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Performance Improvement of the Vertical Cavity Surface Emitting Laser Based on Active Hybrid Design and MIMO Configuration

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Abstract—The performance of the Vertical Cavity Surface Emitting Laser (VCSEL) for hybrid optical links SMF/FSO based on different data rates and MIMO configuration techniques was obtained using OptiSystem^{TM} which is close to the results of the experimental system. The developed system was tested with various transmission distances: 20, 30, 40, and 50 km, and in the existence of many configuration kinds and modulations. In addition to that, the hybrid system was estimated with different weather cases: clear, rain, and snow. The results state that the performance of the OOK-NRZ system is better than OOK-RZ system under the same conditions. Also, the performance of the free space link is better than the fiber link for most of the considered link ranges and configurations. For OOKNRZ of the fiber link, it was found that the MIMO 8×8 technique has better system performance than other configurations, and the Q-factor $= 11.39$ and BER $= 5.4 \times 10^{-30}$ for a length of 50 km while for the FSO link, it was found that MIMO 8×8 indicates a high performance for Q-factor $= 12.7$ and BER $= 1.8 \times 10^{-37}$. The maximum FSO link distances under different weather conditions and coupling ratios were found. For BER $\leq 10^{-9}$, in NRZ format for SMF 50 km utilizing MISO 8×1 technology in clear weather for 10 Gbps, 15 Gbps, and 20 Gbps for FSO links, the maximum accessible lengths are 0.6 km, 0.51 km, and 0.43 km, respectively. The process is expanded to include snow conditions for data rates of 10 Gbps, 15 Gbps, and 20 Gbps for FSO links with lengths of 0.4 km, 0.3 km, and 0.26 km, respectively.

1. INTRODUCTION

The recent adoption of Vertical Cavity Surface Emitting Lasers (VCSELs) has been attributed to its affordability compared to other laser types. It features easy coupling with optical fibers and a capability for wavelength adjustment. It has a low current, which results in a wide frequency L-C band and great energy efficiency for the driving current [1]. Use VCSELs as a low-cost source in local networks it is also thought that VCSELs are one of the key sources in contemporary optical communication systems. The benefit of getting rid of defective devices and being simple to couple with fibers are also advantages [2]. VCSELS shows high performance for data rate modulation of more than 40 Gbps, and the 1550 nm wavelength has been intensively improved during these studies because long wavelength and data modulation speed can be used well despite the poor thermal and optical properties as well as bad chromatic dispersion which is a major problem when using the devices in networks optical links of the communication system to examine the NRZ optical signals that are transmitted through the single-mode fiber [3]. The data was transmitted in optical fibers, a ndthe free-space optics were linked in optical communications, where the signals were sent through the OOK-NRZ (Onoff keying - non-return-to-zero) model, with a data rate of 10 Gbps [4].

The free space optics (FSO) system offers a large bandwidth and a low cost of installation, and this idea has recently garnered significant experimental and commercial studies. However, the challenge

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that these systems confront is weather changes like rain, fog, etc. [5]. This leads to a deterioration in the performance of the system, as it is unable to transmit data completely and at a high speed due to attenuation, which is one of the direct problems due to the absorption that occurs as a result of different gases and the dispersion that occurs due to heavy raindrops [6]. The natural logarithmic distribution model, which is suited in the case of weak weather variations, is used to remove atmospheric disturbances from the receiver's optical signals, which results in clear fluctuations. The statistical distribution of weak to strong weather fluctuations is used by the gamma-gamma distribution model to simulate radiation fluctuations [7]. The group scattering performance in free space is improved by lognormal distribution [8]. Therefore, optical fibers are used because the impact of environmental conditions is low, and data can be transmitted at a very high rate and with high efficiency, but one of the most important problems is the high maintenance costs due to the time of drilling and implementation in the event of a defect in the fiber links [9]. Therefore, the single-mode fiber (SMF) and FSO links were used through a hybrid system FS/FSO. In the case of moderate environmental conditions, FSO links are used, and with difficult weather disturbances, the hybrid system converts the signal from free space to optical fibers, and this does not limit the performance of the system because it does not convert optical signals into electrical signals [10].

Research related to the topic of the OOK-NRZ optical communication system operating in free space, the impact of air pressure and temperature-related dispersion were investigated. To reduce dispersion, we increase the input power for the receiver, as the results indicated that there are fluctuations in the dispersion of the optical pulse along the transmission line of 7.5 km, and the amplitude ratio for the duration of the input pulse of 300 fs is estimated at 2.39 [11]. In the free space FSO, the data rate is 2.5 Gbps, and the main reason for the deterioration of the signal attenuation is difficult conditions under the influence of rain. To overcome the attenuation, using Erbium-Doped Fiber Amplifier (EDFA) as a pre-amplifier, as the results of the free space link appear acceptable, the distance is 1675 m. In the case of the loss of the EDFA amplifier, the ndistance is reduced to 1250 m [12]. The optical communication system has been built to withstand natural phenomena since fog creates high attenuation that can reach hundreds of decibels per kilometer, and eliminating attenuation aids communication systems in organizing and managing their networks [13]. Multiple-input multiple-output (MIMO) technique looks the best available since it significantly lowers the bit error rate and the likelihood of interruption, which enhances the system's performance in dense fog [14]. This research using the NRZ format shows the highest data rate reached 10 Gbps under different conditions for SMF 20 km in the case of the FSO link, for clear weather conditions, at bit error rate (BER) of 10^{-9}, 1.25, 2.5, 5, and 10 Gbps data rates provide maximum link distances of 0.23 km, 0.18 km, 0.15 km, and 0.13 km, respectively. Under rainy conditions, the distances reduce to 0.2 km, 0.16 km, 0.14 km, and 0.12 km for the same data rates [15].

