

Article

Enriching Capacity and Transmission of Hybrid WDM-FSO Link for 5G Mobility

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Abstract: A dramatic increase in user and capacity demands has been noted after the COVID-19 pandemic. These challenges have damaged the 5G communication system mobility. Therefore, developing mobility and enhancing capacity transmission of 5G advanced services are the focused research gaps in the current era. In this paper, the free space optics (FSO) link is modeled with wavelength division multiplexing (WDM) technology based optical fiber system, purposing to enhance the 5G capabilities in multi-channel, high distance, and bidirectional transmissions. In addition, the presented hybrid FSO-WDM supported optical fiber network is analyzed for 4, 8, and 16×10 Gbps downlink and uplink transmission. The paper also includes the mathematical discussion of merged fiber length (SMF = 30 km) and FSO (600 m) with improved mobility management. In another contribution, the tolerance against Rayleigh backscattering (RB) noises is developed through various wavelengths of downlink and uplink channels. Finally, we perform the simulation analysis and reliability of the proposed structure for the 5G advanced communication system.

Keywords: multi-channel transmissions; merged FSO-WDM supported optical fiber system; 5G mobility management; Rayleigh backscattering impairments



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1. Introduction

The Wavelength Division Multiplexing (WDM) based optical communication has successfully achieved the bandwidth requirements, particularly for the end users. The WDM enabled optical network technology is shifted to the WDM based passive optical network (WDM-PON), purposing to fulfill end users' high capacity and multi-user demands [1]. However, the existing WDM-PON cannot perform well for large coverage areas and the user's positions where the fiber has to be deployed over hilly areas, multistory buildings, and rivers. The WDM-PON uses the single mode fiber (SMF) for transmitting high data rate and multi-user data up to long distances [2]. This results in degrading the performance of the WDM-PON communication setup because of various losses like nonlinear and phase impairments. Therefore, new solutions are needed to tackle above mentioned limitations. Currently, the researchers are targeting the combined structure of free space optics (FSO), and optical fiber technology, which is an excellent choice for propagating high capacity information [3]. This methodology has organized the 5G communication based services, including long distance transmissions. On the other side, the current integrated optical fiber and FSO based 5G system faces new issues called Rayleigh backscattering (RB), which has bounded the system outcomes and distorts the mobility of 5G technology [4]. Furthermore, for next generation communication networks, the existing system is considered complex and costly. Thus, in order to design a less complex and cost effective model, various research works have been done so far. Researchers are pushing the 5G new radio (NR) to a higher band, specifically the sub-THz spectrum spanning between 100 and 300 GHz, due to recent advances in sub-terahertz (sub-THz) technology [5]. Due to its high data

rates, 5G NR connections in the sub-THz spectrum are becoming more and more common. The high frequencies needed to increase data rates significantly are present in the sub-THz range [6]. The sub-THz band is highly suited for many future 5G applications that demand extremely fast data rates because of its high-frequency characteristics. The high-frequency property of 5G NR sub-THz communication enables the transmission of massive amounts of data across short distances. However, the significant air loss transmission window of 5G NR sub-THz communication limits the wireless transmission range. Due to its sub-THz connectivity limitations, 5G is appropriate for highly populated locations. In sparsely inhabited places, 5G sub-THz connectivity is not ideal because it cannot deliver signals through long-range wireless transmission. Researchers have naturally looked into other high frequency bands, especially the sub-terahertz (sub-THz) band, which is placed above the millimeter-wave (MMW) band, given the expanding use of MMW communications [7]. The sub-THz spectrum can be used in various developing applications that demand high access data rates because of its enormous bandwidth. MMW and sub-THz communications can deliver fast data rates across close ranges due to their properties. The MMW and sub-THz bands of 5G NR are more suitable for short-range wireless transmission than long-range wireless transmission due to their communication restrictions [8]. Aiming the transmission rates at several tens of Gb/s while employing an integrated fiber optics and FSO-based 5G NR system for the simultaneous transmission of 5G MMW and sub-THz signals is a potential strategy for accomplishing the goals of high transmission capacity and long-haul transmission. By fusing long-reach fiber-FSO convergence with short-range 5G wireless extension, the combined fiber optic and FSO enabled 5G NR system is capable of high transmission capacity, high access data rates, long-haul transmissions, and broad service regions. In [9], the authors have shown recent progress on FSO technology and the factors that interpret the outcomes. The study in [10] evaluates the performance of the FSO system in diverse geographical locations. The channel induced limitations are mitigated using orthogonal frequency division multiplexing (OFDM) and digital signal processing (DSP) techniques. A. Bekkali et al. [11] suggested a full duplex and all FSO transceivers and evaluated its performance. The quality factor and electrical power were investigated for FSO links in [12], and simulation analyses were performed using an optisystem. Intensity modulation and direct modulation (IM/DD) FSO link was studied in [13] in terms of bit error rate (BER). Ref. [14] explained the OFDM mode division multiplexing (OFDM-MDM) based FSO transceiver. The dust effect is estimated using the signal-to-noise ratio (SNR) and total power as key measuring parameters. The impact of sandstorm conditions was analyzed in [15] for FSO links. The backhaul network was introduced in [16] for a 5G based FSO system, and the performance is evaluated and compared with a conventional FSO link. In [17], the role of the FSO framework was investigated for the next generation satellite communication system. However, the COVID-19 pandemic has pushed the online application and marketing services and overburdened the already installed FSO setups. In this paper, the free space optics (FSO) link is modeled with wavelength division multiplexing (WDM) technology based optical fiber system, purposing to enhance the 5G capabilities in multi-channel, high distance, and bidirectional transmissions. The major contribution of this paper are summarized as follows

