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International Journal of Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 2 | Pages 328-333 | e-ISSN: 2347-470X

Integration of Optical and Free Space Optics Network Architecture for High-Speed Communication in Adverse Weather using suitable Optical Bands

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ABSTRACT- Free Space Optics (FSO) is a highly viable solution for high-speed wireless communication and is widely preferred over radio frequency communication systems because of its faster data transmission, no regulatory requirements, highly secure long-range operations. However, the capacity and availability of FSO optical bands are a significant concern in varying atmospheric conditions. Our objective is to enhance network flexibility and expand wireless network coverage in adverse weather conditions by combining optical and FSO links using optical bands C, S, and O. The study analyzed the performance of a hybrid 4 channels FSO-WDM system with a 100GHz or 0.8 nm channel spacing under different conditions, including adverse weather and varying data rates. An attenuation of 0.25 dB/km was fixed, and the system's performance was analyzed up to 3 km. The results showed that as the data rate increased, the system's performance declined, and the O band was the best performer up to 25 Gbit/s. BER values were analyzed at different weather conditions using the Kim model, and the O band consistently outperformed the S and C bands. Eye diagrams were used to evaluate the signal quality, and the O band was shown to perform better than the other two bands, even in adverse weather conditions. Overall, the study suggests that FSO is a viable solution for high-speed wireless communication, particularly when using the O band.

Keywords: FSO; WDM; Optical Band; Hybrid-FSO; BER; Adverse Weather.

ARTICLE INFORMATION

Author(s): Muhammad Towfiqur Rahman, Mushfiqur Rahman, Md. Miraj Hossain and Md. Shahed Hossain Chowdhury;
Received: 06/04/2023; **Accepted**: 25/05/2023; **Published**: 30/05/2023;
e-ISSN: 2347-470X;
Paper Id: IJEER 0604-03;
Citation: 10.37391/IJEER.110212
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-11/ijeer-110212.html

crossref member
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1. INTRODUCTION

Communication is currently required to provide rich bandwidths and high-quality signals which has resulted in the use of optical lasers and FSOs rather than radio frequency (RF) signals. FSO is able to offer a viable point-to-point solution that can meet the requirements of optical network design [1,2]. FSO is a line-of-sight (LOS) technology, so the transmitter and the receiver should maintain the alignment [3]. Due to its high efficiency for continuous high-throughput and low interference, FSO is used frequently in high-speed wireless networks [4]. Free-space optical (FSO) systems have become increasingly popular due to their high bandwidth and low interference compared to radio frequency (RF) systems. However, FSO systems are still faced with several challenges. The main challenge is the effect of atmospheric turbulence, which causes scintillation and beam wandering [5]. These effects can significantly degrade the quality of the FSO signal, resulting in bit-error rates that are too high for reliable communication [6]. The general solution to this problem is the use of adaptive optics, which involves measuring the atmospheric distortion and adjusting the beam to compensate for the distortion. Another issue with FSO systems is the limited range, as the signal can be obstructed by obstacles such as buildings, trees, or even rain [7]. To overcome this, FSO systems can be combined with other wireless technologies such as RF or microwave links to provide a more reliable communication link. Wavelength-division multiplexing (WDM) systems increase the capacity of communication links, and have been applied to Free-Space Optical (FSO) systems for high-speed wireless communication. WDM technology enables multiple signals to be transmitted on a single beam, reducing the need for multiple FSO links, and providing redundancy. WDM-FSO systems are suitable for point-to-point communication, wireless backhaul, and disaster recovery, but are costly to implement due to the need for specialized equipment [8]. Nevertheless, the potential benefits of increased capacity and reliability make WDM technology a valuable tool in FSO systems. A multiplexer at the transmitter and a de-multiplexer at the receiver are used in a WDM system to join multiple signals together. It is possible to have a device that can perform both simultaneously and act as an optical add-drop multiplexer with the appropriate fiber [9]. This technology is somewhat mature and is used extensively in optical fiber networks. A brand-new area of study is the application of WDM technology to the FSO communication system. Numerous attempts have been made at the WDM-FSO.

