSO link [30] and (4) EDFA-MIMO-FSO link. For all the previous mentioned links have been evaluated under in the worst-case meteorological conditions, and at the end of this evaluation it will be concluded which is the most efficient and suitable for the proposed DWDM system for acceptable performance levels (i.e. maximum Q-Factor ~ 6 dB and minimum BER $\leq 10^{-9}$).

The contributions in this article are as follows:

- design of high throughput 2.7 Tbps DWDM system under a SISO-FSO channel for 90 users;
- the use of EDFA with two configurations (booster amplifier and/or pre-amplifier) in order to assess its impact on the proposed system;
- increasing the number of Tx/Rx antennas in the FSO channel to assess their impact on the proposed system;
- exploiting the EDFA-MIMO-FSO link in the proposed system.

3. SIMULATION SETUP

The present work is an attempt to investigate the performance of a 90 wavelengths multiplexed optical network using DWDM technology, where FSO is considered as a optical communication channel (see Fig. 1).

In Fig. 1, the data rate of each user from [1 to 90] is 30 Gbps, the sequences lengths of data are 1024 bits, the samples per bit are 64 and the numbers of samples are 65536. In addition, the suggested FSO channel of DWDM system suffers from atmospheric turbulences characterized by fog, rain, snow and so on. Table 1 summarizes some values of environmental attenuation. The DWDM transmitter characterized by a power of 30 mW, an operating frequency is 190 THz, an inter-channel spacing is 100 GHz and NRZ modulation scheme, and then the 90-wavelengths DWDM multiplexer has a loss of 0.5 dB. After the DWDM transmitter, the FSO channel is employed; the settings of FSO channel are listed in Table 2. At the optical receiver, the 90-wavelengths DWDM demultiplexer has also a loss of 0.5 dB, subsequently, the data transmission are detected by PIN photodetector and filtered with a low-pass filter of 4 order and a cuttof frequency set at 0.75*bit rate.

