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Optimization of free space optics parameters: An optimum solution for bad weather conditions

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ABSTRACT

Free Space Optics Systems (FSO) is one of the most effective solutions, especially for atmospheric turbulence due to the weather and environment structure. Free space optics system suffers from various limitations. A well-known disadvantage of FSO is its sensitivity on local weather conditions-primarily to haze and rain, resulting in substantial loss of optical signal power over the communication path. The main objective of this article is to evaluate the quality of data transmission using Wavelength Division Multiplexing (WDM) with highlighting several factors that will affect the quality of data transmission. The results of these analyses are to develop a system of quality-free space optics for a high data rate transmission. From the result analysis, FSO wavelength with 1550 nm produces less effect in atmospheric attenuation. Short link range between the transmitter and receiver can optimize the FSO system transmission parameters or components. Based on the analysis, it is recommended to develop an FSO system of 2.5 Gbps with 1550 nm wavelength and link range up to 150 km at the clear weather condition of bit-error-rate (BER) 10^{-9}.

1. Introduction

Free space optics based on WDM system suffers from various limitations, especially atmospheric turbulence due to the weather and environment structure [1,2]. Atmospheric attenuation of FSO system is typically dominated by haze and fog, but is also dependent upon rain and dust. The total attenuation is a combination of atmospheric attenuation and geometric losses. Scattering produced by atmospheric particles can be considered as a form of dispersion of the energy that makes the signal divert from its original target. Geometrical scattering is the result of raindrops and snow that are made of larger molecules having an impact similar to Raleigh scattering. Turbulence is the random fluctuation in the refraction index of air produced by differential heating and has the effect of defocusing the beam, producing intensity fluctuations in the received signal (scintillation), and contributing to the spreading of the transmitted beam. Turbulence is partially compensated by tracking and adaptive optics techniques, and it has a greater impact on higher frequencies within the near infrared sub-band (1550 nm is therefore, less affected) [7]. In other words, weather, link distance, scattering, absorption, turbulence, misaiming, laser wavelength, and data rates all have an impact and must be factored into either a custom calculated link budget or a manufacturer's distance rating [3]. Fiber optics continues to be deployed at a measured and sustained pace, but the cost to do so is often prohibitive, the process long, and the investment irreversible. Conversely, optical wireless solutions complement fiber optics in networks with considerably less expense, faster deployment, and flexible service rollouts, including same-day connectivity, due to their ease of installation and maintenance [4]. Implementing optical data links through the atmosphere over long distance and high data rate is challenging due to beam degradation cause by atmospheric turbulence [4,5]. To avoid this limitation various way of designing free space optic based on WDM systems are needed. In this article, a new approach is proposed to overcome the above mentioned limitations. The proposed system is based on optimization the main FSO parameters in order to increase the overall system performance. The remainder of this article is divided as follows: Section 2, analysis the characteristic and expression of free space optic attenuation that involves under Malaysia's weather condition. In Section 3, Simulation Results have been presented. Section 4, optimizes the parameters of the WDM system based on FSO that improved the system performance in terms of quality of the transmission. Finally, conclusion is reported in Section 5.

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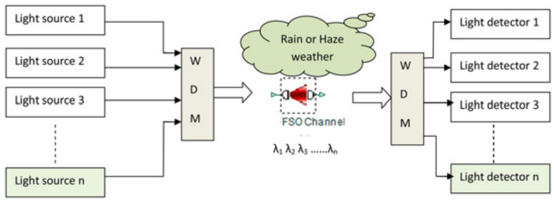

Fig. 1. Typical FSO WDM system.

Table 1
Representative characteristic and data observation.