One or more beams are used in the FSO transmissions. The WDM channels in the single-beam system are modulated by the same signal. Additionally, based solely on simulations, the WDM channels modulated by various signals are proposed. With more WDM channels, the multi-beam WDM-FSO's optical lens costs more, making the network significantly more expensive [10].

In this paper, we have compared three different optical bands: C-band, S-band and O-band for the allocation of channels and hybrid WDM-FSO system with optical fiber as a backhaul system. The performance of the signal can be improved using different amplifier such as EDFA. The combination of C, S and O bands can be preferred among other bands because they have the lowest attenuation of the fiber. The length of a wave has a direct relationship with its attenuation rate – the longer the wave, the les attenuation. This paper also deals with the main problem of the FSO system which is adverse weather conditions and shows performances at different attenuations which is equivalent to the adverse weather conditions. The Eye diagram and a variety of other simulation parameters are used to compare the performance due to different optical bands of the designed system.

The following is the structure of the remainder paper: Section 2 describes the Materials and Methods of the simulations done. Section 3 and 4 provides the system design, results and discussion. Section 5 finally concludes the paper.

2. SYSTEM MODEL

2.1 Background of Simulation

The system developed in this study is a combination of multiple components in the form of transmitter, receiver, filter, combiner and splitters. In the system we have used 4 channels of continuous wave (CW) laser sources as transmitter. But, in-order to pass the data we have to generate it first, and in our system we have used Pseudo Random Bit Generator (PRBS). The PRBG is used to generate a random bit stream that is used as the data input for the optical fiber link. In this model the PRBS generates a sequence of N bits [11]:

$$N = T_w B_r, \tag{1}$$

Where, T_w is the global parameter Time window and B_r is the parameter Bit rate. This allows the performance of the link to be tested under realistic conditions, as the bit stream is representative of the types of data that would be transmitted over the link in a real-world scenario. CW laser beams works as the only transmitter carrying the data signals over the air. In the CW case, the average output *Power* is a parameter that you specify. Laser phase noise is modeled using the probability density function:

$$f(\Delta\varphi) = \frac{1}{2\Pi\sqrt{\Delta f dt}} \cdot e^{-\frac{\Delta\varphi^2}{4\Pi\Delta f dt}}, \tag{2}$$

Where $\Delta\varphi$ is the phase difference between two successive time instants and dt is the time discretization. A Gaussian random variable for the phase difference between two successive time instants with zero mean and a variance equal to $2\pi\sqrt{\Delta f}$ has been assumed, with Δf as the laser Linewidth. The CW laser beam has to pass through a Mach-Zehnder Modulator (MZM) which is an intensity modulator based on interferometric principle. By means of an electro-optic effect, an externally applied voltage can be used to vary the refractive indices in the waveguide branches. The different paths can lead to constructive and destructive interference at the output, depending on the applied voltage. Then the output intensity can be modulated according to the voltage [12].

$$E_{out}(t) = E_{in}(t).cos(\Delta\theta(t)).exp(j.\Delta\phi(t)), \tag{3}$$

Where $\Delta\theta$ the phase difference between the two transmitter and receiver is is defined as:

$$\Delta\theta(t) = \frac{\Pi}{2}.(0.5 - ER.(Modulation(t) - 0.5)), \tag{4}$$

and $\Delta\phi$ is the signal phase change defined as:

$$\Delta\phi(t) = SC.\Delta\theta.(t).(1 + SF)/(1 - SF), \tag{5}$$

Two main factors influence the attenuation of the laser power: Attenuation and the loss of geometry. The atmospheric attenuation of the laser power is described by the first parameter. The spread of the transmitted beam between the transmitter and the receiver results in the second parameter, geometrical loss. The equation of links is:

$$P_{Received} = P_{Transmitted} \frac{d_R^2}{(d_T + \theta R)^2} 10^{-\alpha R/10}, \tag{6}$$