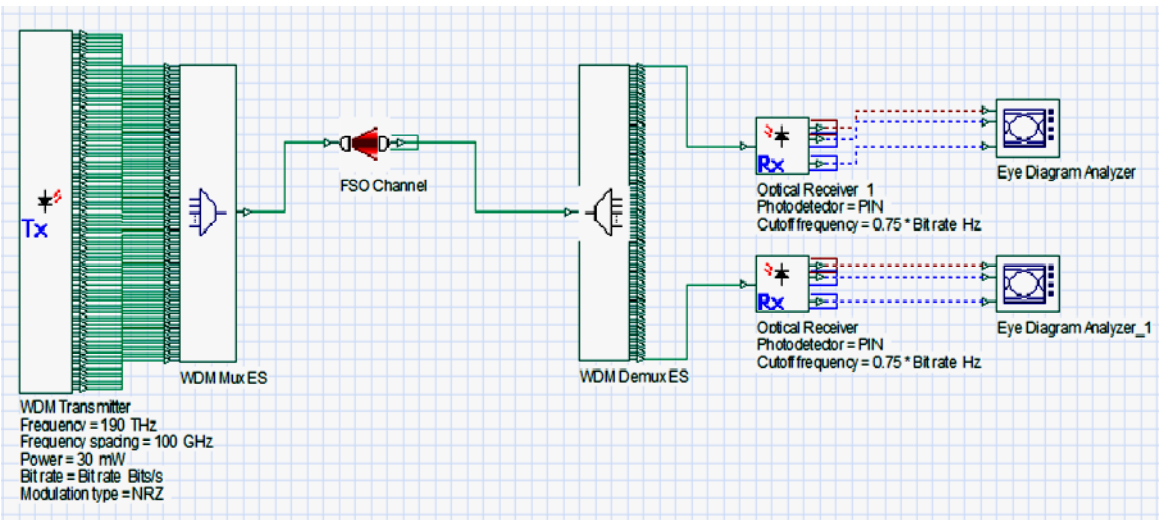


Fig. 1 DWDM system under SISO-FSO link

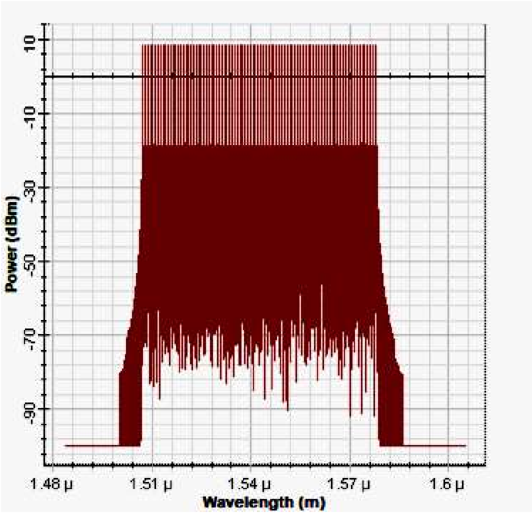


Fig. 2 Power [dBm] vs. 90 wavelengths

The performances of the proposed scheme (see Fig. 1) are evaluated using three different indicators are as follows: the minimum BER performance, the maximum Q-Factor and the optical signal-to-noise ratio (or OSNR) of the optical FSO-link. The eye diagram analyzer is used to observe the original bit sequence, eye diagram, minimum BER and maximum Q-Factor, and the electrical carrier analyzer is also employed to evaluate OSNR performance. Figure 2 illustrates the power of 90 wavelengths after the DWDM multiplexer, which are transmitting under an SISO-FSO.

Table 1 Values of environmental attenuation [28]

Weather conditions	Attenuation [dB/km]
Clear haze	0.233
Light haze	0.55
Heavy haze	2.37
Light rain	6.27
Medium rain, light fog	9.64
Heavy rain, moderate fog, heavy snow	19.28

Table 2 Simulation settings of FSO channel [30]

Settings	Value used
Range	1.2 km
Attenuation	variable
Geometrical loss	Yes
Transmitter aperture diameter	5 cm
Receiver aperture diameter	13.5 cm
Beam divergence	0.25 m rad
Transmitter loss	1 dB
Receiver loss	1 dB
Additional losses	1.2 dB
Propagation delay	1 ps/km

4. RESULTS AND DISCUSSIONS

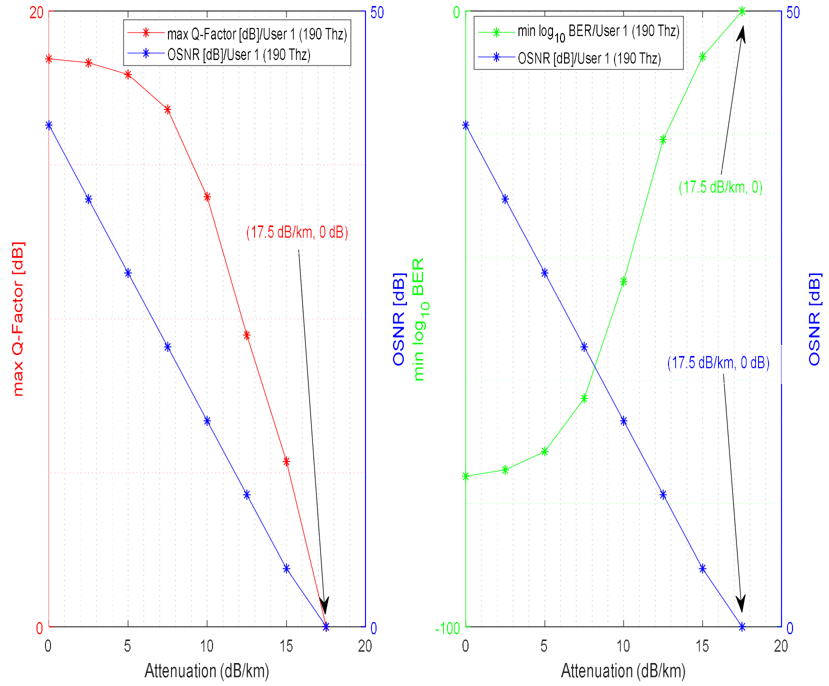
In this section, we present the results and interpretations.