Characteristic		Data Observation
Data rate	2.5 Gbps	Data rate versus bit error ratio
Power	10 dBm	Power versus bit error ratio
Link range	150 km	Link range versus bit error ratio
No. of user	Depend	No. of user versus bit error ratio
Channel spacing	0.8 nm	Channel spacing versus bit error ratio

2. System analysis

2.1. WDM system design

The block diagram of a typical FSO system is shown in Fig. 1. This figure shows the basic concept and devices that have been used in designing the unidirectional WDM system. There are Pseudo-Random Bit Generator, NRZ Pulse Generator, CW Laser, Mach-Zehnder Modulator at transmission part; while, APD photodetector and Low Pass Gaussian Filter at the receiver part. However, some of measurement tools such as Oscilloscope, Optical Time Domain Visualize are used as well. The impact on system design parameters are illustrated in the representative characteristic and data observation given in Table 1; with proper parameters, FSO based on WDM system can be optimized to achieve a maximum link range of operation. The quality of the received signal is greatly depends on the conditions of the free space channel and the WDM system design. In order to suppress the beam diffraction that occurs naturally with propagation, an optical signal is then sent through an optical fiber to a collimating optical system [7].

2.2. Link margin analysis

The receiver typically has a specific minimum sensitivity at a given data rate, and the task is to make sure that the received power stays above minimum sensitivity to guarantee reliable operation of the system. However, an important FSO link parameter is related to the fact that the loss of the media (air) between the transmitter and receiver can vary in time due to the impact of weather. Therefore, it is important for FSO system to take weather conditions into consideration, such as, rain and haze [8].

2.2.1. Rain

Rain intensity factor is capable of attenuating laser power and cause system under performance in a free space optical (FSO) communication system [8]. In general, weather and installation characteristics are the key factors that could possibly reduce visibility and also impair the FSO performance. The derived mathematical model will then be analyzed and correlated with the local rain data [2]. This work will be presented as follows: a numerical model based on the Beer's law and Stroke law. The loss or attenuation from atmospheric effects can be calculated using various models available in propagation literatures. The attenuation of the laser power in the atmosphere is described by Beer's law [4,8]:

$$T(R) = \frac{P(R)}{P(0)} = e^{-\beta R} \quad (1)$$

where R is the link range in meters, $\tau(R)$ is the transmittance at a range R (km), $P(R)$ is the laser power at range R. $P(0)$ is the laser power at the source (Watt), and β is the scattering coefficient (km^{-1}).

The scattering particles are large enough that the angular distribution of scattered radiation can be described by geometric optics. Rain drops, snow, hail, cloud droplets, and heavy fogs will geometrically scatter laser bit's signals. The scattering is called non-selective because there is no dependence of the attenuation coefficient on laser wavelength. The scattering coefficient can be calculated using Stroke law [2]

$$\beta_{\text{rain scat}} = \pi a^2 Na\, Q_{\text{scat}} \left(\frac{a}{\lambda}\right) \quad (2)$$

where a = radius of raindrop (0.001–0.1 cm), Na = rain drop distribution, Q_{scat} = scattering efficiency, and λ = wavelength. The raindrop distribution, Na can be calculated using equation [1,2]:

$$Na = \frac{Za}{4/3(\pi a^3)Va}. \quad (3)$$

Za is rainfall rate (cm/s), a = droplet radius and Va = limit speed precipitation. Limiting speed of raindrop is also given as

$$Va = \frac{2a^2\rho g}{9\eta}. \quad (4)$$

ρ is water density (g/cm^2), g is gravitational constant and η is viscosity of air. Table 2 shows the constant value of these parameters.

Table 2
FSO link parameters, (a) constant value; (b) rainfall rate.

(a)
Constant value

Gravitational constant	980 cm/s^2
Water density	1 g/cm^2
Viscosity of air	1.8×10^{-4} (g/cm)s
Droplet, a	0.001–0.1 cm
Wavelength	1550 nm
Q_{scat}	2

(b)
Za, rainfall rate

Type	mm/h	cm/s
Light	26	7.22×10^{-4}
Medium	40	1.11×10^{-3}
Heavy	80	2.22×10^{-3}

2.2.2. B-haze/fog

The FSO system performance depends on the attenuation value at different visibility level. Because haze results in more particles stay longer in atmosphere compared to rain, it presents more serious degradation on FSO performance. In normal practice of FSO, evaluation of FSO performance is conducted by testing the actual system at the site [6]. This process requires the FSO hardware to be installed temporarily at site to acquire the system performance. If the attenuation performance of the system is satisfactory, the system is then permanently installed and commissioned. On the other hand, if the system shows poor performance, necessary adjustment of system parameters and/or hardware is needed. In this project, a more proactive method to forecast the system performance is proposed without having to physically install the hardware [8]. The alternative method is by using mathematical analysis by using Kim & Kruse Model [1,2,8–12].