Where d_R Aperture diameter of the receiver in meters, d_T is the aperture diameter of the transmitter in meters, R is the Range in kilometers, θ is the beam divergence, α is the attenuation at the atmosphere (dB/km). In this model, the FSO channel is depicted as a subsystem consisting of two telescopic devices and the space channel linking them. It is well-suited for simulating open space transmission links that have a clear line of sight. This component can be utilized to simulate free space optical links, with the range parameter defining the distance of light propagation between the transmitter and receiver. To account for weak, moderate, and strong air turbulence conditions, the Gamma-Gamma Turbulence model is implemented in the FSO channel, allowing for valid intensity levels. The light intensity is described using the Gamma Model [13].

$$P(I) = \frac{2(\alpha B)^{\frac{\alpha+\beta}{2}}}{\eta(\alpha)\eta(\beta)} I^{\frac{\alpha+\beta-2}{2}} K_{\alpha-\beta(\sqrt[2]{\alpha\beta I},\ I>0)}, \tag{7}$$

Where the Gamma function is denoted by $\eta(\alpha)$, while the Bessel function is represented by $K\alpha\text{-}\beta$, where α and β denote the active number of vortices present in the atmosphere. Optical radioactivity in the atmosphere is influenced by several other factors, which are determined by a combination of atmospheric attenuation and scattering. Beer's law is used to describe atmospheric attenuation τ:

$$\tau = \exp[-(\alpha_{abs} + \beta_{scat})L, \tag{8}$$

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Research Article | Volume 11, Issue 2 | Pages 328-333 | e-ISSN: 2347-470X

Where the parameter L denotes the distance between the transmitter and the receiver. The coefficients αabs and βscat are indicative of the atmosphere's absorption and scattering properties, respectively. The performance of the fiber laser system is influenced by the attenuation of laser power, which is primarily due to attenuation and geometrical loss. The optical communication quality is mostly checked by the bit error rate. When measuring BER, digital signal meters or QAM analyzers are utilized. There will be losses in the bits, which are indicated by BER, if bits are transmitted from one side and received from the other side. The equation for this:

$$BER = \frac{bE}{bR.t}, \quad (9)$$

Where t is the measurement period and bR is the bit rate. The bit error ratio is therefore the most crucial quality indicator for the received signal. The signal-to-noise ratio is calculated using the Q factor, commonly referred to as the quality factor. All disturbances, dispersions, and other parameters that lower signal quality and increase bit error rate are included. A formula can be used to determine the Q-factor from the bit error ratio [10].