The use of optical amplifiers EDFAs in all cases was mentioned above; and the detailed characteristics of the laser were not discussed; and the wavelength and optical power were considered. The work discusses the transmission of data through VCSEL with a temperature of 25°C, which is characterized by low cost, and the work of simulating VCSEL and a passive optical network without the use of an EDFA optical amplifier. The use of data rates of 10 Gpbs & 20 Gpbs increases the efficiency of data transmission under conditions of clear weather, rain, and snow, attenuation of 3 dB/km, 10 dB/km, and 20 dB/km. The optical energy is divided. 80% is spread in free space, and the remaining part is spread in the optical fiber links from the optical receiver. The limitation of their work is a single channel. In contrast, our suggestion involves utilizing both free space and fiber optic channels. This approach would enhance data rates at the transmitter, introduce diversity at the receiver, and allow the receiver to capture multiple signal copies, thereby lowering the bit error rate (BER).

The rest of the research paper is organized as follows, in Section 2 hybrid links SMF-FSO system simulation by optisystem, as the results of the program approximate the experimental results because they are more realistic, in Section 3 results obtained and discussed under environmental conditions, in Section 4 conclusion, concepts, and texts reviewed.

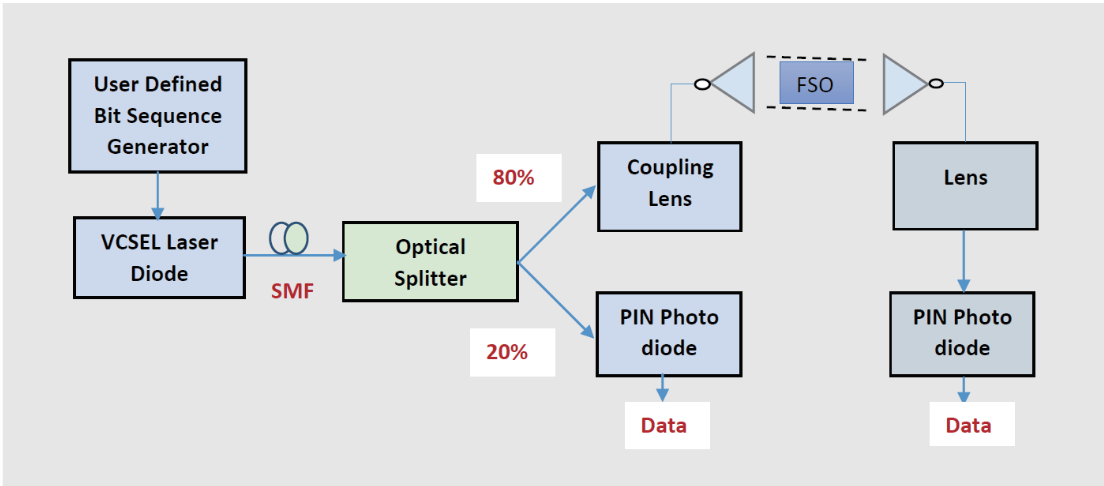


Figure 1. Schematic diagram of the SMF-FSO hybrid link.

2. HYBRID LINKS SMF-FSO SYSTEM SIMULATION

Figure 1 is a graphic illustrating the FSO/Fiber optic (FO) hybrid link's intricate operation while it is affected by the weather. User Defined Bit Sequence Generator (UDBS) in the system defines 1024 bits to see the sequence of output bits through the eye diagram through the non-return-to-zero (NRZ) and return-to-zero (RZ) format, and then they are sent as electrical inputs to the VCSEL laser diode. The generated optical data is sent through SMF to achieve the greatest distance for optical data transmission through the optical fiber. A convex lens transmits 80% of the optical fiber output into free space, which accounts for a significant portion of optical data transmissions, and a PIN photodiode detects the remaining 20% of the power.

Use OptiSystem simulation to study the optimization of optical fiber length by Q factor and BER in NRZ format and RZ format using several MIMO, single-input multiple-output (SIMO), and multiple-input single-output (MISO) techniques and finding the best techniques and increasing the data rate to 20 Gbps under the effect of attenuation 3 dB/km, 10 dB/km, and 20 dB/km when fixing the temperature of 25°C for VCSEL. Table 1 list the value of this research's basic parameters, including optical laser (VCSEL), optical fiber, and FSO link [15].

3. RESULTS OBTAINED AND THEIR ANALYSIS

3.1. Case One

In this case, the proposed system was tested under different transmission distances (20, 30, 40, and 50 km), in different environmental conditions under the influence of 10 dB/km attenuation which indicates rain weather. Based on the User Defined Bit Sequence Generator (UDBS) 1024-bit sequence at a 10 Gbps data rate, the suggested system design shown in Fig. 2 has been simulated using OptiSystem^{TM}.