Attenuation effect on an DWDM system under SISO-FSO link

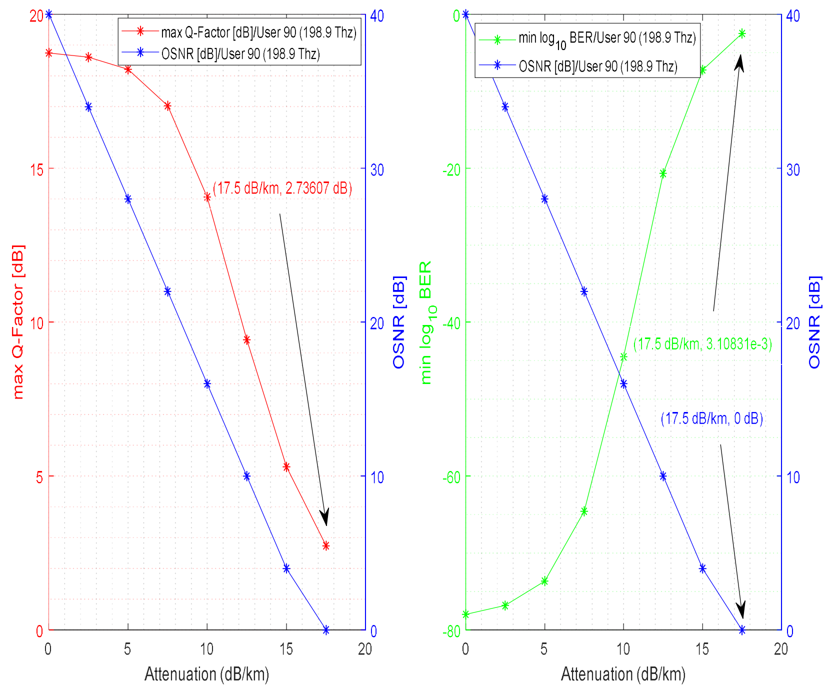
The attenuation or loss of transmitted power is one of the main issues of a transmission DWDM system based on SISO-FSO link. In this sub-section, we examine the attenuation effect on SISO-FSO link in order to determine the best attenuation parameters to ensure good performance of the proposed system (see Fig. 1), with acceptable performance levels, are as follows: maximum Q-Factor ~ 6 dB and minimum BER $\leq 10^{-9}$).

Based on the obtained results in Figs 3 and 4, one can clearly register that the variation of attenuation coefficient for SISO-FSO link can influence the performance of proposed system in Fig. 1. As the attenuation coefficient increases, the maximum Q-factor decreases, the OSNR performance also decreases and, as a result, the minimum BER performance increases. Consequently, the performance of the proposed DWDM system under SISO-FSO link degrades at a higher attenuation coefficient. In addition, the Fig. 4 shows a comparison between the performances of user 1 at 190 Thz and the performances of user 90 at 198.9 Thz in terms of maximum Q-Factor and minimum BER performance. From the obtained results, one can neatly see that the performances of user 1 is the same performances of user 90, this remark confirmed us that the proposed system is more stable for the used wavelengths within [1507.252176973 nm to 1577.855042105 nm] (or frequencies within [190 Thz to 198.9 Thz]). Further, one can observe that the proposed system can operate in five weather zones, namely: (1) clear haze, (2) light haze, (3) heavy haze, (4) light rain, and (5) medium rain and light fog. In conclusion, the system proposed in Fig. 1 cannot operate in the sixth weather zone (Heavy rain, moderate fog, heavy snow) as illustrated in Table 1.

With the interpretations of the obtained results in the two figures 3 and 4, one can notice that the value of the attenuation that one expect to estimate for acceptable performance levels has not yet been selected for the proposed system. To do that, we need to vary the attenuation value around this range [14 dB/km to 15 dB/km]. According to the results recapitulated in Table 3, the attenuation value for SISO-FSO link in the proposed DWDM system, which has been estimated for acceptable performance levels, is: 14.559 dB/km. This value is located in the fifth weather zone.



(a) User 1 at 190 Thz



(b) User 90 at 198.9 Thz

Fig. 3 Max Q-factor [dB], OSNR [dB] and min $\log_{10}$ BER versus attenuation coefficient [dB/km]

