FEASIBILITY ANALYSIS OF FREE SPACE EARTH TO SATELLITE OPTICAL LINK IN TROPICAL REGION

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ABSTRACT: Free Space Optics (FSO) becomes a great attention because of the chances in transmitting data up to 2.5Gbps. There are a lot of advantages offered by FSO such as easily deployment with saving time and cost and no electromagnetic interference. In spite of the advantages, FSO has an uncontrolled drawback which is highly sensitive to atmospheric phenomena because uses air as tranmission medium. Current studies and researches are only focusing on FSO terrestrial link with short path length and based on data from temperate region. Therefore, this paper is aiming to provide feasibility analysis of FSO link from earth to satellite especially Low Earth Orbit (LEO) based on atmospheric data in tropical region. The analysis will include the losses from geometrical attenuation, absorption, scintillation, haze attenuation, and rain attenuation.

ABSTRAK: Ruang Bebas Optik (Free Space Optics (FSO)) mendapat perhatian kerana kebolehannya memancarkan data pada kelajuan tinggi. Di sebalik kelebihannya, FSO amat sensitif terhadap fenomena atmosfera kerana ia menggunakan udara sebagai perantara transmisi. Penyelidikan dan kajian terkini hanya memfokus kepada jalinan darat FSO dengan kepanjangan jarak pendek dan bergantung kepada kawasan tenang. Oleh itu, kertas ini menyasarkan untuk memberikan analisis kebolehlaksanaan jalinan FSO dari bumi ke satelit terutamanya Orbit Rendah Bumi (Low Earth Orbit (LEO)) bergantung kepada data atmosfera di kawasan tropika. Analisa termasuklah kehilangannya akibat pengecilan geometri, penyerapan, kelipan, pelemahan jerebu dan pelemahan hujan.

KEYWORDS: *feasibility; Free Space Optics; availability; atmospheric attenuation; beam divergence angle; elevation angle*

1. INTRODUCTION

FSO is an emerging technology that has a great chance to compliment the traditional wireless communications and offers some inherent advantages compared to microwave links. The advantages include higher bandwidth, lack of use cable, and require no license spectrum. Further, the systems are small, lightweight, have compact dimensions, and low power consumptions which result in big cost savings [1]. However, because FSO uses air as the tranmission channel, the system is very sensitive to poor weather conditions which include absorption, turbulence, and scattering due to presence of aerosols, smoke, dust, rain, fog, and snow.

In temperate region, the most influence condition is because of fog which the attenuation may raise more than 300 dB/km in heavy fog [2]. In tropical region, rain is become main consideration because it occur throughout the year. Attenuation will be the most critical factor for longer FSO links especially to implement it in space. Currently, most studies and researches centred on temperate region and terrestrial link. There are very limited resources to implement FSO link from earth to satellite. Thus, this research will be concentrating on implementing FSO link from earth to satellite especially in tropical region.

Therefore, the goal of this paper is to predict the availability of performing FSO from earth to satellite especially Low Earth Orbit (LEO) satellite by analyzing attenuations that degrade the link under tropical atmospheric conditions. Although it is impossible to change the physics of the atmosphere, it is possible to take advantage on the parameters by choosing the wavelength, receiver capture surface, elevation angle, and beam divergence angle accordingly. The atmospheric phenomena will be quantified by geometrical attenuation, haze attenuation, rain attenuation, absorption, and scintillation. Since there are no standard equations has been derived for FSO earth-to-satellite link, effort has been made to integrate prediction models derived for FSO terrestrial link and microwave earth-to-satellite link.

2. FSO PROPAGATION IN THE ATMOSPHERE

The purpose of this section is to introduce a theoretical basis of the losses that occur during the propagation of a FSO system. The losses containing the losses from atmosphere which are absorption, scintillation, rain attenuation, and haze attenuation as well as geometrical attenuation.