- (1) Long distance optical fiber communication models for 5G services are interrupted by nonlinear issues, so to minimize these issues and provide 5G smart services to the end users, the WDM-FSO link is suggested in this paper.
- (2) The joint structure of the WDM-FSO link is evaluated based on a 600 m FSO range and 30 km FSO volume, aiming to sustain the mobility issue of 5G wired and wireless communication systems.
- (3) The impacts of RB issues are examined and suppressed by applying the presented bidirectional WDM-FSO link with advanced modulation schemes and NR-Sub-THz channels.
- (4) The bidirectional WDM-FSO link performance is evaluated for enhancing the 5G mobility, using mathematical and simulation models in attenuation, received power, different weather conditions, and modulation formats.

The remaining sections of this paper are managed as follows. Section 2 describes the proposed experimental model, the theoretical background of the presented WDM-FSO link is discussed in Section 3, Section 4 mentions the results and discussion of the estimated simulation model designed based on the mathematical model, and the conclusion is summarized in the final section (Section 5).

2. Proposed Experimental Model

The block diagram of the proposed hybrid WDM-FSO link with bidirectional configuration is mentioned in Figure 1. At the input side, a multi-wavelength-based laser source is used, aiming to produce optical pulses. This laser source includes InAs/InP quantum dash laser diode (QDLD), coupler (CP) with 3 dB size, optical circulator (OC), and inducing self-generated optical comb tunable band pass filter (TBPF). The density of QD consists of $2.5 \times 10^{10} \text{ cm}^{-2}$, including 2.4 nm height and 19 nm diameter. In addition, 13 mA operating current is applied to QDLD. The generated optical pulses are then transformed to Mach Zender modulator (MZM), and in parallel, the 64bQAM-OFDM based 5G NR = SubTHz signals are induced and injected into the MZM. The 64QAM-OFDM signals are produced using a series-to-parallel converter (S/P), a cyclic prefix (CP), symbol mapping, a parallel-to-serial converter (P/S), digital-to-analog conversion (DAC), an inverse fast Fourier transform (IFFT). The conjugate symmetric data are made before the IFFT function, further enhancing the 64 OFDM process. After the modulation procedure ends, the data is passed on to the erbium-doped fiber amplifier (EDFA) to amplify the signals before further transmission. The amplified channels with 50 GHz spacing are received by a WDM multiplexer (WDM-Mux) and propagated over SMF/FSO link (15 km SMF + 600 FSO + 15 km SMF). The 64QAM-OFDM demodulation is connected to the end side of the described fiber FSO system in the final stage. All of the important parameters, including P/S and S/P converters, QAM demapper, CP removal, FFT, and ADC, are present in this block. The list of required parameters for investigating the presented model performance and simulation outcomes is mentioned in Table 1.

Table 1. List of required parameters for evaluating the hybrid WDM-FSO outcomes.

Name of Parameter	Description of Parameter
Length of fiber	15 km + 15 km
Range of FSO	600 m
Downlink speed	10 Gbps
uplink speed	2.5 Gbps
WDM mux bandwidth	0.6 nm
Modulation format	64QAM-OFDM
Temperature for SMF	300 K
SMF dispersion	17 ps/nm/km
Dispersion slop	0.075 ps/nm ² /k
Attenuation for clear weather	0.4 dBm/km
Attenuation of rainy weather	6 dBm/km
Attenuation of foggy weather	9 dBm/km
Insertion loss	2 dB
Filter order	2