$$BER = \frac{1}{2}.\left(\frac{Q}{\sqrt{2}}\right), \quad (10)$$

2.2 System Design

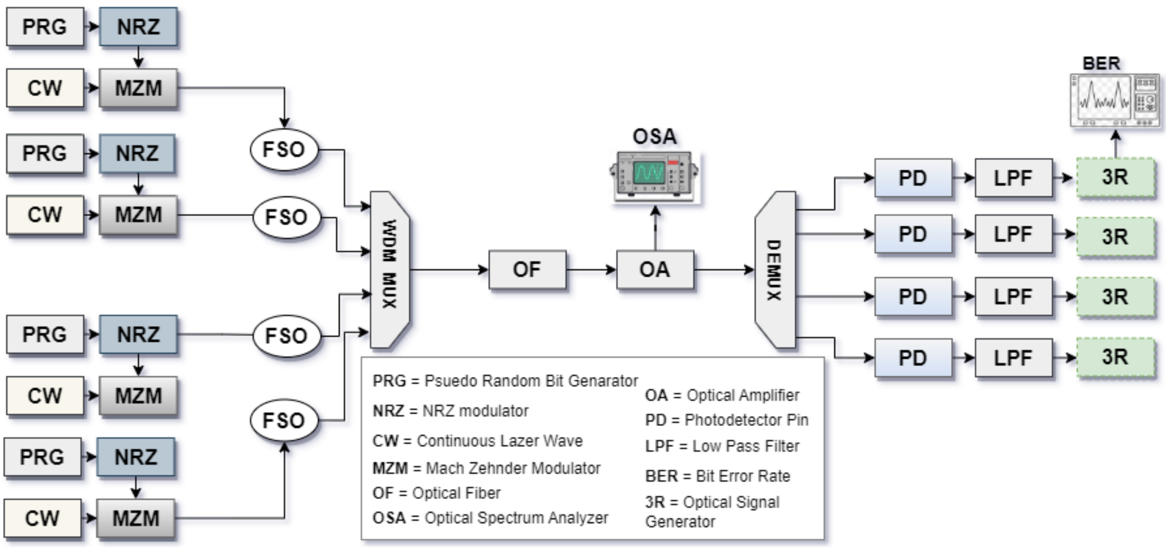

Figure 1: Systematic diagram of the proposed Hybrid Model

The WDM systems uses N number of input signals where N is also the number of output signals. As WDM divides the wavelengths of a laser light into different channels. The designed system shown in *figure 1* requires multiple laser lights at different optical bands which has different wavelengths. This system is designed to work for three different optical bands namely O, S, C. The range of optical bands and selected frequency for this channel have been shown below in *table 1*.

Table 1: Optical bands related to their wavelengths

Optical Bands	Band Range (nm)	Selected Wavelength
O band	1260 – 1360	1308 nm
S band	1460 – 1530	1505 nm
C band	1530 - 1565	1552 nm

The bands have been fixed using different frequency at CW laser parameters. Four laser signal inputs from 1552 nm to 1550 nm are sliced with DWDM with a channel spacing of 100 GHz equivalent to 0.8 nm to reduce the available bandwidth for C optical band. The other two bands are S band ranging from 1505 nm to 1503 nm, O band ranging from 1308 nm to 1306 nm. Optical laser and non-return to zero (NRZ) pulse generator gets modulated using MZM (Mach Zehnder Modulator) before going to the FSO area where it is subjected to attenuation, geometrical loss, and propagation delay and beam divergence. The attenuation divergence due to weather conditions are given in *table 2* with the data availability range.

Table 2: Attenuation in different weather

Weather condition	Attenuation	Data availability
Clear Weather	0.25 dB/km	3 km
Normal dust	2 dB/km	3 km
Hazy	8 dB/km	2 km
Heavy dust	12 dB/km	1.25 km
Foggy	15 dB/km	1 km
Rainy	30 dB/km	0.75 km

MZM is used to modulate the frequency spectra transmitted by CW laser and binary data is created at a data rate ranging from 5Gb/s to 50Gb/s per channel. It is made simpler using the NRZ-

International Journal of
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OOK modulation technique so that MZM can modulate it. The data is then modulated and is influenced to reach the peak point. EDFA is used to amplify the data after reaching fiber channel. The FSO range is set around ~ 3 km dividing it into 12 sections for 0.25 km each. The beam divergence is set to 2mrad with additional loss of 0.2 dB/km. The input laser power is set at 3 dBm for each channel. Other system parameters are tabulated in *table 3*. Optical Spectrum Analyzer (OSA) is then used to see the spectrums and signal strength at any point between MUX-DEMUX. Multiplexed amplified data is Demultiplexed according to various wavelengths. Photodetectors receives the signal and propagates it to a low pass Bessel filter which then goes into 3R generator. Total system performance can be measured by the BER analyzer system block which shows Q factor, OSNR, BER, and detailed eye diagram.