$$\beta = \frac{3.91}{V}\left(\frac{\lambda}{550\,\text{nm}}\right)^{-q}.$$

where, β = haze attenuation, V = visibility in kilometers, λ = wavelength in nanometers and q = the size distribution of

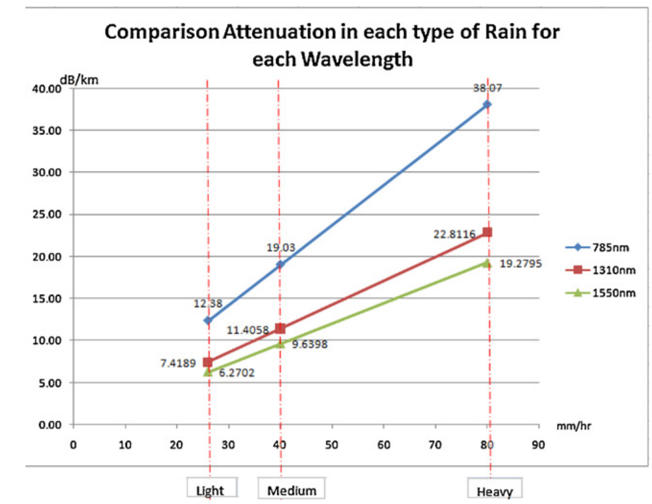

Fig. 2. Comparison attenuation in each type of rain for each wavelength at 1 km.

the scattering particles {1.3 for average visibility (6 km < V < 50 km) and 0.585V1/3 for low visibility (V < 6 km)}. In other references, it adds as 1.6 for very high visibility (V > 50 km) [8]. The International Visibility Codes for Weather Conditions and Precipitation are listed in [8–10]. The term geometrical loss refers to the losses that occur due to the divergence of the optical beam. Analysis on Geometrical Factor and Geometrical Loss are not considered in this article (It has been assumed that there is no beam spreads).

3. Simulation results

3.1. Rain analysis

In the analysis, it was divided by two major key, which is to compare the performance of some relevant attenuation and the attenuation along the rainy condition for the best wavelength. In this case 785 nm, 1310 nm and 1550 nm wavelengths are studied. According to calculated result, Fig. 2 showed that 1550 nm is the best choice with the lowest attenuation in dB/km for every type of rainy condition. Light rain is recorded as 6.27 dB/km, 9.64 dB/km for medium rain while 19.28 dB/km for heavy rain (refer to Fig. 3). However, system performance will be improved by using 1550 nm, while the other wavelengths show the higher attenuation compare to this 1550 nm wavelength.

3.2. Haze analysis

To quantitatively assess which wavelengths, visibility range, attenuation presented in haze had more severe impact on the FSO performance. Therefore, by comparing the performance of

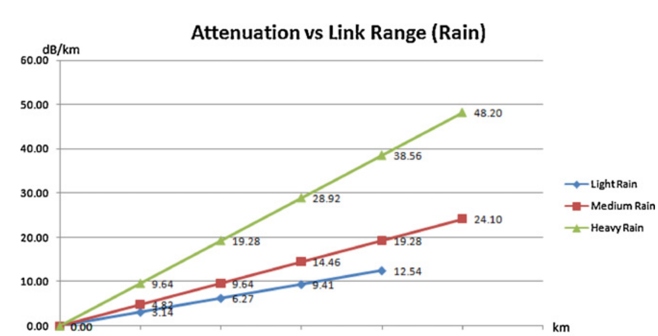

Fig. 3. Attenuation for certain link range by referring to 1550 nm as wavelength.