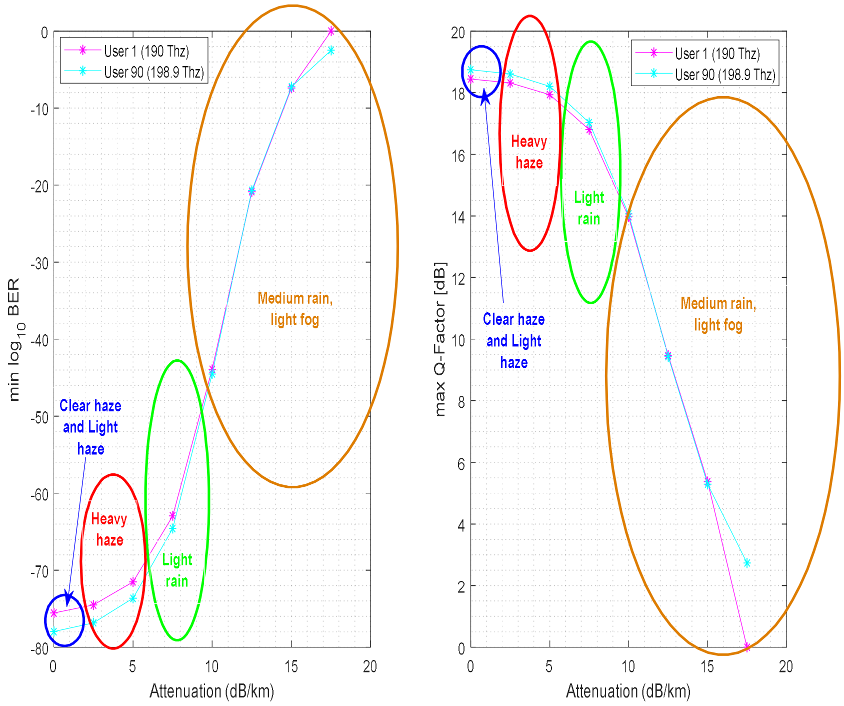


Fig. 4 Max Q-factor [dB] and min $\log_{10}$ BER versus attenuation coefficient [dB/km] in different weather zones

Table 3 Max Q-factor [dB] and min BER performance versus attenuation coefficient [dB/km] : SISO-FSO link

	14 dB/km	14.4 dB/km	14.559 dB/km	14.8 B/km	15 dB/km
Min BER of User 1	3.87535e-12	2.43127e-10	1.05874e-9	8.2571e-9	3.90169e-008
Min BER of User 90	6.53596e-12	3.97291e-10	1.70314e-9	1.2944e-8	5.9787e-008
Max Q-factor [dB] of User 1	6.84268	6.22308	5.98813	5.64463	5.37121
Max Q-factor [dB] of User 90	6.76784	6.14601	5.91071	5.56719	5.29414

In addition, the Fig. 4 shows a comparison between the performances of user 1 at 190 Thz and the performances of user 90 at 198.9 Thz in terms of maximum Q-Factor and minimum BER performance. From the obtained results, one can neatly see that the performances of user 1 is the same performances of user 90, this remark confirmed us that the proposed system is more stable for the used wavelengths within [1507.252176973 nm to 1577.855042105 nm] (or frequencies within [190 Thz to 198.9 Thz]). Further, one can observe that the proposed system can operate in five weather zones, namely: (1) clear haze, (2) light haze, (3) heavy haze, (4) light rain, and (5) medium rain and light fog. In conclusion, the proposed system in Fig. 1 cannot operate in the sixth weather zone (Heavy rain, moderate fog, heavy snow) as illustrated in Table 1.

Finally, the performances of proposed DWDM system under SISO-FSO link in this sub-section are degraded when the value of environmental attenuation is at a higher level. As a solution to this problem, we have recommended the following configurations:

Use the optical amplifier with the SISO-FSO link. As the EDFA type can be used as a booster amplifier and/or pre-amplifier. EDFA is the erbium-doped fiber amplifier.

Increase the number of Tx/Rx antennas of the FSO channel. This term has been recognized in telecommunications by the MIMO (or Multiple-Input Multiple-Output) technique. Therefore, the optical channel becomes as MIMO-FSO link.

Use the optical amplifier (or EDFA) with the MIMO-FSO link.

Attenuation effect on an DWDM system under EDFA-SISO-FSO link

In this sub-section, we examine the attenuation effect on EDFA-SISO-FSO link in order to improve the performance of the proposed DWDM system (see Fig. 1), with two configurations, as shown in Fig.5.
However, we have retained the same parameters of the system proposed in Fig. 1, but in the new analysis we use the optical amplifier (or EDFA) with the following parameters: a gain of 2 dB and a noise figure of 6 dB. At the end, the tests of two new configurations for the proposed DWDM system have been successfully completed and Fig. 6 shows the obtained results of the attenuation effect on the proposed DWDM system under EDFA-SISO-FSO link, around this range [14 dB/km to 15 dB/km].