The current proposed hybrid system is enhanced for the work done in [15]. The previous results indicate that at the length of 20 km for a fiber link in NRZ format, the Q-factor was 7.01 and BER $= 1.2 \times 10^{-12}$, while in the case of FSO with 0.1 dB/km, the Q-factor was 7.5; BER $= 1.99 \times 10^{-14}$ for the single channel (SISO) represents previous work; and the maximum reach distance of SMF is 20 km by 10 Gpbs transmission for [15]. The hybrid system was created using cutting-edge technology to enhance optical signal transmission quality and boost data transmission rates in transmission lines.

In this work, two-modulation schemes have been suggested which are OOK-NRZ and OOK-RZ with different MIMO configurations. In the NRZ format of the fiber link, it was found that all the

Table 1. Parameter values for the VCSEL-SMF-FSO link.

Input Parameters Description	**Value**
VCSEL Laser diode	
Differential gain (GN)	$2.152 \times 10^4\,\mathrm{s}^{-1}$
Carrier lifetime at threshold (τe)	1.21 ns
Photon lifetime (τp)	19 ps
Carrier number at transparency (Nt)	10.2×10^6
Carrier number at threshold (Nth)	1.21×10^7
Scale factor (F)	9.417 mA/mW
Single Mode Fiber	
Fiber dispersion constant (D)	17 ps/nm/km
Optical wavelength (λ)	1550 nm
Attenuation factor (αf)	0.2 dB/km
Free Space Optic link	
Transmitted aperture diameter (DT)	2 mm
The optical efficiency of a transmitter (τt)	0.75
The optical efficiency of the receiver (τr)	0.75
Beam divergence (θ)	1 mrad
Receiver aperture (DR)	180 mm
FSO attenuation factor (αFSO)	[Clear = 3, rain =1 0, Snow = 20] dB/km
The velocity of light (c)	3×10^8 m/s
PIN Photodiode	
Detector responsivity (η)	0.8 A/W
Dark current (ID)	6 nA
Load resistor (RL)	50 Ω
Temperature (Tabs)	288 K

MIMO, SIMO, and MISO techniques used show better results than the SISO used in the research [15]. As in Fig. 3, the length of the SMF used is 20, 30, 40, and 50 km in a hybrid FO/FSO system where the data is sent to two channels. The first is the optical fiber channel, and the second is the FSO channel, where the data is sent over the FSO channel to the free space of the 0.1 km link under an attenuation of 10 dB/km. In the case of fiber links, the MIMO 8×8 technique indicates high efficiency for Q-factor = 13.49 and BER = 1.68×10^{-41} for a length of 20 km, and when the fiber length is increased to 50 km, it turns out that the MIMO, SIMO, and MISO technologies keep sending signals to the longest possible distance due to the multiplicity of data transmission paths, and the transmission slots are divided equally, as MIMO 8×8 is characterized by high output for Q-factor = 11.39 and BER = 5.4×10^{-30}. In the case of FSO links, it was found that MIMO 8×8 indicates a high spread along the transmission line from 20 km to 50 km, as the data loss rate is lower than in the rest of the cases. The Q-factor = 12.7 and BER = 1.8×10^{-37} for 50 km indicate that it gives twice the distance and a high data transfer rate compared to SISO where the Q-factor = 4.5 and BER = 1.8×10^{-6} for the same transmission distance.

To achieve more system efficiency, the current system has been tested on a high data rate. The proposed system was developed by increasing the data rate from 10 Gpbs to (15 Gpbs & 20 Gpbs) for NRZ format, and the SMF length is 50 km with an attenuation of (10 dB/km) which indicates the effect of rain weather. All types of MIMO 8×8, MISO 8×1, and SIMO 1×8 configuration techniques were tested at data rates of 15 and 20 Gbps, and the results confirmed the superiority of the proposed system over the results of the work performed in [15]. For example, for MISO 8×1 configuration, it was