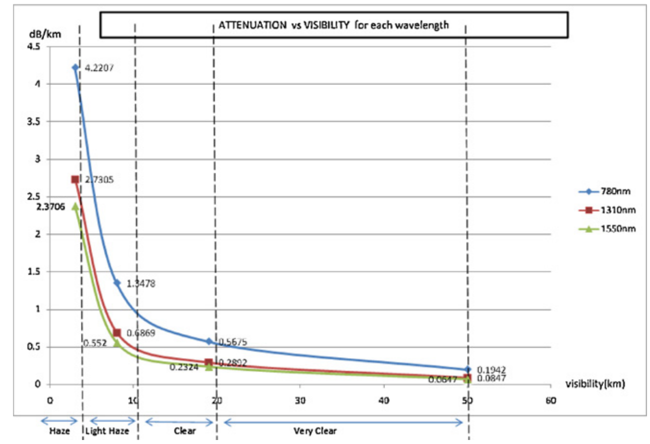

Fig. 4. Attenuation versus visibility for each wavelength.

some relevant attenuation and then evaluated the attenuation along the haze condition for the best wavelength. In haze analysis, the clear weather condition is included in this analysis. By referring to Figs. 4 and 5, for the very clear weather conditions is not showing many precipices of each wavelength. In clear condition also describing the minimize precipice which is 0.23 dB/km for 1550 nm, 0.28 dB/km for 1310 nm and 0.56 dB/km for 785 nm. However, it was start give a high gap when in haze condition. Therefore, the results show that the attenuation is high at 785 nm wavelength. Hence, the best choice to face the haze attenuation is to use a 1550 nm wavelength.

4. FSO parameters optimization

By subjecting the attenuation value (for each weather condition), some parameters should be highlighted in term of optimization structure for the system. These parameters such as laser power, data rate, and optical amplifier gain, aperture size of transmitter/receiver, and link range should be optimized according to the highest priority to achieve the best FSO system performance [13]. However, by evaluating the best optimization parameters, the factors will be adjusted by the high priority to the low priority as shown in Fig. 6.

As a result, the optimization is achieved successfully to handle the condition on clear weather, with certain parameters change. Table 3 shows the parameter's optimization, this system is running at 150 km and the aperture size is within the standard which is 15 cm. The bit-error-rate (BER) performance is shown in Figs. 7 and 8 for clear, light haze weather conditions, respectively.

The worst result has been obtained in a heavy haze condition, although changes to the data rate had made. However, another

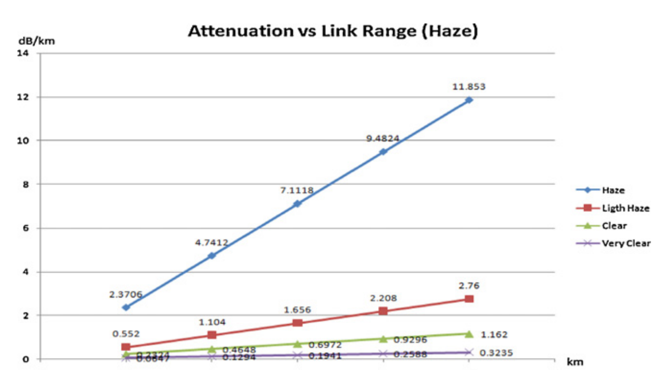

Fig. 5. Attenuation versus link range for 1550 nm as wavelength.

Table 3
Optimization to handle the condition of weather at 150 km.

BIL	Cond weather	ATT (dB/km)	Bit rate	Laser PWR (dBm)	Opt AMP gain(dB)
1	Very clear	0.065	2.5 Gbps	−10	15:7
2	Clear	0.233	2.5 Gbps	10	20:7
3	Light haze	0.55	2.5 Gbps	20	50:15
4	Heavy haze	2.37	155 Mbps	40	100:100
5	Rain	Special optimization			

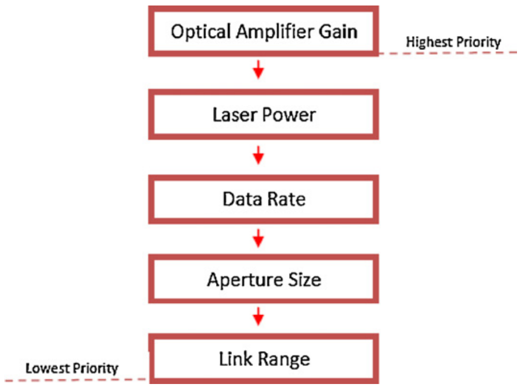

Fig. 6. Priority optimization.