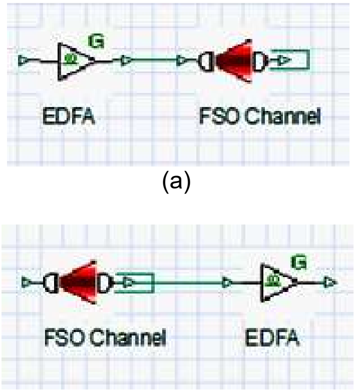


Fig. 5 EDFA-SISO-FSO link configuration: (a) booster amplifier and (b) pre-amplifier

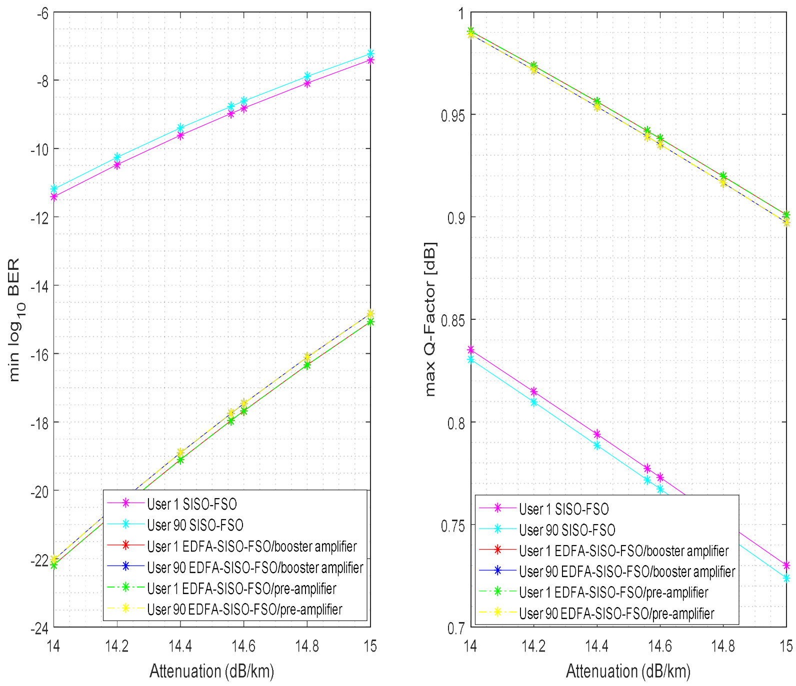


Fig. 6 Max Q-factor [dB] and min $\log_{10}$ BER versus attenuation coefficient [dB/km] in different EDFA configuration

From Fig. 6, one can note that the use of two configurations for EDFA-SISO-FSO link, namely: EDFA as booster amplifier and/or EDFA as pre-amplifier, provided an improvement in terms of the minimum BER performance and the maximum Q-Factor for the proposed DWDM system in Fig. 1. In addition, one can also observe that the EDFA as booster amplifier and/or the EDFA as pre-amplifier have provided the same performances for the proposed DWDM system. Moreover, in the Tables 4 and 5, one can clearly see that the minimum BER performance and the maximum Q-Factor of the proposed DWDM system using EDFA-SISO-FSO link at a 14.559 dB/km, are improved compared to the performances of proposed DWDM system using SISO-FSO link (see the colored column in Tables 4 and 5 compared to the colored column in Table 3). As conclusion, the new attenuation value for EDFA-SISO-FSO link in the proposed DWDM system, which has been estimated for acceptable performance levels, is: 16.23

dB/km (see the green column in Tables 4 and 5). This value is always located in the fifth weather zone of Fig. 4. So, at the end of this sub-section, one can conclude that the proposed DWDM system with EDFA-SISO-FSO link can neatly operate at 16.23 dB/km.