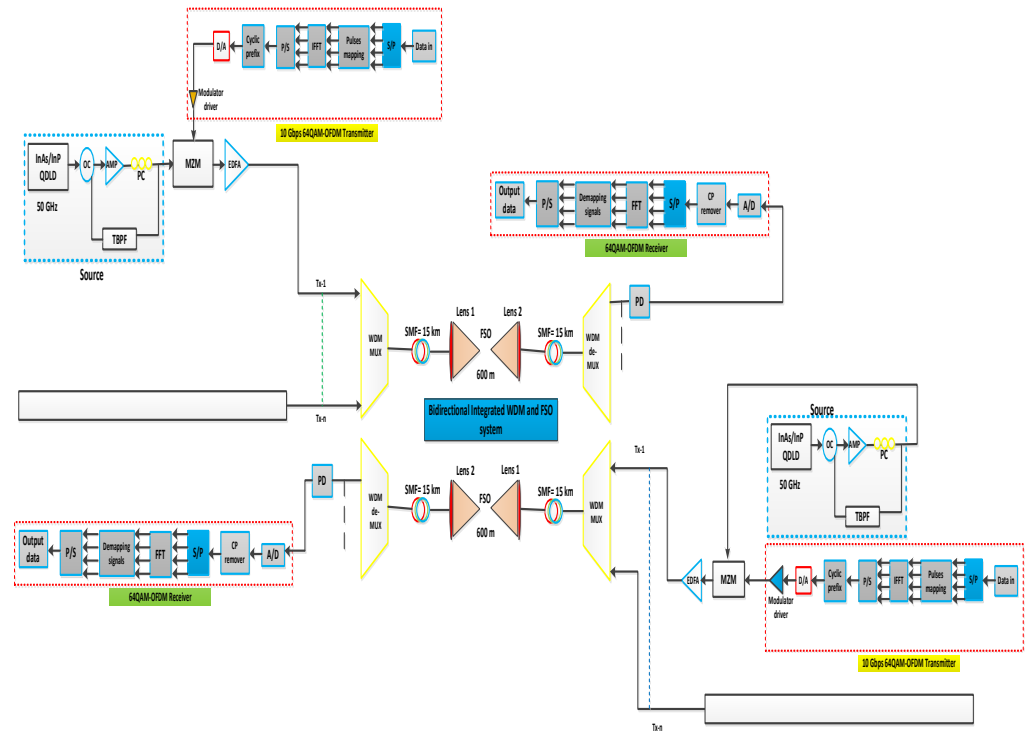


Figure 1. Bidirectional hybrid WDM-FSO link presented model.

3. Theoretical Background

The mixed FSO and fiber link system is introduced in this paper, purposing to minimize the nonlinear issues and FSO related impairments like RF alignment issues, FSO pointing errors, and Co-channel interference. This section includes the analytical calculations for the proposed FSO and optical systems. The channel model of FSO is defined [18,19] as

$$F_{ch} = \psi_a \psi_p \psi_l. \quad (1)$$

where the F_{ch} presents the FSO channel, ψ_a , is the atmospheric turbulence loss, ψ_l is the geometric loss, and the ψ_p is the FSO pointing issues. Three components are considered for optical signal transmission [20]. (1) Line of sight component. (2) Line of sight coupled with the scattered component. (3) Independent scattered component. The power distribution function (pdf) for free space is expressed [21–24] as

$$f_{F_{ch}}(F_{ch}) = B \sum_{n=1}^{\beta_m} a_n F_{ch}^{\frac{\alpha_m + n}{2} - 1} N_{\alpha - n} \left(2 \sqrt{\frac{\alpha_m \beta_m F_{ch}}{\gamma \beta_m + P'}} \right) \quad (2)$$

and B means

$$B = \frac{2\alpha_m^{\alpha_m/2}}{\gamma^{1+\alpha_m/2} \varphi(\alpha_m)} \left(\frac{\gamma \beta_m}{\beta_m + P'} \right)^{\beta_m + \alpha_m/2} \quad (3)$$

where α_m is the large scale scattering process, β_m is the fading parameter, γ is the independent scattering component, and $\varphi(\cdot)$ represents gamma function. The p' is defined as

$$p' = p + 2\tau b_0, \quad (4)$$

where the p is the power for the first line of sight component and $2\tau b_0$ is the coupled line of sight and scattered component. The parameter a_n is further explain [25] as

$$a_n = \left[\frac{\beta_m - 1}{n - 1} \right] \frac{(\gamma\beta_m + p')^{1-\frac{n}{2}}}{(n-1)!} \left(\frac{p'}{U} \right)^{n-1} \left(\frac{\alpha_m}{\beta_m} \right)^{\frac{n}{2}} \quad (5)$$

where β_m is the fading element, α_m is the effective number of large scale scattering process. The transceiver and structural ways condition the FSO system performance; this leads to FSO pointing impairments, and it is calculated in terms of PFD [26,27] as

$$f_{\psi_p} = \frac{u^2}{A_0 u^2} (\psi_p)^{u^2-1}, 0 \leq \psi_p \leq A_0 \quad (6)$$

where A_0 is integrated optical power function, u is related to jitter deviation and equal to $\frac{\omega_z}{2\sigma^2}$. The data-carrying laser beam's width is denoted by ω_z . The statistical analysis of FSO pointing errors, turbulence fading, and co-channel interference is expressed as

$$f_{F_{ch}}(F_{ch}) = \int f_{F_{ch}/\psi_a}(F_{ch}/\psi_a) f_{\psi_a}(\psi_a) d\psi_a \quad (7)$$