Table 3. System Parameters

Parameter Name	Value
Bit Rate / Channel	5-50 Gb/s
Laser Frequency	Table 1
FSO Range	~ 3 km
FSO Attenuation	Table 2
Beam divergence	2 mrad
Additional loss	0.2 dB/km
Input laser power	3 dBm
Transmitter aperture diameter	3 cm
Receiver aperture diameter	20 cm
Optical fiber length	50 km
Extinction Ratio	30 dB
Line width	10 MHz
Filter Type	Bessel
Amplifier	EDFA
Noise Figure	2 dB
Receiver Responsivity	1 A/W
PD dark current	10 nA

3. RESULTS AND DISCUSSION

This section details the investigation of the projected WDM-based hybrid FSO link's transmission performance using three different optical bands (O, S, C). 5 different analyses have been done to check performances at various scenarios. From many possible outputs combinations design, we have selected those that satisfies the goal of this study which is to find out the suitable optical bands for data transmission and their attenuation levels.

3.1 Performance analysis of optical bands at different range

Light signals get transmitted from one point to another point namely transmitter to receiver [3]. FSO systems are dependent on the weather conditions. Adverse weather conditions make it difficult to transmit data at a fixed rate [14]. For this section attenuation of 0.25 db/km has been fixed for experiment purpose of this plot, it shows BER data variations at different ranges up to ~3km subdivided into 12 different sections by 250 meters per section. Different wavelengths been set for different optical bands O, S, C of the frequency are shown in Figure 2. Between the optical bands O band gives a distant better performance than the other two bands.

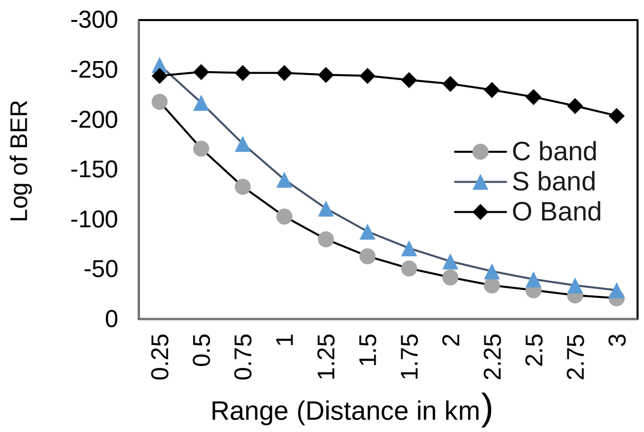

Figure 2: BER values at different distances

3.2 Analysis of BER at various data rate

The system is optimized for using different credential performance testing i.e., different data rate, adverse weather, different optical band. This section describes the performance of the system in different data rate starting from 5 Gbit/s upto 50 Gbit/s which is shown in *figure 3*. The data rate was set at PRBS generator while generating data for the simulation. From the graph we can observe that the performance of the system declines as data rates kept increasing. All the bands performed upto 30 Gbit/s and then started declining. O band was the better performer up until 25 Gbit/s

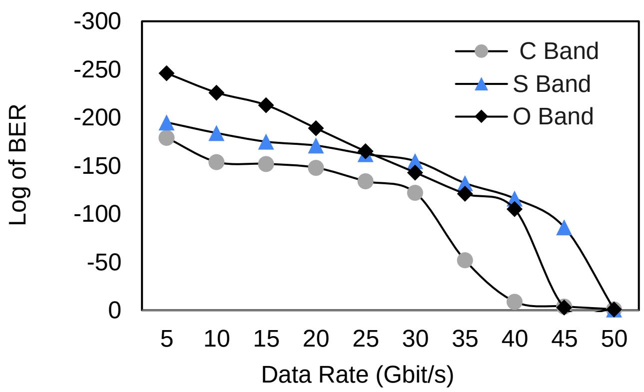

Figure 3: BER values at different data rates

3.3 Performance variation depending on weather variance

Before reaching optical fiber, it has to go through FSO system. We have taken data before reaching optical fiber to measure FSO only performance. FSO system performance varies under the various weather conditions. This section explains the atmospheric attenuation coefficients BER rate at different

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weather according to Kim model for laser source [15]. We have kept the attenuation upto 30 dB/km as we are trying to mimic real life scenario for the weather in this study. The weather and it's attenuation is given in Table 2. We can see that; all the bands performance is declining at the increase of the attenuation. But among the three bands O band performs better in this scenario.