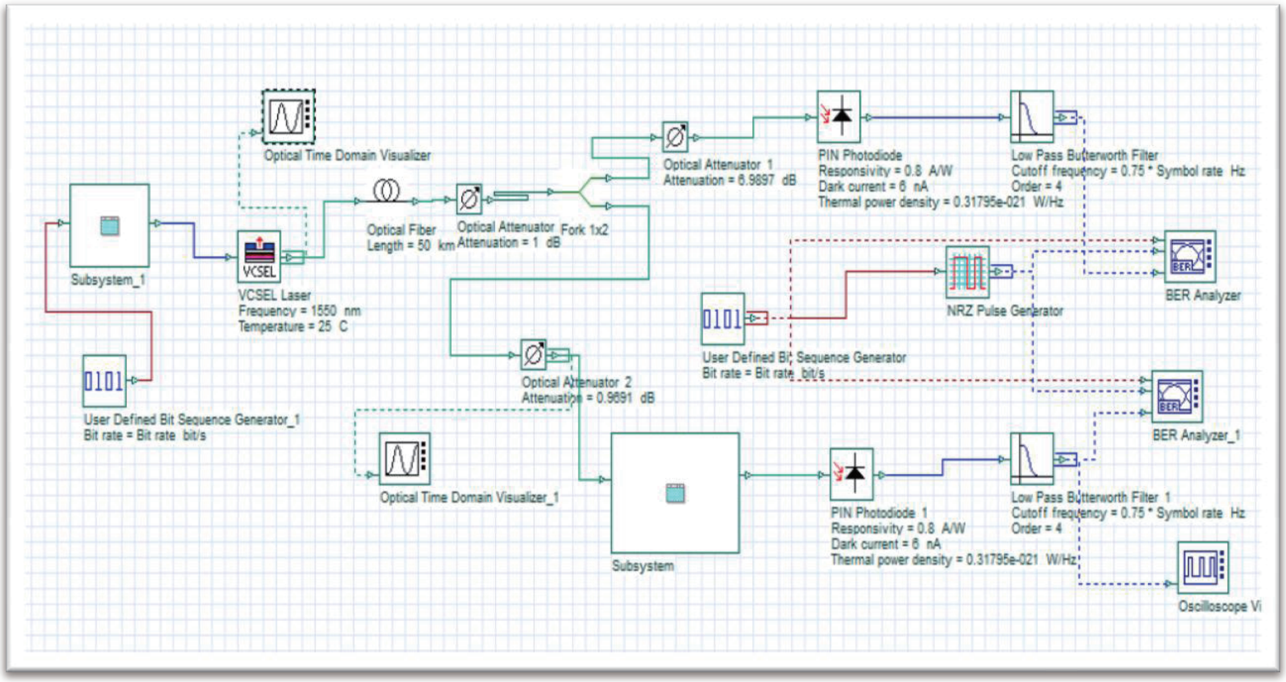


Figure 2. VCSEL simulation of SMF-FSO links using OptiSystem^{TM} simulator.

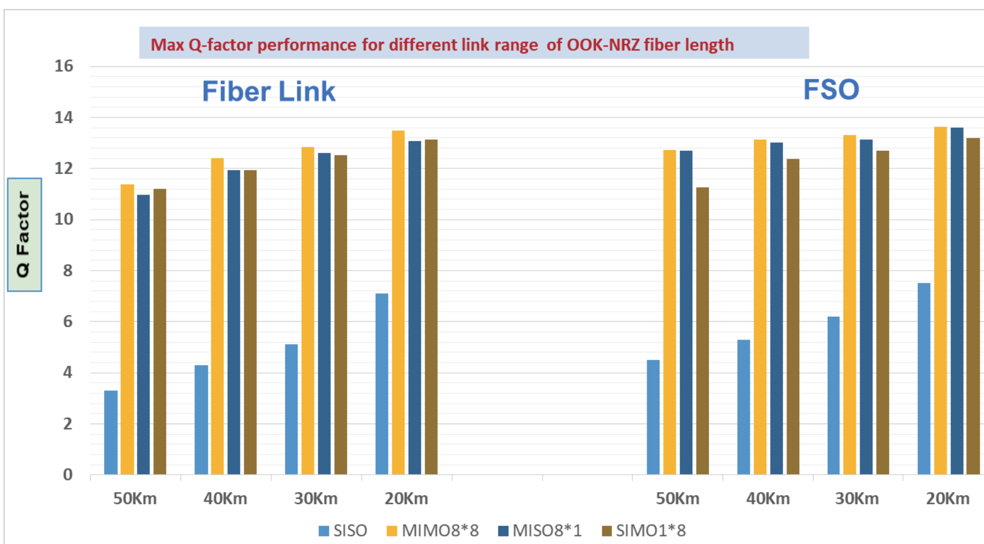


Figure 3. System performance of SMF-FSO links for different link ranges of OOK-NRZ for 10 Gbps data rate.

found that MISO 8×1 has high eye diagram performance in the fiber links for Q-factor $= 9.8$ and BER $= 9.3 \times 10^{-23}$ because it reduces the chromatic dispersion that limits the bandwidth. In the case of the FSO link, the Q-factor $= 11.4$ and BER $= 1.9 \times 10^{-30}$ indicate that the optical data transmission has low errors through eye-opening as in Fig. 4. At a data rate of 20 Gpbs at the same input parameters, MISO 8×1 gives a high data transfer rate in fiber links with Q-factor $= 7.8$ and BER $= 2.1 \times 10^{-15}$. In the case of FSO, the Q-factor $= 9.3$, BER $= 6.3 \times 10^{-21}$, and the information is taken from the eye diagram.