2.1 Geometrical Attenuation

Geometrical attenuation is loss that occurs due to beam diverges which result detector receives less signal power. This attenuation is the only parameter that is independent to the atmospheric condition. The loss can be calculated using Eq. (1) [3].

$$\mathrm{Att_{Geo}} = 10\log_{10}\left(\frac{S_d}{S_{ccpture}}\right) = 10\log_{10}\left(\frac{\frac{\pi}{4}(d\theta)^2}{S_{capture}}\right) \quad dB \tag{1}$$

where S_d is surface area of transmit beam at range d, $S_{capture}$ is receiver capture surface (m^2), θ is beam divergence angle (mrad), and d is emitter-receiver distance (km). Divergence will determine how much signal will be collected at the receiver end. Therefore, in order to have low geometrical losses, it is suggested to have small beam divergence angle and bigger receiver capture surface to concentrate all incoming light to the receiver.

2.2 Absorption

Absorption is caused by many different types of gaseous in the atmosphere, the dominant one being water vapor, which is the wavelength region used for wireless optical links[2]. Absorption along earth to space path for the frequency between 150 THz and 375 THz, and the elevation angle above 45^o can be calculated using Eq. (2) where τ' is the extinction ratio from h_E (height of the earth station above mean sea level in km), θ is the elevation angle, and λ is wavelength in μm [4].

$$A_s = \frac{4.3429\,\tau'}{\sin(\theta)} \tag{2}$$

2.3 Scintillation

Scintillation is the fluctuations in the detector signal as a result of random variations in the refractive index of the turbulent atmosphere along the channel [5] that increase the amount of spreading beam. According to [4] and [6], the strength of scintillation is measured in terms of the variance of the beam amplitude and can be calculated by using Eq. (3) where C_n^2 is turbulence profile ($m^{-2/3}$), h_o is height of earth station above ground level (m), h is height above ground-level (m), and Z is effective height of the turbulence which typically 20km

$$\sigma_{E\text{-}S}^2 = \sigma_{dBN}^2 = \frac{3.622 \times 10^9 \int_{h_o}^{Z} C_n^2(h)(h-h_o)^{5/6} dh}{\lambda^{7/6} \sin^{11/6}\theta} \ dB^2 \tag{3}$$

2.4 Haze Attenuation

Haze is one of local weather that gives significant impact on FSO communications. According to [7], haze is caused by tiny particulates suspended in the atmosphere which diminished horizontal visibility at high concentrations. Haze attenuation can be calculated by using Beer's Law equation [8];

$$\tau(R) = e^{-\sigma L} \tag{4}$$

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q} \tag{5}$$

where L is measurement distance occured (km), V is visibility (km), λ is wavelength (nm), σ is specific attenuation coefficient per unit of length, and q is size of distribution of diffusing particles based on Kim and Kruse model [9].

2.5 Rain Attenuation

Rain is classified under non-selective scattering since the drop size is much larger than the wavelengths. In Malaysia, rain is a dominant mechanism of signal loss and distortion because it occurs almost year-round and most instances the rainfall rate is much higher than temperate region. Rain intensity is the parameter used to locally describe the rain and based on [10], average rain intensity for Malaysia exceeding 0.01% of the year is 120 mm/hr. According to [3], specific rain attenuation of optical link based on dB/km is given in Eq. (6) where R is rain intensity (mm/hr) and Carbonneau model is used as the reference for the k and α value which are 1.076 and 0.67 respectively.

$$A_{rain} = kR^{\alpha} \tag{6}$$

In order to calculate long-term statistics of the slant-path rain attenuation, 10 steps provided in ITU-R P.618-9 [11] is followed.

3. RESULTS AND ANALYSIS

In order to check the availability of the link,each of the attenuation has been calculated and analyzed by using Matlab and Excel software by varying elevation angles and percentage of time. There are some fixed parameters that is considered in the calculation which is based on the FSO equipment that already been installed in Kulliyyah of Engineering, International Islamic University Malaysia (IIUM), Gombak campus. The parameters include λ=850 nm, beam divergence=2 mrad, and receiver capture surface = 32 cm.

