Optical Wireless Link Budget Analysis for Optical Wireless Communication Networks

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Abstract— Power link budgets are prepared for wireless optical communication systems to illustrate the optical losses that happen during transmission. This paper has presented optical wireless links which offer ultra multi gigabit per second data rates and low system complexity. For ground space and terrestrial communication systems, these links suffer from atmospheric loss mainly due to fog, and scintillation. Optical wireless links provide high bandwidth solution to the last mile access bottleneck. However, an appreciable availability of the link is always a concern. Wireless optical links are highly weather dependent and fog is the major attenuating factor reducing the link availability. Link margin, received signal power, transmission bit rate, bit rate distance product, signal to noise ratio (SNR), and bit error rate (BER) are the major interesting design parameters in the current study.

Index Terms— Link Margin, Signal to noise ratio, High visibility, Bit error rate, Received power, Transmission distance, and Bit rate.

I. INTRODUCTION

The optical wireless communication (OWC) system has attracted significant interest because it can solve the last mile problem in urban environments. The last mile problem is when Internet providers cannot connect the fiber optic cables to every household user because of the high installation costs. The only disadvantage of the OWC system is that its performance depends strongly on weather conditions. Fog and clouds scatter and absorb the optical signal, which causes transmission errors. Most previous studies consider only single-scattering effects and assume that the received signal has no intersymbol interference (ISI), which is true only for light-fog conditions [1]. Maintaining a clear line of sight (LOS) between transmit and receive terminals is the biggest challenge to establish optical wireless links in the free space especially in the troposphere [2]. The LOS is diminished due to many atmospheric influences like fog, rain, snow, dust, sleet, clouds and temporary physical obstructions like e.g., birds and aeroplanes [3]. Moreover, the electromagnetic interaction of the transmitted optical signal with different atmospheric effects results in complex processes like scattering, absorption and extinction that are a function of particle physical parameters. Hence the local atmospheric weather conditions mainly determine the availability and reliability of such optical wireless links since there is always a threat of downtime of optical wireless link caused by adverse weather conditions [4]. Optical wireless links are also influenced by atmospheric temperature that varies both in spatial and temporal domains. The variation of temperature in the optical wireless channel is a function of atmospheric pressure and the atmospheric wind speed. This effect is commonly known as optical turbulence or scintillation effect and causes received signal irradiance or power fades in conjunction with the variation of temperature along the propagation path. As a result of this scintillation phenomenon, the optical wireless channel distance and the capacity are reduced. Thereby restricting the regions and times where optical wireless links can be used potentially. In order to take full advantage of the tremendous usefulness of optical wireless technology require a proper characterization of different atmospheric effects influences and a meaningful interpretation of the filed measurements in such adverse conditions [5]. The Optical Wireless Communication is the only elucidation to the next generation wireless communication owing to a quantity of advantages over the existing RF wireless systems are, large information bandwidth, low transmitted power, high directionality, high speed data transmission (Gbps), high signal security, free from electromagnetic interference, very less bit error rate (10^-12), size and weight of the optical components are very small. Optical Wireless communication, also known as free space optical (FSO), has emerged as a commercially viable alternative to radio frequency (RF) and millimeter wave wireless for reliable and rapid deployment of data and voice networks. RF and millimeter wave technologies allow rapid deployment of wireless networks with data rates from tens of Mb/s (point-to-multipoint) up to several hundred Mb/s (point-to-point). Though emerging license free bands appear promising, they still have certain bandwidth and range limitations [6]. Optical wireless can augment RF and millimeter wave links with very high (>1 Gb/s) bandwidth. In fact, it is widely believed that optical wireless is best suited for multi Gbps communication. The general acceptance of free space laser communication (lasercom) or optical wireless as the preferred wireless carrier of high bandwidth data has been hampered by the potential downtime of these lasercom systems in heavy, visibility limiting, weather [7-9].

In the present study, broadband spectrum of optical wireless communication is available, which can fulfill the requirements of high speed wireless communication. This is the basic advantage of optical wireless communication over conventional wireless communication technologies. Wireless optical communication system has received a great deal of attention lately both in the military and civilian information society due to its potentially high capacity, rapid deployment, portability and high security. Therefore we have employed high bit rate capacity technique namely modified Shannon transmission technique over wide range of the affecting parameters for increasing signal to noise...
ratio (SNR) and decreasing bit error rate (BER) and then to increase the transmission bit rates over wireless optical communication systems.

II. SYSTEM MODEL ANALYSIS

In a terrestrial free space optics (FSO), the communication transceivers are typically located in the troposphere. Troposphere is home to all kinds of weather phenomena and plays a very detrimental role for FSO communications in lower visibility range conditions mainly due to rain, snow, fog and clouds. The estimated of fog, snow and rain attenuation effects using empirical models as mentioned in Ref. [10]:

$$\alpha_{fog}(\lambda) = \frac{3.912}{V} \left( \frac{\lambda}{55 \times 10^3} \right)^q$$

(1)

Where V is visibility range in km, $\lambda$ is transmission wavelength in μm. $\alpha_{fog}(\lambda)$ is the total extinction coefficient and q is the size distribution coefficient of scattering related to size distribution of the droplets. In case of clear or foggy weather with no rain or snow, Ref. [11, 12] approximations of the q parameter to compute the fog attenuation, that are very accurate for the narrow wavelength range between 1.3–1.55 μm which equal 0.585 V/0.55 for 0.5 km ≤ V ≤ 6 km, 1.3 when 6 km ≤ V ≤ 50 km and equal zero for V ≤ 0.5 km. Transmitted optical pulses in free space are mainly influenced by two main mechanisms of signal power loss, absorption and scattering. Absorption is mainly due to water vapoors and carbon dioxide, and depends on the water vapour content that is dependent on the altitude and humidity. By appropriate selection of optical wavelengths for transmission the losses due to absorption can be minimized. It was found that scattering is the main mechanism of optical power loss as the optical beam looses intensity and density due to scattering. The beam loss due to scattering can be calculated from the following empirical, visibility range dependent formula [13]:

$$\alpha_{scat}(\lambda) = 17 \left( \frac{550}{\lambda} \right)^{0.199V}$$

(2)

Where V is visibility range in km, $\lambda$ is transmission wavelength in μm. Then the total attenuation of wireless medium communication system can be estimated as:

$$\alpha = \alpha_{fog}(\lambda) + \alpha_{snow} + \alpha_{rain} + \alpha_{scat}(\lambda)$$

(3)

When the optical signal passes through the atmosphere, it is randomly attenuated by fog and rain. Although fog is the main attenuation factor for optical wireless links, the rain attenuation effect cannot be ignored, in particular in environments where rain is more frequent than fog. As the size of water droplets of rain increases, they become large enough to cause reflection and refractive processes. These droplets cause wavelength independent scattering [13]. It was found that the resulting attenuation increases linearly with rainfall rate; furthermore the mean of the raindrops size is in the order of a few millimeters and it increases with the rainfall rate [14]. