

Hybrid WDM/multibeam free-space optics for multigigabit access network

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Abstract Hybrid wavelength division multiplexing/multibeam free-space optics (FSO) is a promising technique to overcome atmospheric attenuation due to tropical rain and to fulfill the growing demand for increased communication bandwidth and scalability. In this study, a hybrid four channel 1.25-Gb/s WDM/multibeam FSO network having four wavelengths with standard downlink channel spacing of 0.8 nm (100 GHz) is proposed. The hybrid WDM/multibeam FSO technique improved the performance of an FSO link in terms of the received power, link distance, data rate, and scalability. The proposed technique provided access data to four end users, each at a data rate of 1.25 Gb/s along an FSO link distance of 1,100 m.

Keywords Hybrid WDM/multibeam FSO · Optical networks · Atmospheric attenuation · Network scalability

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1 Introduction

Free-space optics (FSO) communication offers potentially wide bandwidth and high data rate, which makes this type of communication system highly attractive in meeting the increasing demand for broadband traffic, which is mostly driven by Internet access and high-definition television broadcasting service. In current optical communications, the fiber optics technology with a capacity beyond 1 Tb/s is ubiquitously used, which is achieved using the wavelength division multiplexing (WDM) technology. FSO is totally similar to the fiber optics communication system but with more improvement from the point of flexibility of being fiber free and high speed. An FSO system is a line-of-sight communication system [1]; thus, no laying of fiber optic cables is needed, no expensive rooftop installations are required, and no security upgrades are necessary. In addition to all these advantages, upgrading of the system can be easily performed, and no RF license is required [2]. Currently, the FSO system can transmit large capacity of data at a data rate of 1.25 Gb/s [3]. Although the FSO system has all these advantages, it suffers from degradation from atmospheric occurrences such as absorption, scattering, and nonselective scattering due to large-sized raindrops [4]. The nonselective scattering is considered as the main drawback of the FSO in tropical countries such as in southeast Asian countries. Other parameters that degrade the FSO transmitted power are its physical characteristic such as the installation, location, and increase in the link distance between the transceivers.

Because the FSO system is a free-space communication system, it is subjected to unpredictable atmospheric attenuation, which can vary from a few decibels per kilometer to hundreds of decibels per kilometer [5]. In tropical region such as in southeast Asia, fog and snow are not present; therefore, these factors are not taken into account in evaluating

atmospheric attenuation; however, heavy rain and haze are projected to have major effect on the availability of an FSO link.

The link performance of an FSO communication system with a single-beam transceiver is less efficient during heavy rain. To enhance the link performance, using more than one beam at the transmitter and receiver could be a possible option [6]. The technique of combining more than one beam in a multibeam FSO system reduces the effect of turbulent atmosphere, such as scintillation and loss of power in the detector due to heavy rain [7]. The performance of an FSO system that uses the multiple-beam technique has been studied in terms of geometrical losses, received power, and link margin, regardless of the atmospheric losses [6]. Most of the recurrent physical obstructions such as birds, insects, scintillation, rain, and snow are excluded in the use of the multibeam FSO system, and the system provides a fail-safe operation [8]. In coastal areas, low visibility due to fog can also be a problem; therefore, a solution to this problem is to use a multiple-beam system to maintain higher link availability [9]. In the present study, up to four beams at the same wavelength have been employed in a multiple-beam FSO system because this technique is prominent, as suggested by [6]. The performance of a multibeam FSO system, especially using four beams, has been known to be far greater than that of the one-beam, two-beam, and three-beam FSO systems in clear weather without any atmospheric attenuation. Consequently, performance improvement in using several beams greater than four is negligible [6, 10]. The concept of the multibeam FSO system is the replacement of the single-beam transceiver by multiple-beam transceivers. By this replacement, multiple channels with different attenuation levels in the atmosphere are obtained. A channel with less attenuation will cause less degradation to the transmitted power.