3.1 Attenuation Analysis

Specific attenuation caused by geometrical, absorption, scintillation, haze, and rain with respect to elevation angle for 0.01% of an average year is shown in Table 1. Few assumptions has been made to calculate the attenuations which are haze attenuation calculation based on measurement distance, L=20 km due to the average depth of troposphere in tropical region [12], and visibility range for slant path=10km according to researh done by [13]. Then, to calculte absorption, height of earth station above mean sea level, h_E=0.06 km taking IIUM as the reference, and ground wind speed=1.5 m/s for scintillation calculation.

Table 1 shows that when the elevation angle increases, each of the attenuation will decreases accordingly, result in lower total attenuation when it reach 90 degree elevation angle. However, the range of the total attenuation for 99.99% availability is still quite high which is in between 300-1100 dB, make it impossible to establish the link to LEO satellite. Therefore, the availability needs to be reduced in order to have lower attenuation to make the link feasible. Note that, scintillation and absorption contribute only small portion of attenuation when compared to rain and geometrical loss.

Table 1: Calculated attenuations for different elevation angles.

Elevation angle (degree)	Types of attenuation					Total Attn. (dB)
	Geometrical (dB)	Absorption (dB)	Scintillation (dB)	Haze (dB)	Rain (dB)	
10	88.63	17.72	1.26	111.06	905.81	1124.5
20	82.74	8.99	0.67	56.39	507.11	655.9
30	79.44	6.15	0.48	38.57	374.88	499.5
40	77.26	4.78	0.38	30.01	311.03	423.5
50	75.73	4.01	0.32	25.17	275.22	380.5
60	74.67	3.55	0.29	22.27	253.89	354.7
70	73.96	3.27	0.27	20.52	241.23	339.2
80	73.55	3.12	0.26	19.58	234.48	331.0
90	73.42	3.08	0.25	19.28	232.36	328.4

Figure 1 shows the difference of total attenuation between several values of percentage of time with respect to the elevation angle. Six different percentages has been selected in order to determine the total losses occur during data propagation which is 0.001%, 0.01%, 0.05%, 0.1%, 0.5%, and 1% of percentage time which equivalent to 99.999%, 99.99%, 99.95%, 99.9% and 99.5%, and 99.0% availability respectively. Previous data in Table 1 shows the specific value of total attenuation for 99.99% availability is impossible to establish not to mention 99.999%. Consideration can be made if the availability is reduced to 99.9% and below which the attenuation is lower than 500dB. More discussions about the availability are presented in next section.

3.2 Availability of the Link

System availability is the probability that the system works correctly at the time t[2]. The availability of a FSO link system mainly depend on the power link budget and the local climate conditions as it is the measure of optical signals can penetrate atmospheric attenuation in different weather conditions. There are few parameters that can be varied and need to be concerned in order to make the link between earth and satellite is feasible which are transmitted power, receiver sensitivity, beam divergence angle, and elevation angle. Since the total attenuation is quite high during rain, so tranmitted power and sensitivity values are set to maximum which are 40dBm and -90dBm respectively due to combat the total attenuation occured during the signal tranmission.

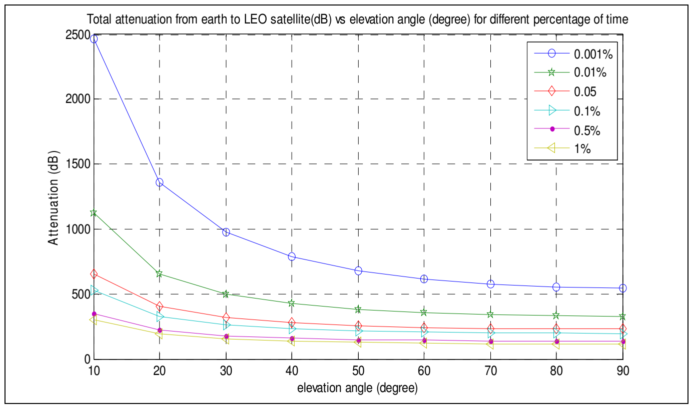

Fig. 1: Total Attenuation vs elevation angle for different percentage of time.