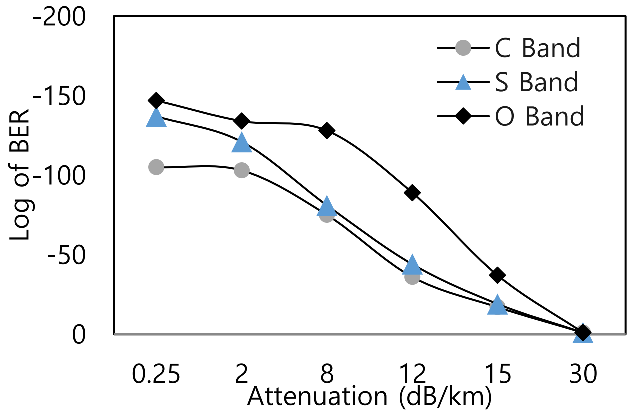


Figure 4: BER values in different weather

3.4 Performance analysis of FSO-only system

The overall hybrid FSO-WDM system designed for this study has been tested at various steps. In *figure 5*, we have shown the BER values for FSO only system at different distances for O, S, C optical bands. This portion explains the performance of the three bands in FSO only system where the data did not pass through any optical fiber, means how the system will work if there is no additional optical fiber for prolonging the system. As all of the cases above O band performs way better than the other two band.

3.5 Optical band performance measurement using Eye Diagram

Eye diagrams are a graphical tool used to evaluate the quality of digital signals, such as those transmitted over fiber optic or copper communication channels. An eye diagram is created by overlaying multiple waveform cycles on top of each other to create a composite picture that resembles an eye [15]. A clean and well-formed eye diagram with a large eye opening indicates a high-quality signal with minimal impairments. In contrast, a distorted or closed eye diagram with a small eye opening indicates a low-quality signal that may not be reliably detected by a receiver. Therefore, by analyzing the eye diagram, it is possible to determine whether a digital signal is good or bad. In this experiment we have shown eye diagrams of O, S an C bands performing at an attenuation of 2 dB/km and 8 dB/km which resembles normal dust and hazy weather respectively, we can see from *figure 2*. These graphs are collected at a 1 km distance. From the graph we can clearly see that O band is performing better than S and C bands.

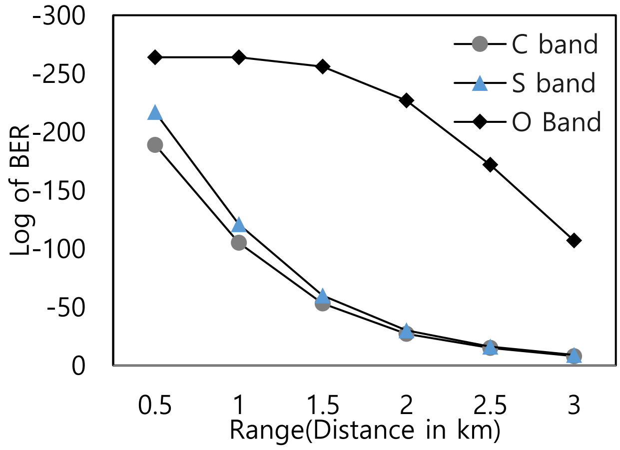
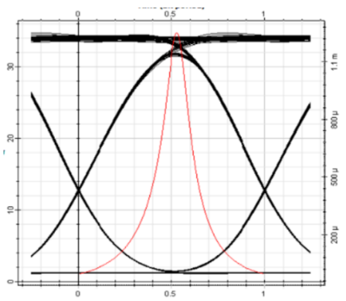
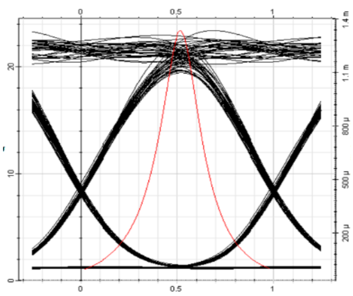