WDM is a multiplexing technique in which multiple optical signals are multiplexed on a single medium using different wavelengths. It is a technique to carry more than one optical signal with different wavelengths. Although the FSO system is a well-studied topic, the advent of the WDM technique and the high demand for broadband communications have become a new study in communication area [11]. This technique is proposed to overcome the limited received power, limited distance, and limited scalability, which are experienced by ordinary single-beam FSO systems. Implementing the WDM technique and multibeam concept in an FSO system results in an increase in the number of end users (EUs) capable of accessing high data rate at low price. To the best of our knowledge, the hybridization between multibeam FSO and WDM technique is proposed here for the first time.

In the WDM-based access, the bandwidth demand has increased rapidly; thus, it is a potential solution for future data transport with regard to all optical wide area networks [12]. In fiber optics communication, WDM is well known and used extensively. Several single-beam FSO WDM transmission systems have been successfully demonstrated [11, 13], where the different wavelengths are carried by one beam. Even though more than one wavelength is used to increase the data rate, after all, this system lies under a single-beam attenuation affect. In the current study, the performance and applicability of the four-beam FSO system in rainy weather are proposed and investigated using WDM. The study is conducted based on simulation using on-site attenuation and rain intensity measurements. It considers the received power, geometrical losses, and atmospheric losses due to heavy rain.

This paper is organized as follows: Sect. 2 demonstrates the architecture of the proposed network. Section 3 is dedicated to the result analysis and discussion, and finally, Sect. 4 concludes the paper and suggests a future work.