In Equation (6) the $f_{F_{ch}/\psi_a}(F_{ch}/\psi_a)$ declares the conditional probability. By substituting the Equation (1) to Equation (5) in Equation (6), the CDF of the N channel is defined as

$$f_{F_{ch}}(F_{ch}) = \frac{u^2 B}{2} \sum_{n=1}^{\beta_m} (a_n \left[\frac{1}{A_m} \right]^{\frac{\alpha+n}{2}}) G_{2,4}^{3,1} \left(\frac{F_{ch}}{AB_0 l_l} \right) \quad (8)$$

where $G_{2,4}^{3,1}$ is the Meijer's G function. On the transmitter side, multi-pulse position modulation (MPPM) based intensity modulation direct detection system is used for the FSO system. The electrical filter is installed on the receiver side to remove unwanted signals from the original signals. The output of the filtered signal is calculated as

$$y(t) = R \frac{N}{n} P_R \sum_{n=0}^{N-1} C_n + k(t) \quad (9)$$

The average received optical power, R is the photodetector responsivity and, $k(t)$ is the additive white Gaussian (AWG), C_n is the signal time slot. The transmitter and receiver telescope gains are expressed as

$$G_t = G_r = (\pi d / \lambda_k)^2 \quad (10)$$

G_t is the transmitter gain, G_r is the receiver gain, and d is the diameter. The receiver signal-to-noise ratio (SNR) of the FSO system is estimated as

$$SNR(F_{ch}) = R^2 P_t^2 \left(\frac{\eta B_r}{\lambda_k L} \right)^4 \frac{Mod \log_2 Mod}{2M\sigma_n^2} F_{ch} \quad (11)$$

σ is the variance of channel noise, η is the efficiency, Mod is the modulation order, and M is the number of transceivers. The conditional probability error of the presented integrated optical network and FSO system is calculated [28] as

$$BER(F_{ch}) = \frac{Mod}{4} \text{erfc} [Rp_R(F_{ch}) \sqrt{Mod \log_2 Mod / 2\sigma_k}] \quad (12)$$

where erfc is the error function. The outage probability of the fading channel is calculated as

$$p_{out} = p(SNR) \leq SNR \quad (13)$$

The flow diagram of the presented theoretical model is mentioned in Figure 2, which explains how the mathematical is utilized for the experimental structure.

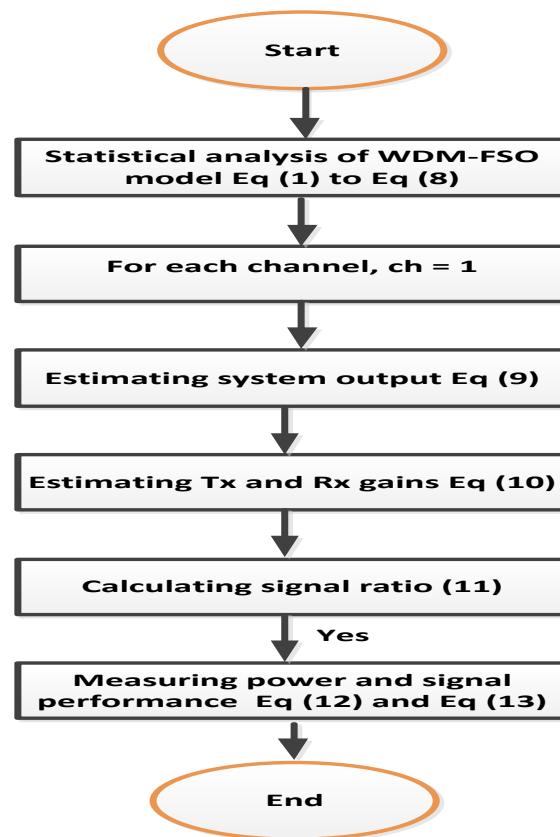


Figure 2. Theoretical model Flow chart for estimating the system performance.