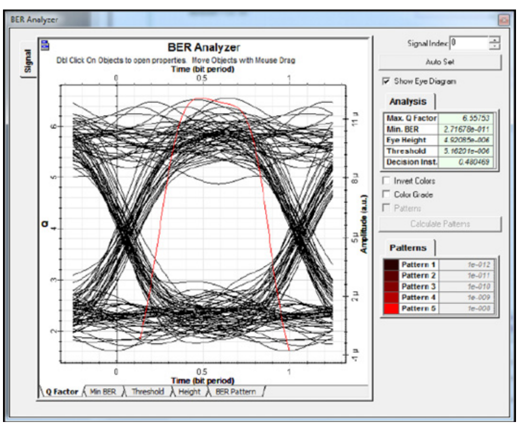

Fig. 7. BER on CLEAR weather at 150 km.

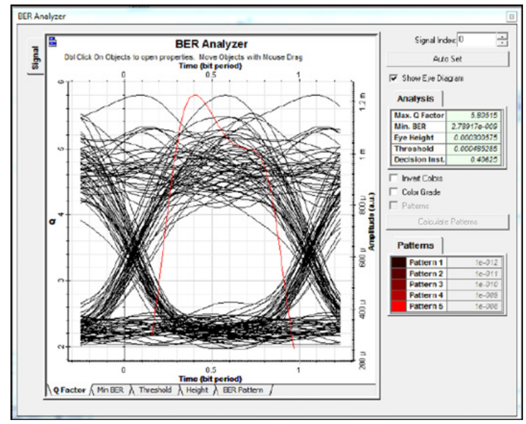

Fig. 9. BER on HEAVY HAZE weather after second optimization at 55 km.

optimization process should be made to overcome the effects of heavy haze, which is by changing the aperture size and link range is needed to give significant impact. Therefore, by simulating the weather condition with 2.37 dB/km, it needed to use 30 cm aperture size, and hence it can travel along 55 km with carrying out the bit rate at 155 Mbps. The power of laser source needs to increase until 30 dBm to supports these changes. The optimized result is shown in Fig. 9.

Heavy haze gives the worst result; rain also gives the bad result as well because the rain attenuation is much higher than haze. Therefore, a special optimization is needed to achieve a better system performance, which involved link range optimization. In this part, we are shows how the attenuation has a significant impact on system performance (BER) and link range (km). The laser power was set up constant with 30 dBm, and the optical amplifier gain was set to top performance with 50 dB gain. The results are reported in Table 4, Figs. 10 and 11.

Rain is the biggest affecting in the free space optical systems. However, it still can be successfully with considered to the parameters of the attenuation. Hence, the results are showing that maximum data rate only at 622 Mbps for all types of rain. Therefore, the link range can be longer by stepped down the data bit rate to 155 Mbps. For the light rain, the system could be achieved up to

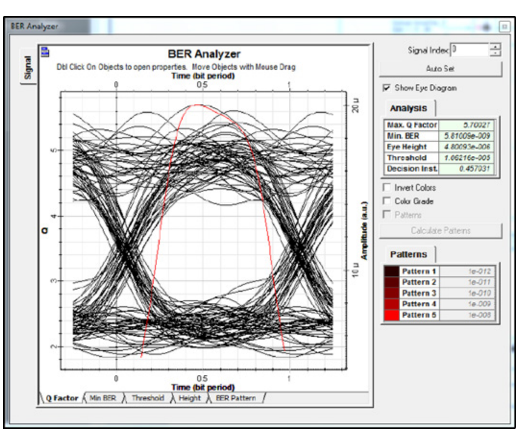

Fig. 8. BER on LIGHT HAZE weather at 150 km.