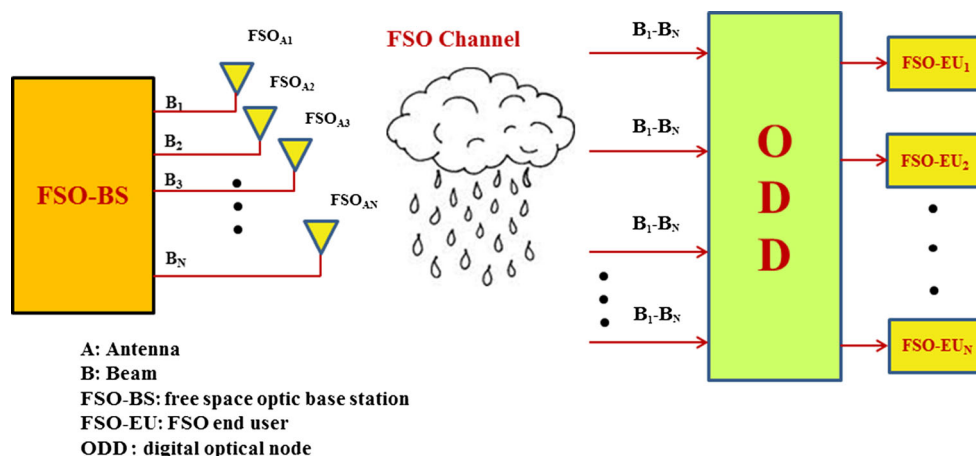


Fig. 1 Hybrid WDM/multibeam FSO network architecture

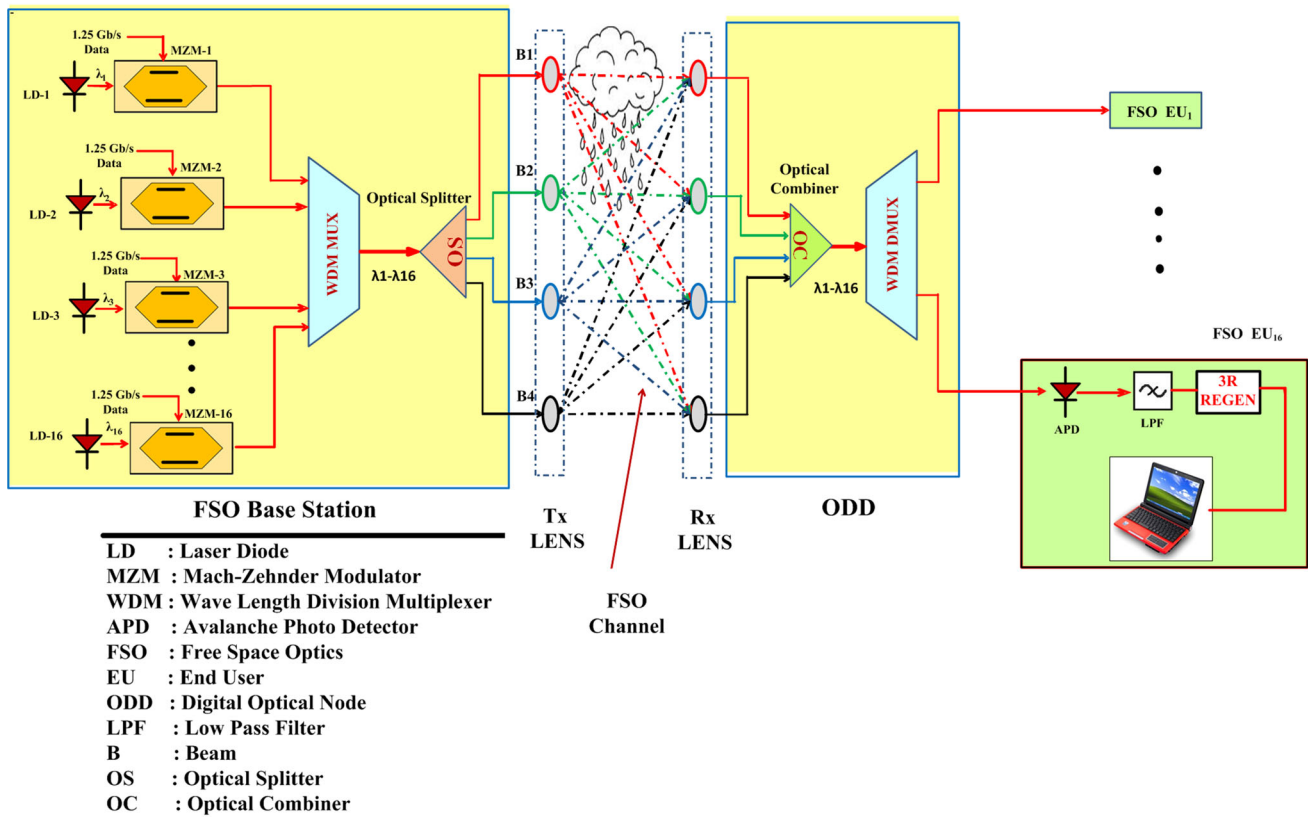


Fig. 2 Detailed block diagram of the hybrid WDM/multibeam FSO layout

2 Layout of hybrid WDM/multibeam FSO network

The general architecture of the proposed hybrid WDM/multibeam FSO network is shown in Fig. 1. It comprises an FSO base station (FSO BS), a free-space optical channel, a digital optical distribution node (ODD), and multiple FSO EUs (FSO EU_S). At the FSO BS, the pseudo-random sequence bit data streams B_1, B_2, \dots, B_N are transmitted into the FSO channel utilizing multibeam transmitters FSO_{A1}, FSO_{A2}, ..., FSO_{AN}. The ODD is responsible for receiving the signals with different wavelengths and thereby distributing them to EU units.

Figure 2 clearly shows that the hybrid WDM/multibeam FSO layout is architecturally structured into four sections as follows: (1) FSO BS, (2) multibeam FSO channel, (3) ODD, and (4) FSO EU_S. The FSO BS is designed with four transmitters, one optical 4×1 WDM multiplexer, one optical splitter, and four spatially diverse lenses. Four laser diodes (LDs) are installed, which produce optical carrier signals at different wavelengths ($\lambda_1, \lambda_2, \lambda_3$, and λ_4), with a transmit power of 7.7 dBm. These downlink wavelengths are selected in the 850-nm band with a channel spacing ($\Delta\lambda$) of 0.8 nm (100 GHz) with standard ITU-T G.694.1 from 850 to 847.6 nm, as shown by power spectrum in Fig. 3.