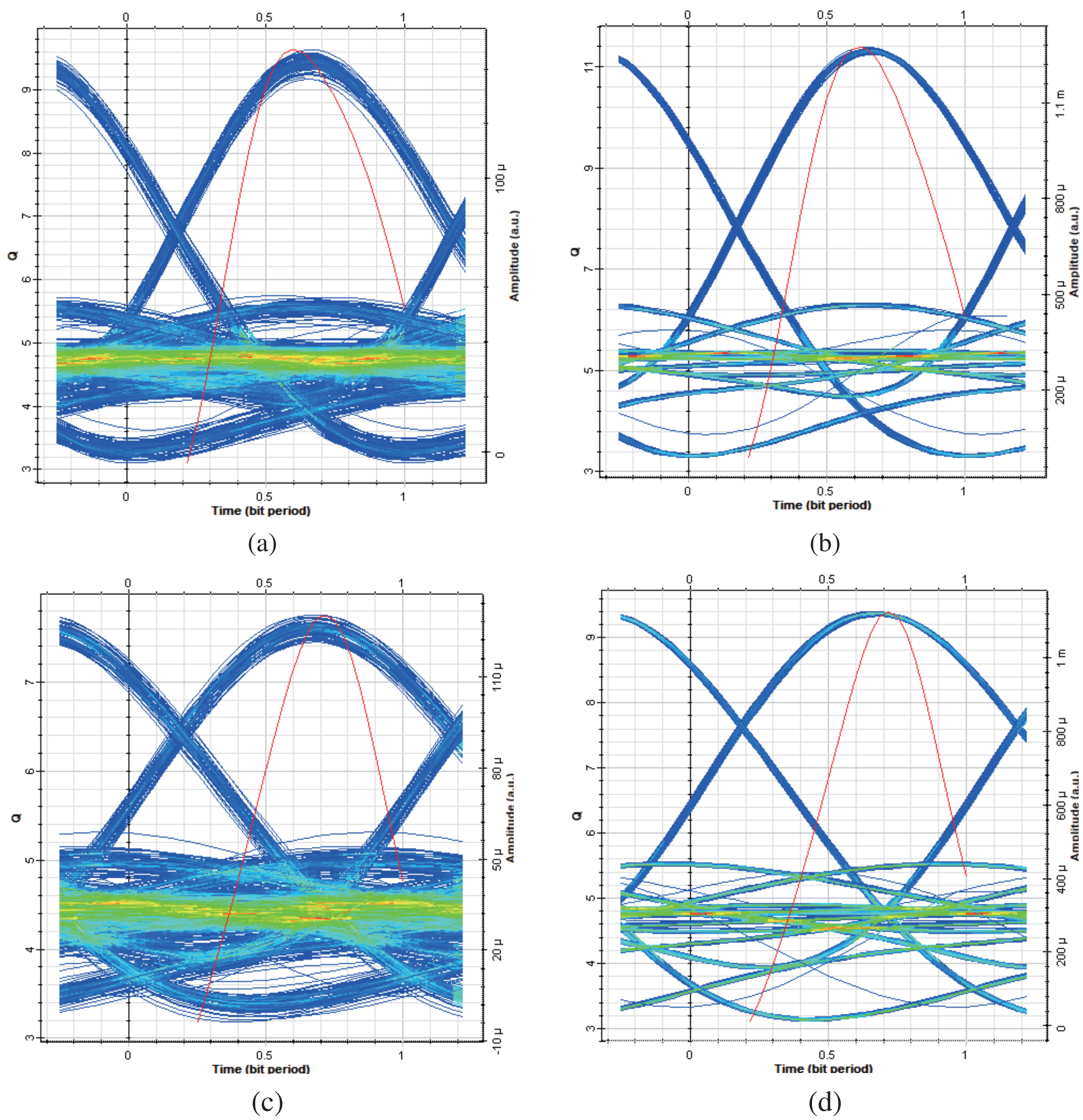


Figure 4. Eye diagrams performance for an SMF link of length 50 km and FSO links of length 0.1 km using the NRZ format and MISO 8×1 (a) data rate of 15 Gpbs for fiber links (b) data rate of 15 Gpbs for FSO links (c) data rate of 20 Gpbs for fiber links(d) data rate of 20 Gpbs for FSO links.

In the RZ format of the fiber link, it is found that the MIMO technique has better system performance in terms of Q-factor than other techniques under the same condition. As shown in Fig. 5, the MIMO 8×8 technique indicates high efficiency for Q-factor $= 11.31$ and BER $= 1.68 \times 10^{-30}$ for a length of 20 km. In the case of FSO links, it was found that MIMO 8×8 indicates a high performance, the Q-factor $= 11.52$, and BER $= 1.8 \times 10^{-31}$. For 50 km distance, the MIMO 8×8 technique also reveals optimum performance where the Q-factor $= 9$ and BER $= 9.9 \times 10^{-20}$ for the fiber link and in the case of FSO, the Q-factor $= 11.10$ and BER $= 3.5 \times 10^{-29}$ for the FSO link at distance 50 km. Table 2 summarizes the system performance results obtained for different transmission distances for the hybrid fiber optical/FSO link for both modulation schemes.

The results mentioned in Table 2 show that all MIMO, MISO, and SIMO technologies are the results of the current work, and they are superior to the previous system represented by SISO technology [15]. It is noted that the performance of the OOK-NRZ system is better than the performance of the OOK-

Table 2. Summarizes the system performance results for different transmission distances for the SMF-FSO link.