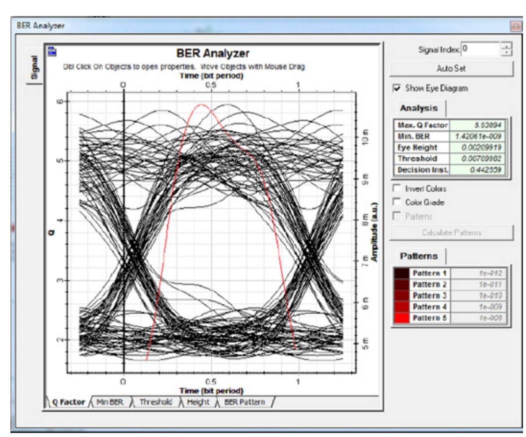

Fig. 10. BER on LIGHT RAIN with maximum optimization at 20.8 km.

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Table 4
Rain weather link optimization.

BIL	Weather condition	ATT (dB/km)	Laser power (dBm)	Aperture size	Data bit rate	Link range (km)
1	Heavy haze	2.37	30	30 cm	155 Mbps	55
					622 Mbps	51.5
2	Light rain	6.27	30	30 cm	155 Mbps	22
					622 Mbps	20.8
3	Medium rain	9.64	30	30 cm	155 Mbps	14.7
					622 Mbps	13.9
4	Heavy rain	19.28	30	30 cm	155 Mbps	7.6
					622 Mbps	7.2

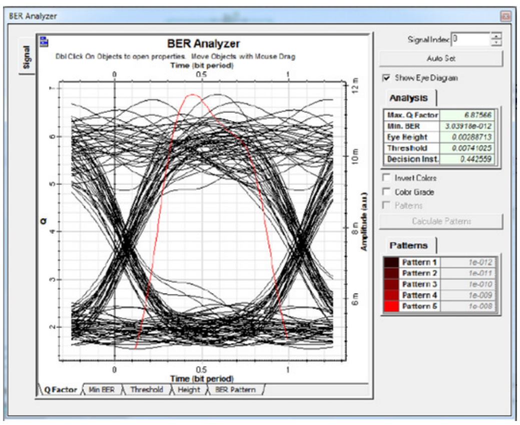

Fig. 11. BER on HEAVY RAIN with maximum optimization at 7.2 km.

Table 5
Received power (dBm) versus aperture size.

Weather	Aperture			
	15 cm	30 cm	45 cm	60 cm
Heavy haze	−67.33	−55.28	−48.24	−43.24
Light rain	−66.96	−54.92	−47.87	−42.87
Medium rain	−67.22	−55.18	−48.14	−43.14
Heavy rain	−-66.31	−54.27	−47.23	−42.23

22 km with a BER of 3.16×10^{-10}. For the medium rain, link range could be improved up to 14.7 km with a BER of 1.55×10^{-9}. Finally, the transmission link range could be achieved up to 7.6 km with a BER of 3.93×10^{-12}. According to the results which have been demonstrated, the received powers are optimized by changing the aperture size used for the system parameters. The results are shown in Table 5, which shows that the aperture sizes are giving an impact on received power. Large aperture size will give a better received power.

5. Conclusion

Nowadays, development in the communications sector is very encouraging. In this article, a numerical expression and simulation modeling of a WDM FSO system have been investigated successfully. External parameters represented the different weather conditions proven the FSO performance was influenced very much by the rain and haze condition. However for the clear weather condition, a 150 km with 2.5 Gbps data rate has been successfully achieved. The simulation results indicate the tradeoff between simulation parameters (data rate, link range and input power). For example, at 2.5 Gbps under clear weather, the BER value of 2.72×10^{-11} is achieved for 150 km, while at 155 Mbps the BER value of 2.19×10^{-8} is achieved for 175 km transmission distance. The effects of weather condition has been presented both theoretically and experimentally (using OptiSystem version 7.0) and illustrates some useful comparison. For example, result of a propagation study on an FSO link at 850 nm, 1310 nm and 1550 nm on 150 km long path are presented. Given these wavelength; for longer links, heavy haze, light rain, medium rain and heavy rain become critical issue. Finally, short link range and low data rate can optimize the FSO system transmission components.

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