Figure 2 presents the power received at different availability for different beam divergence angle during clear air and hazy days. During clear air, haze and rain are neglected and only scintillation, absorption, and geometrical loss is considered in the calculation. From Fig. 2(a), it is clearly shows that, when 40dBm power is transmitted, receiver will capture all the signals even though beam divergence increases until 5mrad with total losses is in the range between 40-120dB. For example, for beam=0.1mrad, FSO system can operate with a 48.42dB link margin with received power=-41.56dB and penetrate the losses relatively unhindered. In addition, Fig. 2(b) describes about power received during hazy days. Sensitivity is still set up to -90dbm and if the signals are above the limit, means the signal will be captured by the receiver. From the graph, receiver can receive signals if the elevation angle is above 30 degree for all beam divergence angles. However, the elevation angle can be improved if the beam angle is reduced up to 0.1mrad onwards. Therefore, during clear air and hazy days, there are possibilities to transmit FSO signal from earth to LEO satellite.

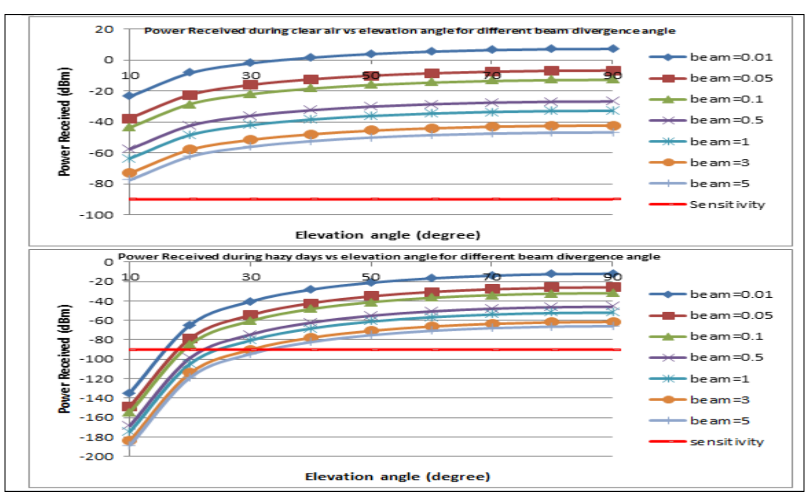

Fig. 2: Power Received (dBm) vs elevation angle (degree) for different beam divergence angle during clear air and during hazy days.

Moreover, Fig. 3 describes about the effect of elevation angles to the availability and power received for different beam divergence angle during all types of attenuations occur including haze and rain. Three different beam angles are set which are 0.01, 0.1, and minimum elevation angle will be indicated as the point of reference in order to establish the link. From the figure, it is possible to have link at beam angle=1mrad but with availability less than 99.5% with minimum elevation angle is 50 degree. Better consideration can be made if the beam angle is lower than 0.01mrad, as at 0.01mrad, power will be received at elevation angle 30 degree and above at 99.3% availability. Therefore in order to maintain percentage of availability and to make all elevation angles possible to use, one need to cogitated lower beam divergence angle.