Distance SMF	Configuration technique	OOK-NRZ				OOK-RZ			
		Fiber Link		FSO Link		Fiber Link		FSO Link	
		Q-Factor	**BER**	**Q-Factor**	**BER**		**BER**	**Q-Factor**	**BER**
20 km	SISO [15]	7.1	1.2×10^{-12}	7.5	3.5×10^{-14}	6.9	9.9×10^{-11}	7.3	1.2×10^{-10}
	MIMO 8×8	13.498	1.6×10^{-41}	13.640	2.2×10^{-42}	11.319	1.6×10^{-30}	11.524	6.7×10^{-31}
	MISO 8×1	13.08	1.9×10^{-39}	13.594	2.9×10^{-42}	11.114	2.1×10^{-29}	11.619	1.6×10^{-31}
	SIMO 1×8	13.139	6.3×10^{-40}	13.183	5.4×10^{-40}	11.0313	1.1×10^{-29}	11.037	2.1×10^{-29}
30 km	SISO [15]	5.1	6.5×10^{-8}	6.2	9.9×10^{-11}	5	1.8×10^{-7}	6	1.2×10^{-10}
	MIMO 8×8	12.839	7.4×10^{-38}	13.321	3.6×10^{-40}	10.869	1.1×10^{-28}	11.374	4.5×10^{-30}
	MISO 8×1	12.602	9.7×10^{-37}	13.123	1.3×10^{-39}	10.624	7.5×10^{-27}	11.413	1.1×10^{-30}
	SIMO 1×8	12.527	7.7×10^{-36}	12.701	2.7×10^{-37}	10.433	7.9×10^{-26}	10.843	1.2×10^{-27}
40 km	SISO [15]	4.3	5.3×10^{-6}	5.3	9.8×10^{-9}	4	3.1×10^{-5}	5.1	5.5×10^{-8}
	MIMO 8×8	12.413	8.4×10^{-36}	13.119	4.1×10^{-40}	9.743	9.7×10^{-28}	11.119	8.9×10^{-29}
	MISO 8×1	11.931	3.7×10^{-33}	13.015	1.2×10^{-39}	9.998	1.3×10^{-29}	11.2873	1.9×10^{-29}
	SIMO 1×8	11.9324	7.1×10^{-33}	12.378	2.5×10^{-32}	9.823	4.3×10^{-29}	9.8482	9.9×10^{-25}
50 km	SISO [15]	3.3	1.1×10^{-4}	4.5	8.7×10^{-7}	3	6.68×10^{-4}	4.1	5.2×10^{-6}
	MIMO 8×8	11.39	5.4×10^{-30}	12.737	1.8×10^{-37}	9.002	9.9×10^{-20}	11.103	2.3×10^{-29}
	MISO 8×1	10.964	1.9×10^{-28}	12.707	4.3×10^{-37}	8.821	3.4×10^{-19}	11.029	9.4×10^{-28}
	SIMO 1×8	11.206	3.7×10^{-29}	11.267	3.8×10^{-29}	8.767	8.2×10^{-19}	9.003	3.7×10^{-20}

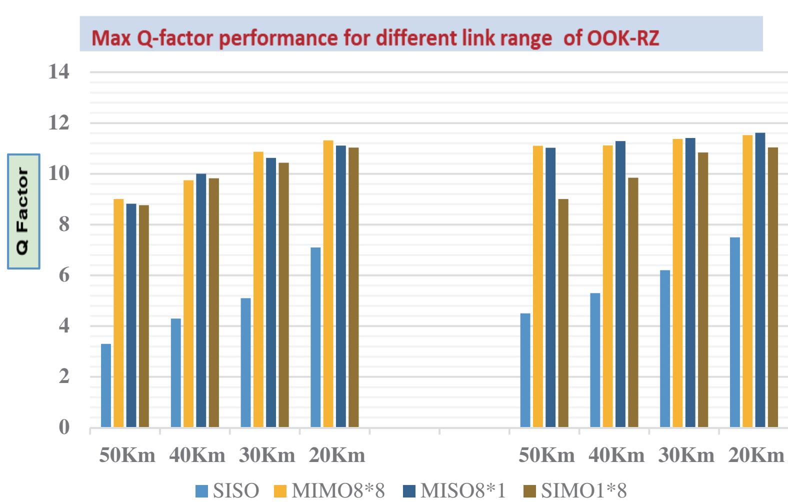
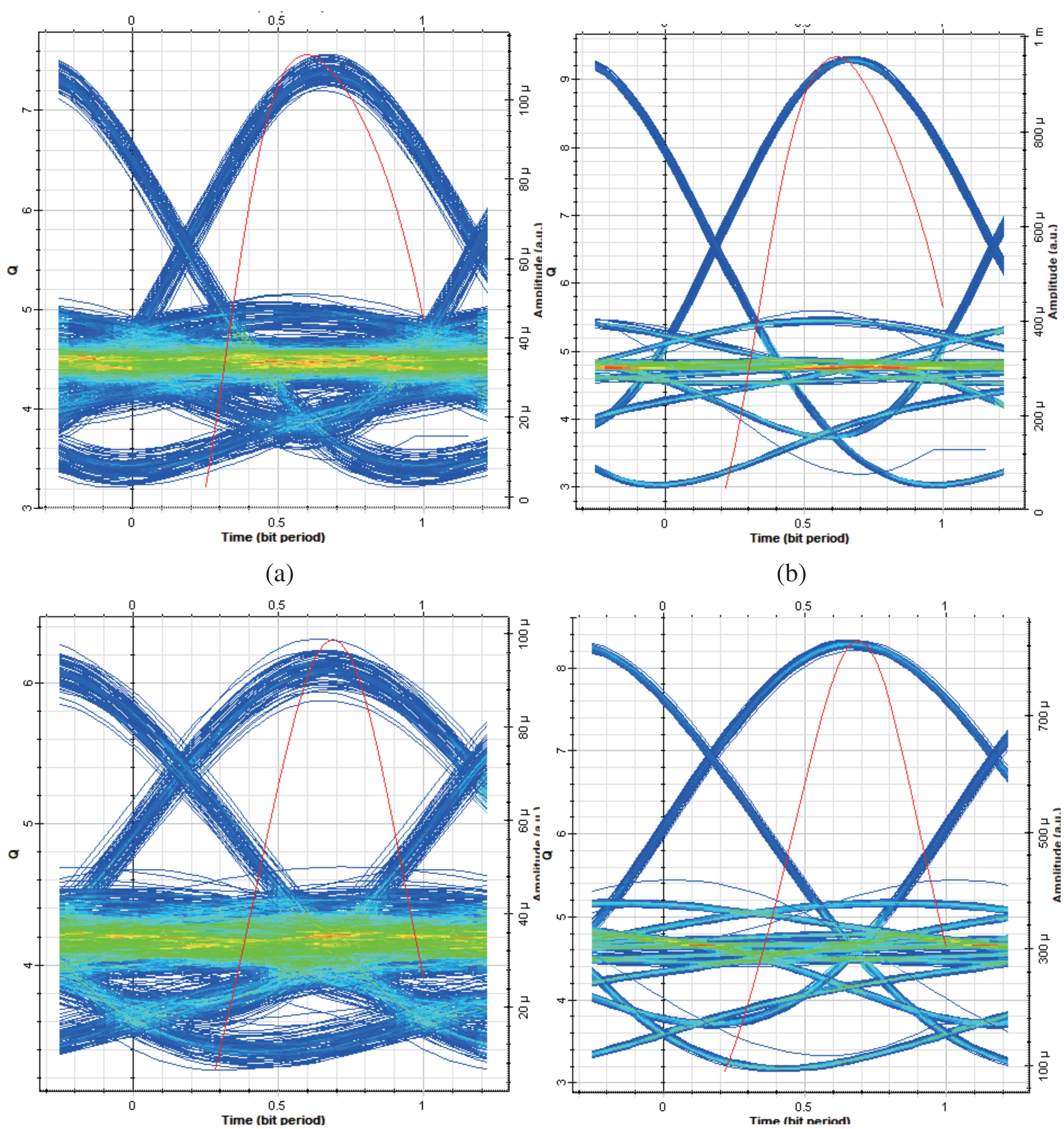