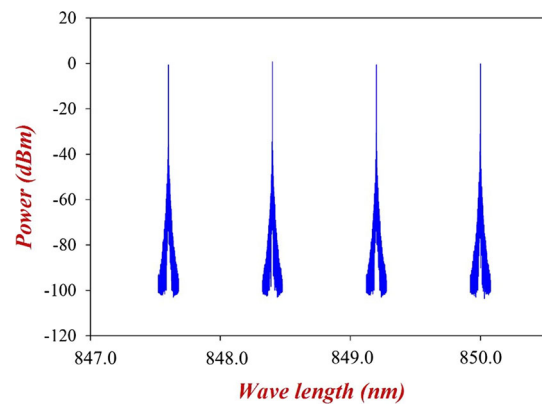


Fig. 3 Power spectrum of transmitted power for the four beams with different wavelengths

In addition to the LD, each transmitter has one Mach-Zehnder modulator (MZM). The data, which consist of binary bits at a data rate of 1.25 Gb/s, are generated using a pseudo-random binary sequence generator and are modulated with laser using the MZM. These data are then optically multiplexed using the WDM multiplexer into one downlink signal carrying the four wavelengths ($\lambda_1, \lambda_2, \lambda_3$, and λ_4), as shown in Fig. 2. The multiplexed signal is split into four

Table 1 Values for average of maximum rain intensity on rainy days, geometric loss, and average attenuation for 7 months

Month/year	Average of max. rain intensity on rainy days (mm/h)	Rain attenuation (dB/Km)	Geometric loss (dB)	Average attenuation for 7 months (dB/km)
Nov 2011	76.1	19.6	29.94	18.5
Dec 2011	64.4	17.0		
Jan 2012	68.8	18.3		
Feb 2012	85.6	21.2		
Mar 2012	77.9	19.9		
Apr 2012	72.5	19.4		
May 2012	54.4	15.7		

Table 2 Typical parameters used in the simulation of the proposed network

Parameter	Value	Unit
Link distance	500–1,200	m
Transmitted power	7.7	dBm
No. of beams	4-beam	–
Operating wavelengths (λ_1 – λ_4)	(850, 850.2, 850.4, 850.6)	nm
$\Delta\lambda$	0.8	nm
Multiplexer	DWDM	–
Atmospheric loss (heavy rain fall)	19.0	dB/km
Geometrical loss	21.94	dB
Data rate	1.25	Gb/s
Bandwidth for each channel	10	GHz
Avalanche photodiode (APD) gain	3	–
APD dark current	10	nA
Receiver sensitivity (S_R)@ 10^{-9} BER	–45	dBm
System loss (L_{sys})	8	dB

beams ($B_1, B_2, B_3,$ and B_4) using the optical power splitter. The four beams are sent to the FSO channel through an optical lens transmitter (T_x). Due to the short spacing between the receiver lenses and diverging effect of transmitted beam, each transmitted beam is received by the four receiver lenses. In total, 16 paths are produced propagating through the FSO channel carrying the transmitted data.

Rain data were collected from November 1, 2011 through May 29, 2012, and the average values of maximum rain rate events for each month were collected as shown in Table 1 and implemented on rain attenuation formula given in Eq. 1.

The FSO channel is subjected to rain attenuation and geometrical loss of 19.0 dB/km and 21.94 dB, respectively. The overall measured FSO transceiver loss is 8 dB. The values of the rain attenuation and geometrical loss were evaluated