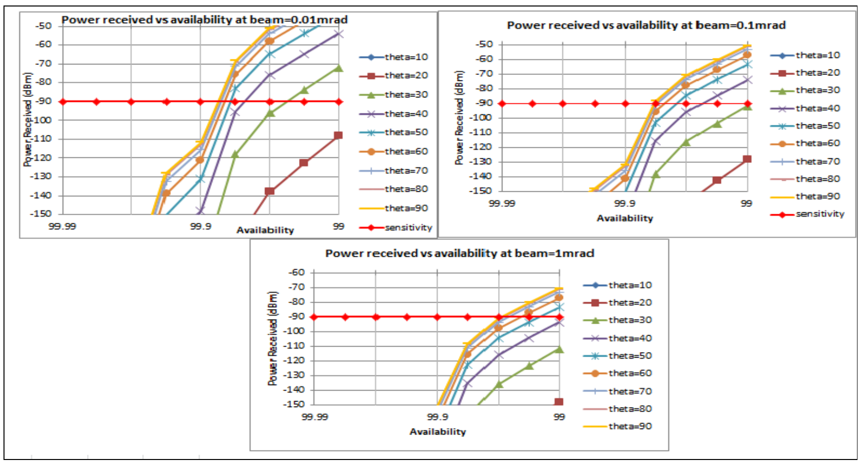

Fig. 3: Power Received (dBm) vs Availability for different elevation angles at certain values of beam divergence angle.

Last but not least, in order to see the effect of beam divergence angle to the power received and the availability, an elevation angle at 70 degree was chosen as the benchmark and red line which is receiver sensitivity is set to -90 as the limit. From the Fig. 4, it is clearly presents that, the maximum availability the link can be established is 99.7% with beam divergence needed to decrease up to 0.05mrad. The link will be impossible is one look at the availability above 99.9% even though beam divergence is set up to smaller value like 0.01mrad. If the system needs to tolerate the angle of beam divergence, it can be increased up to 3mrad with the availability of 99.0%.

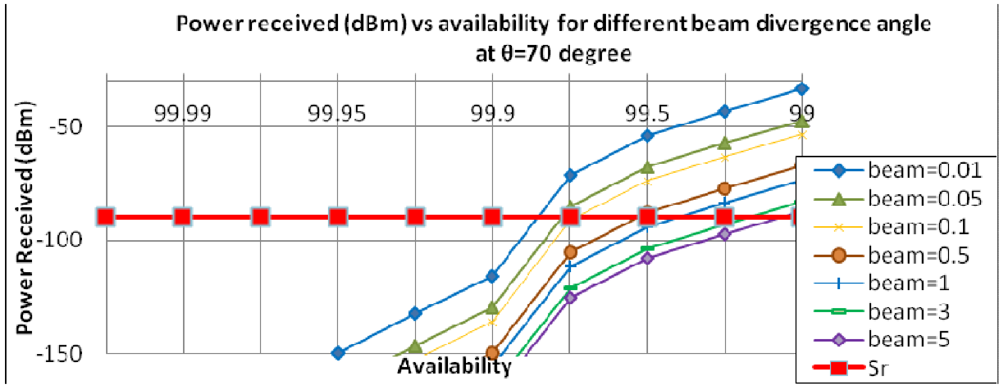

Fig. 4: Power Received vs Availability for different beam divergence angle at θ=70°.

4. CONCLUSION

FSO is a growing technology that offers high data rates which is suitable for future near-Earth, solar system, and space applications. This paper has estimated the availability of FSO system from earth-to-satellite in tropical region . Total attenuation is calculated by adding all the attenuations contibuted by absorption, scintillation, geometrical, rain, and haze. From the analysis, there are three main parameters that can be compensated for each other which are availability, elevation angles, and beam divergence angles. Furthermore, attenuations during rain is very high which contributes significantly the availability of the link. For example, at elevation angle 60 degree, rain attenuation at 0.001% is 513.1dB, 0.01% is 253.9dB, 0.1% is 104.5dB, and 1.0% is 20.47dB. FSO link is feasible to establish from earth to satellite if the availability is set to 99.5% with elevation angle higher than 40 degree and beam divergence angle is lower than 0.01mrad. If one need to decrease the elevation angle, beam divergence angle need to decrease or to increase transmit power for same availability. It is recommended to design the feasible link with availability 99.0% and beam divergence angle 0.01mrad in order to have lower elevation angles which is 30 degree. This result can be as a benchmark in designing FSO system for earth-to-space.

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