Figure 5. System performance of SMF-FSO links for different link ranges of OOK-RZ for 10 Gbps data rate.

RZ system for all distances used and configuration techniques. Furthermore, the performance of the free space channel (FSO) is better than the fiber link channel under all link ranges considered and system configurations.

Figure 6 explains the eye diagram in RZ format with SMF-FSO links of the length of 50 km under the influence of rain. To increase the system efficiency, the current system has been tested at a high data



(a) (b)

(c) (d)

Figure 6. Eye diagrams performance for an SMF link of length 50 km and FSO links of length 0.1 km using the RZ format and a MISO 8×1 (a) data rate of 15 Gpbs for fiber links (b) data rate of 15 Gpbs for FSO links (c) data rate of 20 Gpbs for fiber links (d) data rate of 20 Gpbs for FSO links.

rate (15 Gbps and 20 Gbps) for RZ format, and the SMF length is 50 km with attenuation of (10 dB/km) which indicates the influence from rain weather. At 15 Gbps data rate for MISO 8×1 configuration, as in SMF for Q-factor $= 7.5$ and BER $= 2.7 \times 10^{-14}$ while in the case of FSO links the Q-factor is equal to 9.2 and BER $= 1.6 \times 10^{-20}$.

3.2. Case 2

For further investigation, the proposed hybrid system was tested under the influence of high data rates (10, 15, and 20 Gbps) and under the presence of different weather conditions (clear, rain, and snow). In addition to that, the links were tested to mimic MISO 8×1 configuration using OOK-NRZ. Calculations