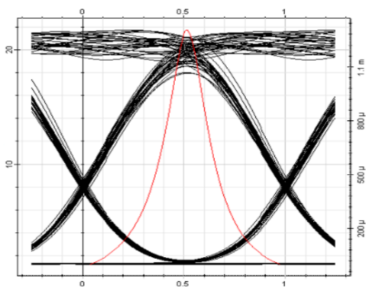
Figure 5: Performance of FSO at different range



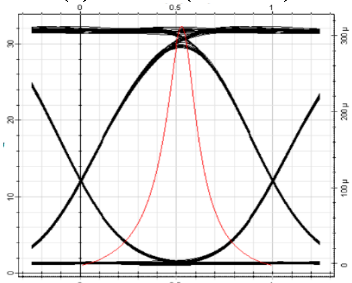
(**a**) O band (2 dB/km)



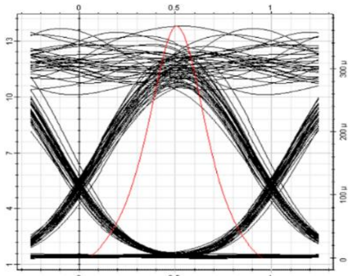
(**b**) S band (2 dB/km)



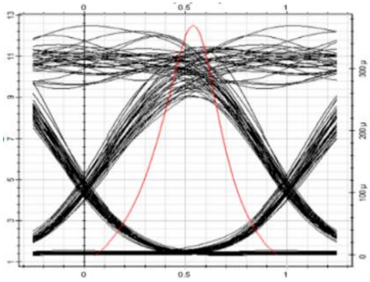
(**C**) C band (2 dB/km)



(**a**) O band (8 dB/km)



(**b**) S band (8 dB/km)



(**c**) C band (8 dB/km)

Figure 6: Eye diagrams of O, S and C bands performing at an attenuation of 2 dB/km and 8 dB/km

4. CONCLUSIONS

In this paper, 4 channels of hybrid WDM-FSO system has investigated for three different optical bands O-band, S-band, and C-band with a wavelength of 1308 nm ,1505 nm and 1552 nm respectively. These optical bands can be used as a primary source of transmitting data at various rates. We have shown data transmission up to 50Gb/s starting from 5Gb/s through different optical bands. For measuring BER (bit-error-rate) and Eye diagram. FSO link distances are ranged up to 3 km for testing performance. Different attenuation is also applied to mimic the adverse weather turbulence. It is observed that using optical band O at 1308 nm we get better results than the other bands. Comparing Figure. 2 and Figure. 4 we can see that hybrid model used in this system gives better output overall than using only FSO system. Also we got data rate upto 30 Gb/s per channel for all the bands using the hybrid system. FSO links are well-suited for high-capacity communication in densely populated urban areas where line-of-sight transmission is possible. The backhaul optical system can be varied according to requirements. This hybrid system may be the best option for a high-capacity, low-cost countrywide communication link architecture, particularly for improved FSO link throughput.

In all the experiments done here we have seen that the O band are a suitable option for high-speed communication than some other bands. Additionally, the hybrid FSO system concept can be used in developing nations with complex landscapes and harsh weather.

Author Contributions: "Conceptualization, M T Rahman; methodology, Mushfiq and Miraz; software, Miraz. and Mushfiq; validation, M T Rahman and Mushfiq; formal analysis, Mushfiq; investigation, Miraz and Shahed; resources, M T Rahman and Shahed; data curation, Miraz and Shahed; writing—original draft preparation, Mushfiq and Miraz; writing—review and editing, M T Rahman and Mushfiq; visualization, Shahed and Miraz; supervision, M T Rahman; funding acquisition, M T Rahman; All authors have read and agreed to the published version of the manuscript".

Acknowledgments: We would like to thank the Institute of Energy, Environment, Research, and Development (IEERD, UAP) and University of Asia Pacific for their funding

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