Table 4 Max Q-factor [dB] and min BER performance versus attenuation coefficient [dB/km] : EDFA-SISO-FSO link/booster amplifier

	14 dB/km	14.4 dB/km	14.559 dB/km	14.8 B/km	15 dB/km	...	16.23 dB/km
Min BER of User 1	6.56592e-23	7.91299e-20	1.09013e-18	4.66533e-17	8.60638e-16	...	1.1006e-9
Min BER of User 90	9.44491e-23	1.25982e-19	1.78367e-18	7.84848e-17	1.46565e-15	...	1.76969e-9
Max Q-factor [dB] of User 1	9.78406	9.03851	8.74717	8.31262	7.95954	...	5.98181
Max Q-factor [dB] of User 90	9.74757	8.9879	8.69179	8.25107	7.89379	...	5.9044

Table 5 Max Q-factor [dB] and min BER performance versus attenuation coefficient [dB/km] : EDFA-SISO-FSO link/pre-amplifier

	14 dB/km	14.4 dB/km	14.559 dB/km	14.8 B/km	15 dB/km	...	16.23 dB/km
Min BER of User 1	6.56609e-23	7.91317e-20	1.09015e-18	4.66543e-17	8.60654e-16	...	1.10061e-9
Min BER of User 90	9.44486e-23	1.25981e-19	1.78367e-18	7.84846e-17	1.46565e-15	...	1.76968e-9
Max Q-factor [dB] of User 1	9.78406	9.03851	8.74716	8.31262	7.95954	...	5.98181
Max Q-factor [dB] of User 90	9.74757	8.9879	8.69179	8.25107	7.89379	...	5.9044

Attenuation effect on an DWDM system under EDFA-MIMO-FSO link

In this sub-section, we compare the performances of the proposed DWDM system under MIMO-FSO link (see Fig. 7) and EDFA-MIMO-FSO link (see Fig. 8) with the previous proposed system in Fig. 1. However, to view and assess the performances of the two links, namely: 2x2-FSO link and EDFA-2x2-FSO link, we examine the attenuation effect on them. To do that, we use the same configuration in Fig. 1 with the same SISO-FSO (or 1x1-FSO) channel parameters but we increase the number of Tx/Rx antennas of the FSO channel to 2x2 (see Fig. 7).

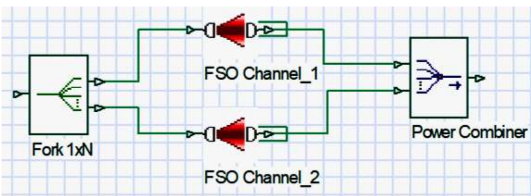


Fig. 7 2x2-FSO link

In addition, to obtain the configuration shown in Fig. 8, we made the 2x2-FSO link cascade with the EDFA module (EDFA parameters are the same in previous sub-section). To test the performances of the proposed links (see Figs. 7 and 8), the variation of attenuation effect is around this range [14 dB/km to 15 dB/km].

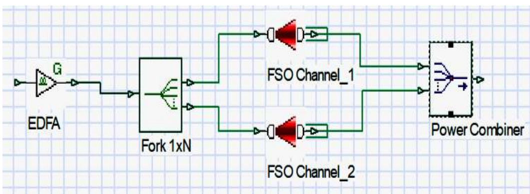
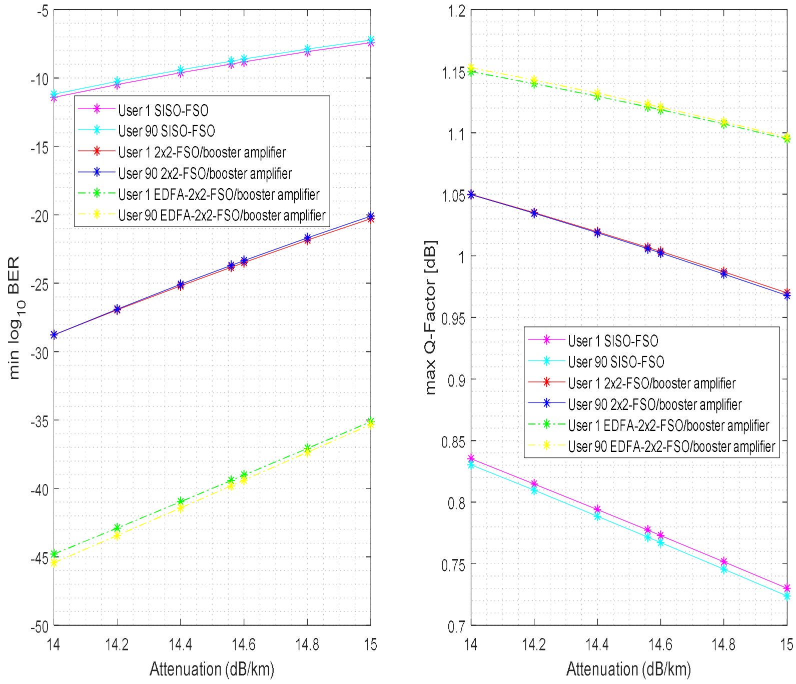


Fig. 8 EDFA-2x2-FSO link

In addition, to obtain the configuration shown in Fig. 8, we made the 2x2-FSO link cascade with the EDFA module (EDFA parameters are the same in previous sub-section). To test the performances of the proposed links (see Figs. 7 and 8), the variation of attenuation effect is around this range [14 dB/km to 15 dB/km].