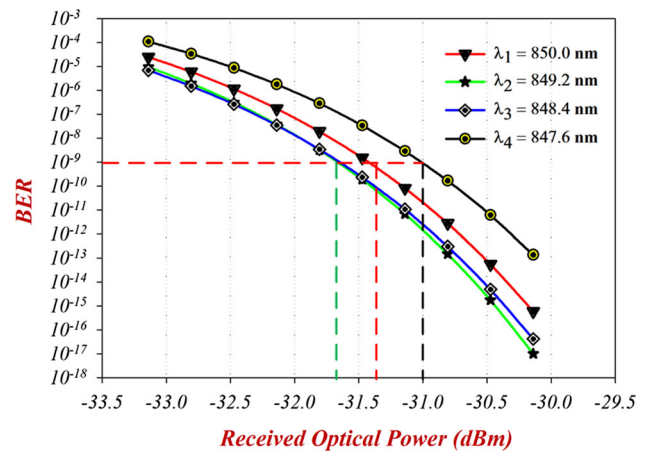


Fig. 4 BER performance of the received optical power at the FSO EUs

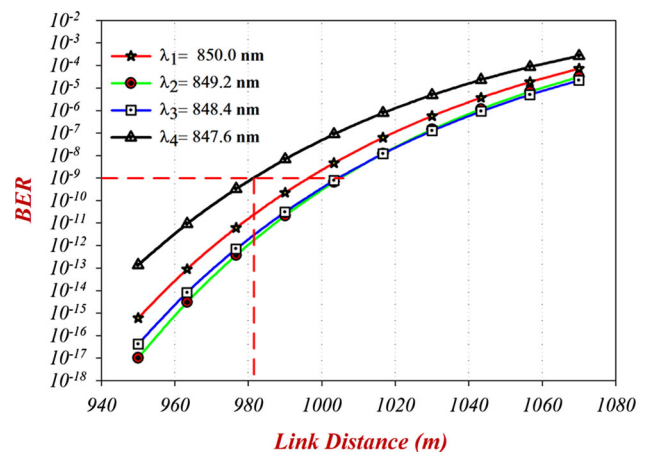


Fig. 5 Optimum link distance achieved by the proposed network

by [1] using expressions (1) and (2), respectively, given as

$$\gamma_{\text{Rain}} = k \cdot R^\alpha = A_{\text{atmos}} \tag{1}$$

where γ_{Rain} —rain attenuation (dB/km); R —rain intensity (mm/h); k and α —rain coefficients; k and α depend on the rain characteristics such as the frequency, rain temperature,

Fig. 6 Eye diagrams for the entire network at link distance of 1,100 m

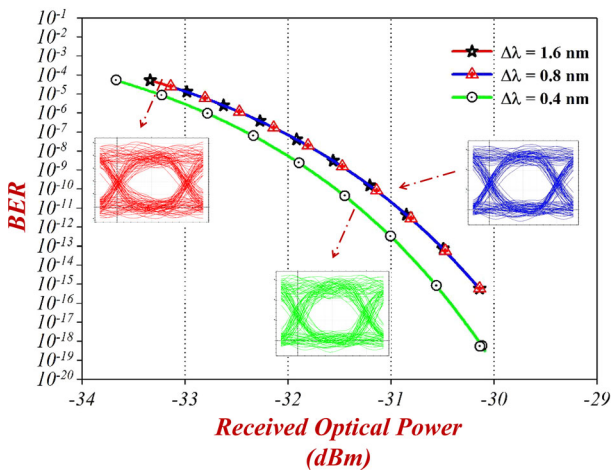
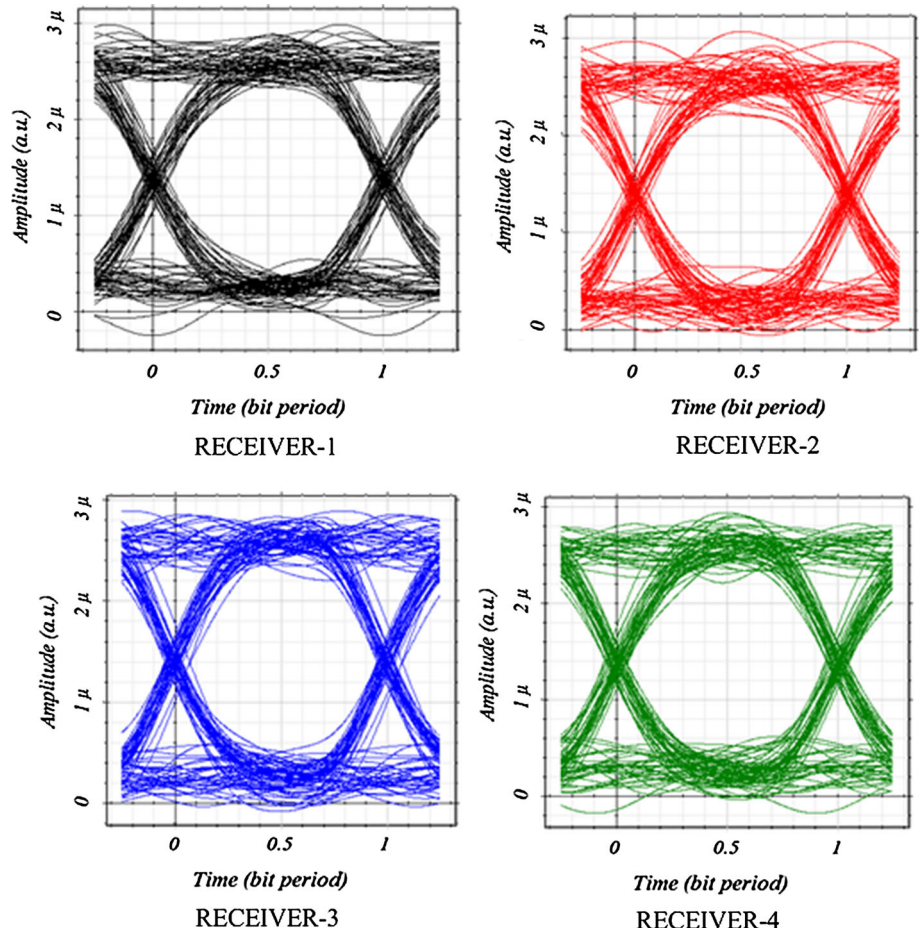