4. Results and Discussion

The presented hybrid WDM-FSO link is modeled and discussed mathematically in previous sections. This section includes the results analysis of the simulation framework based on weather conditions, attenuation, RB losses, received power, FSO range, and fiber length. Figure 3 mentions the consequences of simulation setup for different weather conditions like summer, spring, autumn, and winter as a function of attenuation. The analysis of the presented model is also compared in Figure 3 with conventional WDM and FSO structures. Two types of estimations are described in Figure 3, wherein the first type explains that the attenuation of the WDM, FSO, and WDM-FSO links varies according to weather statuses. Like in summer, by reason of high temperature, the attenuation rate is maximum as equated to winter, autumn, and spring. To equate the attenuation rate of the presented WDM-FSO link against the standard WDM framework for summer, the WDM-FSO link is 3dBm less attenuated than standard WDM technology. The investigation of the Q-factor against various weather statuses (clear, drizzle, rainy, storm, and foggy) is measured in Figure 4 for the presented WDM-FSO link using modern modulation schemes. It is seen from Figure 4 that the WDM-FSO link with 64QAM-OFDM generated 5G NR-SubTHz signals gives an acceptable Q-factor even in bad weather conditions. On the other side, the performance of the WDM-FSO link is degraded at foggy and storm weather statuses using 8, 16, 32, and 63 QAM-OFDM modulation structures. It is also evaluated from the results that the ratio of RB generation increases with rainy, foggy, and storm weather statuses. The investigations of RB suppressed outcomes, and RB included WDM-FSO link outcomes are analyzed in Figure 5. These outcomes are evaluated in terms of Q-factor and transmission length. Figure 5 also compares the achievements of WDM-FSO link transmitting 32 and

64QAM-OFDM based 5G NR-subTHz signals with 600 FSO length and 10 Gbps data rate speed. It is investigated that the Q-factor of the output signal decreases with increasing transmission path of SMF. Furthermore, it is noted that RB suppressed based WDM-FSO link gives the output data with satisfactory Q-factor. Next, it is clarified from Figure 5 that achieving the WDM-FSO system enhances by applying a high modulation format (64QAM-OFDM). Figure 6 describes the output power in terms of SMF range simulation analysis at 50 GHz channel spacing, 600 m FSO range, and 10 Gbps data rate speed. These outcomes are then compared among suppressed RB based signals, and RB included signals. The relation between 64QAM-OFDM and 32QAM-OFDM propagated channels is also discussed in Figure 6. This explains that the desired pulses are attained at the receiver side with less power consumption by installing the 64QAM-OFDM based transmitter. Secondly, it is studied that the propagated channels with suppressed RB consumed less power in matching with RB added channels.

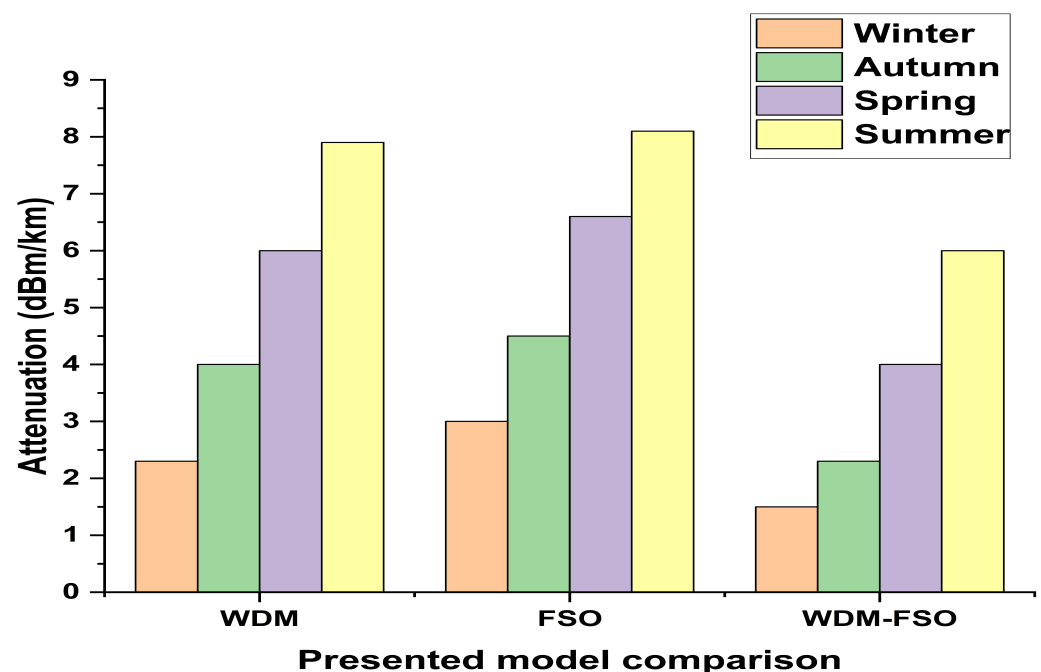


Figure 3. Comparison analysis of standard and presented models against attenuation in different weather conditions.