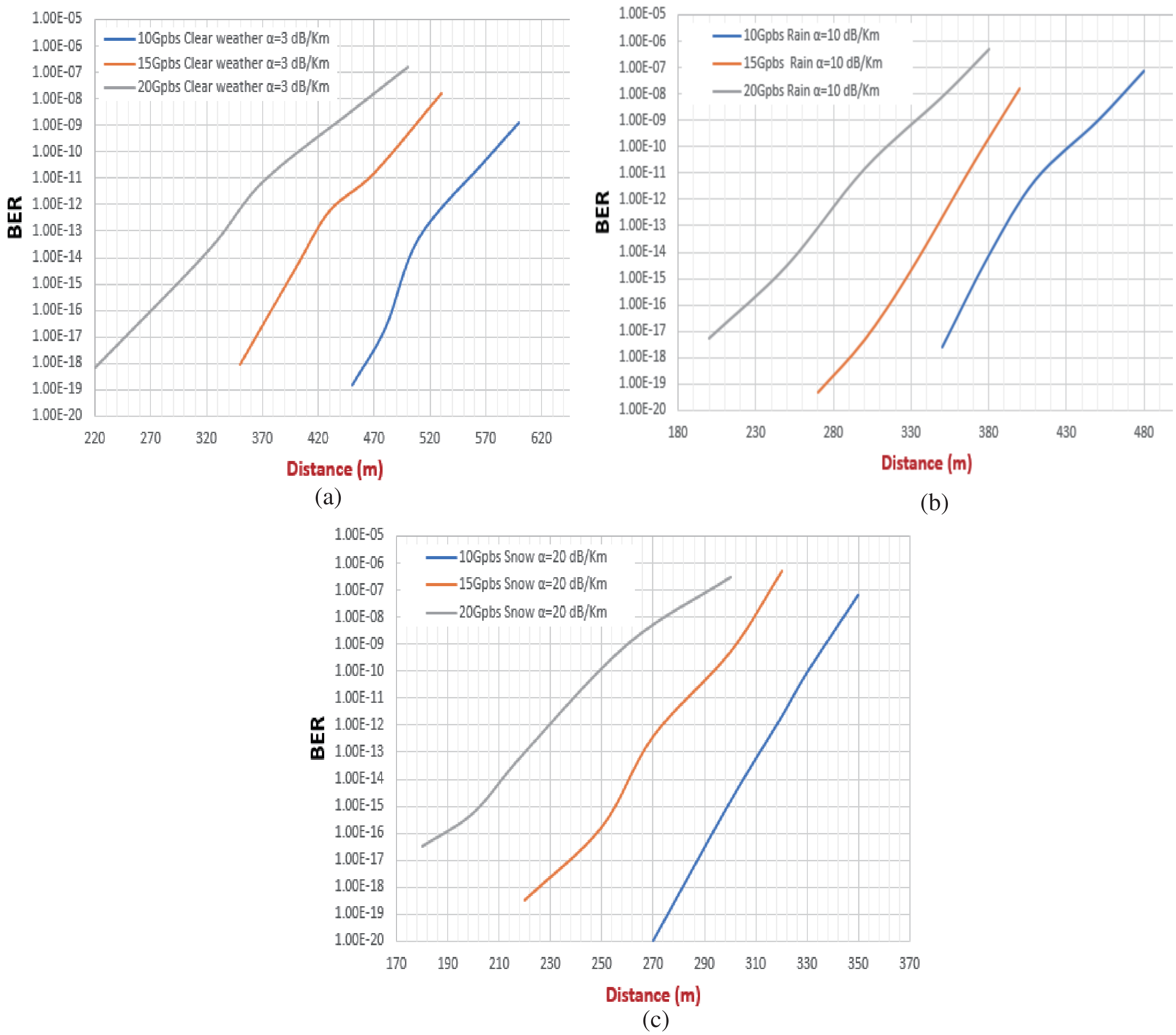


Figure 7. BER Vs transmission distance for FSO links with SMF length 50 km under weather conditions (a) clear, (b) rain and (c) snow.

for the BER range of 10^{-20} to 10^{-5} were also made, and the associated distance was recorded. As shown in Fig. 7, the SMF's length is fixed at 50 km with a tuning data rate. The performance of the link is impacted by the transmission distance, data rate increase, and weather case change. When SMF links are used, the bit error rate rises with the increasing data rate, reaching 20% for fiber-optic links when using FSO links with BER $\leq 10^{-9}$ in the clear weather at various data speeds of 10, 15, and 20 Gbps. In clear weather, the highest distances that may be reached are 0.6 km, 0.51 km, and 0.43 km for 10, 15, and 20 Gbps, respectively. The signals are attenuated to 0.45 km, 0.39 km, and 0.35 km due to the reduction in the distance brought on by the rain effect for the same data rates. When the snow effect is applied, the maximum distances are reduced to 0.4 km, 0.3 km, and 0.26 km, respectively. It was found that the current system has been improved, by increasing the data rate of 20 Gbps instead of 10 Gbps, which is the maximum reached by the previous system, and we visited the length of the SMF to 50 km instead of the distance used in the comparative research of 20 km. Here, the superiority of the current system is shown, in addition to a clear development in the FSO distance compared to [15].

4. CONCLUSION

In the present study, an efficient method has been implemented for hybrid optical links consisting of cascading SMF and FSO based on different data rates and MIMO configuration techniques for VCSEL. The proposed system was tested under different transmission distances (20, 30, 40, and 50 km) and in the presence of different kinds of configuration technology and modulation schemes. Furthermore, the proposed hybrid system was tested under the impact of different weather conditions: clear, rain, and snow. The results state that the performance of the OOK-NRZ system is better than the performance of the OOK-RZ system under the same assumption. Furthermore, the performance of the free space channel is better than the fiber link channel under most link ranges. For instance, for OOK-NRZ of the fiber link, it was found that the MIMO 8×8 technique indicates better system performance than other configurations, and the Q-factor $= 11.39$ and BER $= 5.4 \times 10^{-30}$ for a length of 50 km while for FSO link, it was found that MIMO 8×8 indicates a high performance where the Q-factor $= 12.7$ and BER $= 1.8 \times 10^{-37}$. The results of the proposed system confirmed its superiority over the previous work under the same system inputs. Future work includes design and testing of a hybrid FS/FSO system under challenging environmental conditions with high attenuation based on orthogonal frequency division multiplexing (OFDM).

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