Fig. 7 Channel spacing limitation of the proposed technique

raindrop size distribution, and polarization. Their values can be obtained from ITU-R P.838-3 [9].

$$A_{geo}(dB) = \frac{P_r}{P_t} = 10 \log_{10} [N_{RX} (A_{RX}) / \pi(\theta l)^2] \text{dB}, \quad (2)$$

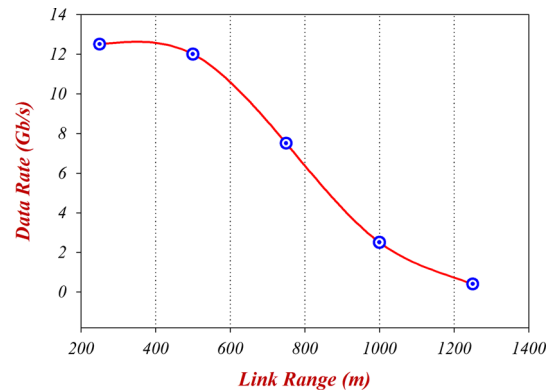


Fig. 8 Data rate per user achievable according to the FSO link

where P_r —received power = $4A_{RX} \frac{P_t}{\pi(\theta l)^2}$; N_{RX} —number of receivers used; θ —beam divergence (mrad); l —link distance (km).

As noted in [14], the multiple beams that leave the FSO transmitter are completely independent, but over distance, they overlap. By the time they reach the receiver head, they turn to a single high-power spot of beam carrying a strong signal. These four beams are received by four optical lens

Table 3 Comparison of others work on FSO link using WDM technique with our study

Reference	[13]	[11]	Our study
Type of FSO systems	Single beam	Single beam	Multibeam
Number of beams	1	1	4
Weather condition	Heavy rain $R = 80$ mm/h	Heavy rain	Heavy rain $R > 120$ mm/h
Link distance (m)	1,500	2,400	1,110
Atmospheric loss (dB/km)	19.28	8.86	19.0
Geometrical loss (dB)	0	0	21.94
Transmitted power (dBm)	30	10	7.7
Wavelength (nm)	1,550	850	850
Data rate Gb/s/Ch	0.622	0.64	1.25
Multiplexer	DWDM	DWDM	DWDM

receivers (R_x) that are connected to the ODD. The ODD combines all received beams using the optical combiner and then demultiplexes them using the 1×4 WDM demultiplexer. Consequently, the output from the ODD produces four high-power beams at a high data rate of 1.25 Gb/s with different wavelengths ($\lambda_1, \lambda_2, \lambda_3$, and λ_4). These four beams are then sent to the respective FSO EUs to be accessed as Internet service or any other digital services. Each EU is composed of one avalanche photodetector (APD) with a gain of three to convert the optical signal to an electrical signal, followed by one low-pass filter (LPF) to filter the unwanted signals. The typical parameters used in the simulation of the proposed network are listed in Table 2.