The analysis of various divergence angles as a function of the Q-factor is estimated in Figure 7. This figure also matches the outlets of 64QAM-OFDM based WDM-FSO link across rainy and clear weather statuses and suppressed RB based outcomes and without RB suppressed outcomes. From investigations, it is found that there is a clear difference among the products of the WDM-FSO link in clear and rainy weather statuses. However, it is evaluated that the presented model with suppressed RB channel has efficient outcomes in both rainy and precise weather conditions. Estimating the divergence angle, it is declared that system performances are degraded with increasing divergence angle. Figure 8 contains the proposed model measurements in eye diagrams. Where Figure 8a declares the eye diagram of suppressed RB based WDM-FSO link with 64QAM-OFDM generated 5G NR-SubTHz channel in clear weather. Figure 8b includes the outcomes of suppressed RB enabled WDM-FSO link with 64QAM-OFDM generated 5G NR-SubTHz signals in rainy weather. Similarly, the outputs of proposed without suppressed RB based WDM-FSO in clear and rainy weather statuses are presented in Figure 8c,d, respectively. In final step of results and discussion the proposed model products are compared with current models as depicted in Table 2, which shows that the presented has better outcomes as correlated to current frameworks.

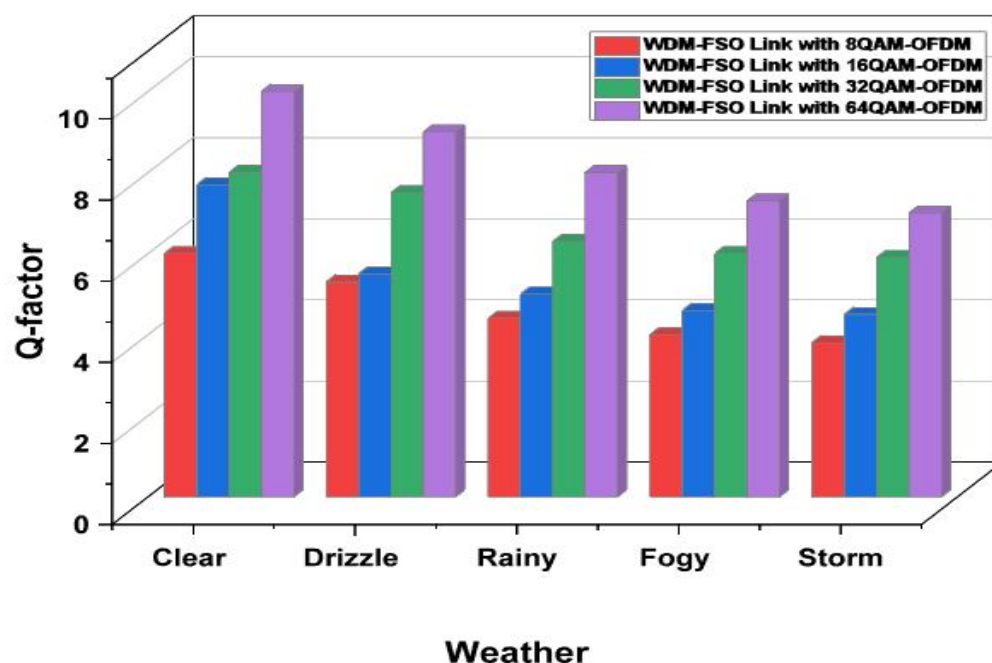


Figure 4. Weather conditions vs. Q-factor simulation investigations for different modulation formats.