In collaboration with the obtained results in Fig. 9, it is perfectly clear that the proposed DWDM system under 2x2-FSO link is superior to the proposed system with SISO-FSO link in Fig. 1, in terms of the minimum BER performance and the maximum Q-Factor. Then, one can also observe that the proposed DWDM system under EDFA-2x2-FSO link is more efficient than the proposed DWDM system either on 2x2-FSO link or on SISO-FSO link. However, when we use dual antennas to transmit and receive under FSO link, the Q-Factor increases and the minimum BER performance decreases, although the beamforming gain of the 2x2-FSO link is not high. Here, the beamforming gain of the 2x2-FSO link is 4.



(a) (b)

Fig. 9 Comparing 2x2-FSO link and EDFA-2x2-FSO link than SISO-FSO link: (a) min $\log_{10}$ BER versus attenuation coefficient [dB/km] and (b) max Q-factor [dB] versus attenuation coefficient [dB/km]

For example, at 15 dB/km attenuation value under 1x1-FSO link, the performances of user 1 are as follows: the minimum BER performance is worth to 3.90169e-8 and the Q-Factor is approximately 5.37121 dB (see Table 3). On the other hand, at the same attenuation value under 2x2-FSO link, the performances of user 1 are improved and are as follows: the minimum BER performance is worth to 5.16238e-21 and the Q-Factor is about 9.33228 dB (see Table 6).

Regarding the performance of EDFA-2x2-FSO link for the proposed DWDM system (see Fig. 1) compared to the performances of the used links, namely : 1x1-FSO link and 2x2-FSO link, one can notice that the performances of user 1 at 15 dB/km, are further significantly improved under EDFA-2x2-FSO link, and are as follows: the minimum BER performance is worth to 7.63505e-36 and the Q-Factor is about 12.4426 dB (see Table 7).

Furthermore, as the attenuation value of 15 dB/km under 2x2-FSO link and EDFA-2x2-FSO link has significant performances (see Tables 6 and7) compared to the acceptable performance levels under 1x1-FSO link at 14.559 dB/km (see Table 3), then in this case, we have the opportunity to reach the new attenuation value under 2x2-FSO link and EDFA-2x2-FSO link that we estimate for the previously selected acceptable performance levels (i.e. maximum Q-Factor ~ 6 dB and minimum BER $\leq 10^{-9}$). To do this, the attenuation value must be varied and increased from 15 dB/km to the new value that we expect to estimate.

According to the summarized results in Table 6, the new attenuation value under 2x2-FSO link that has been estimated for acceptable performance levels is equal to 16.98 dB/km (see the green column in Table 6). In addition, for the summarized results in Table 7, one can get the new attenuation value under EDFA-2x2-FSO link that has been estimated for acceptable performance levels, which is equal to 18.65 dB/km (see the green column in Table 7). In addition to the above, the two attenuation values estimated, namely: 16.98 dB/km and 18.65 dB/km are always located in the fifth weather zone of Fig. 4. So, at the end of this sub-section, one can conclude that the proposed DWDM system under 2x2-FSO link and EDFA-2x2-FSO link can neatly operate at 16.98 dB/km and 18.65 dB/km, respectively.

Beamforming gain effect on an DWDM system under EDFA-MIMO-FSO link

However, based on the previous sub-section, when the beamforming gain of FSO link has been set to 4 (see Figure 3.6), the performances of the proposed DWDM system under EDFA-2x2-FSO link are considerably improved. This remark therefore motivated us to vary the beamforming gain of FSO link and see its influence on the performances of the proposed DWDM system under EDFA-MIMO-FSO link.

The purpose of this sub-section is to exploit the proposed DWDM system under EDFA-MIMO-FSO link in the sixth weather zone. To do that, we need to further increase the number of Tx/Rx antennas of the FSO channel in order to reach the new attenuation value at approximately 19.28 dB/km. As indicated in Table 1, the value of 19.28 dB/km is considered as a predefined attenuation value for optical communication systems operating in the sixth weather zone, i.e. heavy rain, moderate fog and heavy snow.