3 Results and analysis

The bit error rate (BER) versus optical received power at the FSO EUs for the four downlink wavelengths ($\lambda_1, \lambda_2, \lambda_3$, and λ_4) is analyzed, as shown in Fig. 4, which also shows power receiver sensitivity difference of the receivers for different wavelengths at varying transmitted power.

The power receiver sensitivity difference of the receiver for different wavelengths at a BER of 10^{-9} is clearly a small value, which is roughly less than 1 dB.

Figure 5 clearly shows that the minimum and maximum distance achieved by the network is 1,100 and 1,110 m, respectively, at a BER of 10^{-9} in the worse scenario. The increase in the distance beyond the stated optimum distance causes channel overlapping and degradation of the system performance.

The eye diagrams for the entire network at link distance of 1,100 m are depicted in Fig. 6. It is clearly seen that the eye opening for all FSO receivers is identical with adequate eye opening to detect the received signal.

The effect of channel spacing $\Delta\lambda$ on the performance of the proposed hybrid WDM/multibeam FSO network is

shown in Fig. 7. The proposed network is analyzed under different channel spacing $\Delta\lambda = 1.6, 0.8$, and 0.4 nm. The channel spacing $\Delta\lambda$ of 1.6 and 0.8 nm exhibits the same performance on the network from the viewpoint of the received optical power, whereas $\Delta\lambda = 0.4$ nm shows a slight difference in the received optical power, which is considered negligible. Consequently, the communication network of the three noted channel spacing values operates successfully with acceptable eye opening for the received power.

In any communication network, the data rate is inversely proportional to the link distance; this is clearly shown in Fig. 8. The relationship shown in Fig. 8 confirms the results shown in Fig. 5, which indicates that the proposed network can successfully reach a link distance of 1,100 m at a data rate of 1.25 Gb/s at a BER of 10^{-9} . It is clear that at shorter link distance, for example, at 800 m, the data rate may reach to approximately 6.2 Gb/s which is good enough.

4 Comparison of the proposed technique with others work

From Table 3, it is clear that the study performed by [11, 13] concerning the rain rate as carried out in temperate regions, where the rain rate did not exceed 80 mm/h. Moreover, the geometrical loss was not considered by [11, 13] since this type of loss is essential in the field of FSO communications. Both researchers have used single-beam FSO system which is vulnerable to high attenuation. The data rates achieved by each end user were only 0.622 and 0.64 [11, 13], respectively, due to the result of attenuation on single-beam FSO system. The transmitted power used by [13] was too high which is not practical in case of FSO system [15]. Although with all noted drawbacks of the system designed by [11], it achieved good link range of 2,400 m. To decrease the transmitted power of the FSO system within limited value, reduce heavy rain attenuation in the FSO link, and increase data rate per end user, it

is necessary to design and analyze hybrid WDM/multibeam FSO system to operate in tropical weather.

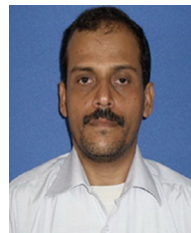
5 Conclusion

In this paper, a hybrid WDM/multibeam FSO network has been proposed. The hybrid WDM/multibeam FSO network has provided a significant improvement in the link distance, received optical power, geometrical loss, and scalability. The network performance has been analyzed, and the study concludes that a maximum channel spacing beyond 0.4 nm is applicable for this network. The power receiver sensitivity difference of the receiver for different wavelengths at a BER of 10^{-9} was noted to be a small value, which is approximately less than 1 dB. Meanwhile, in terms of scalability, four users can access data each at 1.25 Gb/ss, which is considered sufficient compared to conventional multibeam technique accessing data to only one EU. The hybrid WDM/multibeam FSO network can be a good candidate to solve the last mile problem and the rapid increase in capacity demand without requiring new FSO transceivers. At the moment, the evaluation is going on for a real-time system operating in heavy rain as compared to simulation presented here. In the future, increasing the capacity of the hybrid WDM/multibeam FSO network can be studied and implemented to reach up to 32 channels.

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