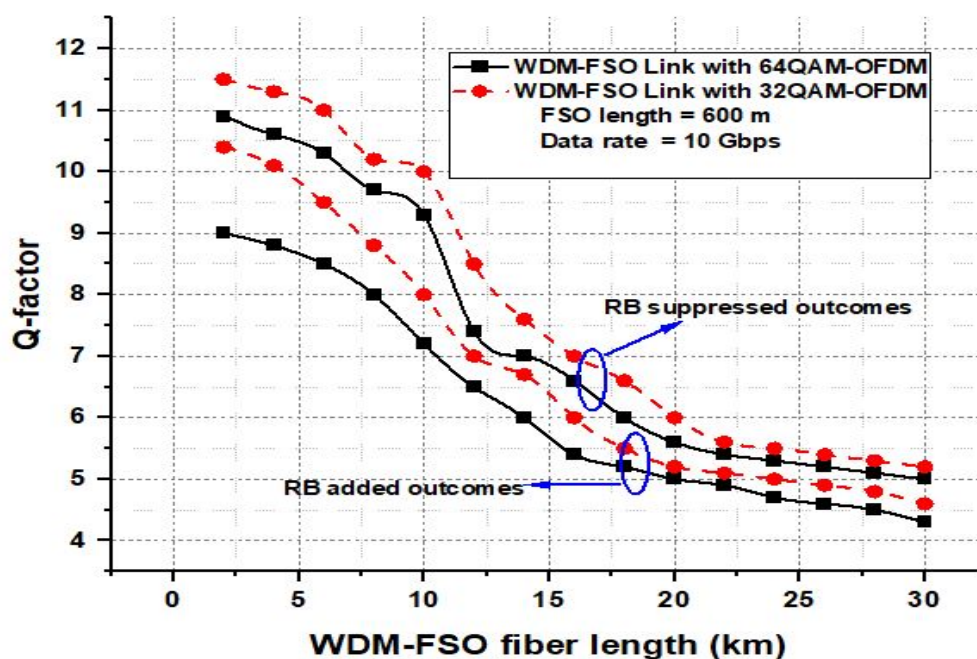


Figure 5. WDM-FSO transmission range as a function of Q-factor estimations.

Table 2. Comparison estimations of presented hybrid WDM-FSO link with current approaches.

Name of Used Technique	[29]	[30]	[31]	Presented Hybrid WDM-FSO Link
FSO range	500 nm	500 nm	300 nm	600 nm
Modulation format	OOK	OFDM	DDOOK	64QAM-OFDM
SMF	20 km	25 km	22 km	30 km

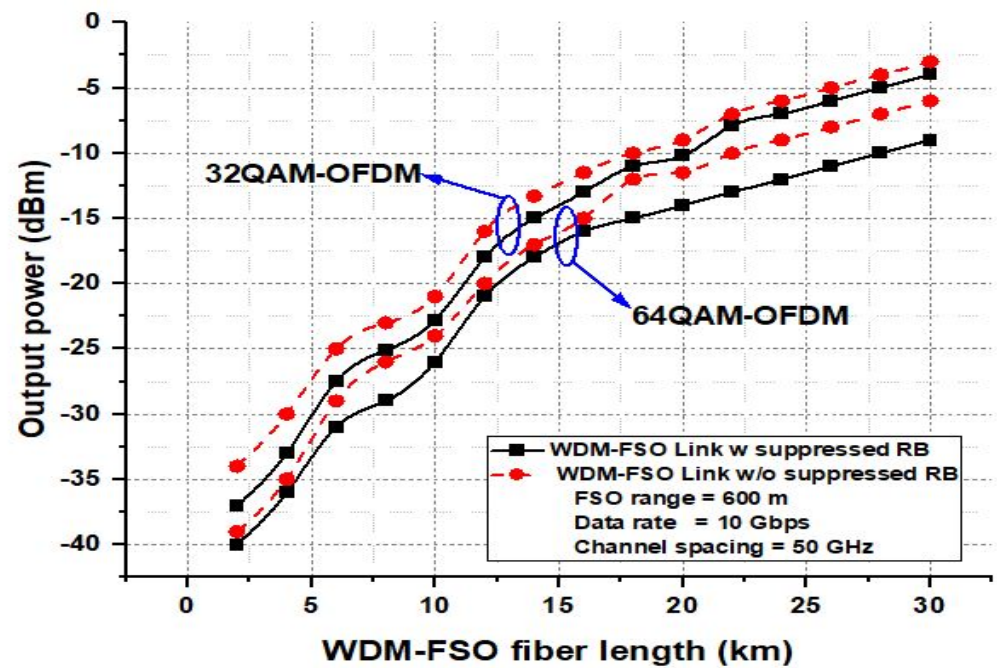


Figure 6. Fiber length estimations against Q-factor for matching the outcomes of suppressed RB based WDM-FSO and without suppressed RB based WDM FSO link.