From the obtained results in Tables 4, 7 and 8, one can conclude that the increase number of Tx/Rx antennas of the FSO channel improves the performances of the proposed DWDM system under EDFA-MIMO-FSO link, where: the minimum BER performance is reduced and the maximum Q-Factor is increased. In addition, the new attenuation value estimated after some variation of attenuation coefficient under EDFA-3x3-FSO link for acceptable performance levels is equal to 20.12 dB/km (see the green column in Table 8). Consequently, the proposed DWDM system under EDFA-3x3-FSO link can neatly operate in the sixth weather zone.

Table 6 Max Q-factor [dB] and min BER performance versus attenuation coefficient [dB/km] : 2x2-FSO link

	14 dB/km	14.4 dB/km	14.559 dB/km	14.8 B/km	15 dB/km	…	16.98 dB/km
Min BER of User 1	1.69261e-29	6.49046e-26	1.4828e-24	1.41314e-22	5.16238e-21	…	1.01916e-9
Min BER of User 90	1.71926e-29	8.13505e-26	1.98785e-24	2.05888e-22	7.94484e-21	…	1.64019e-9
Max Q-factor [dB] of User 1	11.2161	10.4611	10.1604	9.70621	9.33228	…	5.99432
Max Q-factor [dB] of User 90	11.2151	10.44	10.1322	9.66813	9.28685	…	5.91691

Table 7 Max Q-factor [dB] and min BER performance versus attenuation coefficient [dB/km] : EDFA-2x2-FSO link/booster amplifier

	14 dB/km	14.4 dB/km	14.559 dB/km	14.8 B/km	15 dB/km	…	18.65 dB/km
Min BER of User 1	1.61108e-45	1.07778e-41	3.78502e-40	8.54698e-38	7.63505e-36	…	1.05008e-9
Min BER of User 90	3.71504e-46	3.79771e-42	1.5662e-40	4.45007e-38	4.74723e-36	…	1.68937e-9
Max Q-factor [dB] of User 1	14.1113	13.4776	13.2108	12.7964	12.4426	…	5.98946
Max Q-factor [dB] of User 90	14.2146	13.553	13.2773	12.8473	12.4808	…	5.91205

Table 8 Max Q-factor [dB] and min BER performance versus attenuation coefficient [dB/km] : EDFA-3x3-FSO link/booster amplifier

	14 dB/km	14.4 dB/km	14.559 dB/km	14.8 B/km	15 dB/km	…	20.12 dB/km
Min BER of User 1	8.22066e-58	8.14834e-55	1.52629e-53	1.56788e-51	8.60724e-50	…	1.07456e-9
Min BER of User 90	3.96019e-59	5.87867e-56	1.30226e-54	1.73413e-52	1.1845e-50	…	1.72829e-9
Max Q-factor [dB] of User 1	15.984	15.5482	15.3594	15.0561	14.7888	…	5.98571
Max Q-factor [dB] of User 90	16.1721	15.7159	15.5183	15.2012	14.922	…	5.9083

5. CONCLUSION

In conclusion, we have designed a 2.7 Tbps high-throughput DWDM system under SISO-FSO channel as an optical back-up link for 5G networks. However, we have observed that the proposed DWDM system under SISO-FSO link is not compatible with the worst-case meteorological conditions. From the obtained results, we have concluded that, the proposed SISO-FSO link adapts with five weather zones (i.e. (1) clear haze, (2) light haze, (3) heavy haze, (4) light rain, and (5) medium rain and light fog) according to the estimated attenuation value for acceptable performance levels, which is: 14.559 dB/km. The objective outlined in this article is to operate the proposed DWDM system under the worst-case meteorological conditions with acceptable performance levels. To do that, we have proposed several links to improve the performances of the proposed DWDM system, and the obtained best link is EDFA-3x3-FSO link with the estimated attenuation value 20.12 dB/km. Finally, we have also concluded that the MIMO technique under FSO channel can decrease the attenuation effect caused by the increased beamforming gain. But this technique poses the problem of energy consumption. In future work, we will consider the processing of DWDM signals propagated under FSO channel using the Beta-average recursive estimator.

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