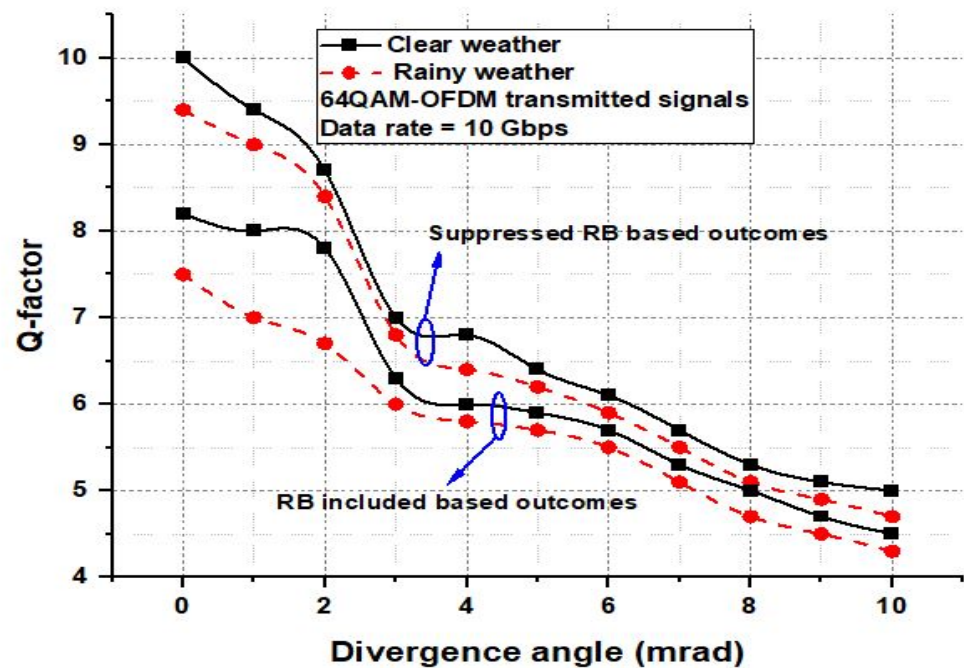


Figure 7. Measuring suppressed and without suppressed RB based WDM-FSO link for 50 GHz channel spacing, 10 Gbps data rate, and 600 m FSO range.

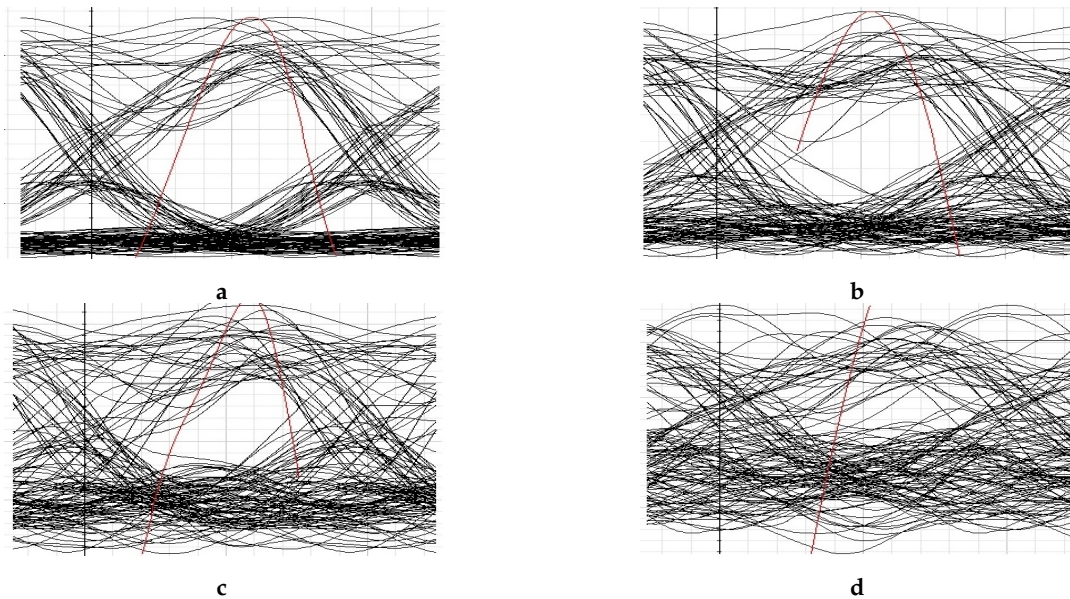


Figure 8. Estimation of eye diagrams; (a) WDM-FSO outcomes with suppressed RB and clear weather, (b) WDM-FSO outcomes with suppressed RB and rainy weather, (c) WDM-FSO outcomes without suppressed RB and clear weather, and (d) WDM-FSO outcomes without suppressed RB and rainy weather.

5. Conclusions

The deployment of extended range communication networks is significant in this era, aiming to entertain the end users with 5G enabled innovative applications and devices. However, the end users based communication networks generate several hurdles (nonlinear losses, high cost, and RB issues). To resolve these limitations, a new approach called hybrid bidirectional WDM-FSO link is tested in this paper, using NR-Sub-THz channels and modern modulation schemes. The presented model is successfully estimated for 600 m FSO length 30 km SMF range based on different weather conditions and attenuation. This study finds that the attenuation varies with the status of weather and modulation formats. Furthermore, it is concluded from the simulation analysis that the presented hybrid bidirectional WDM-FSO link gives satisfactory outlets after addressing the RB issues. The structures of the proposed model can be further optimized for sustaining 5G mobility in the future by applying deep learning advanced generations.

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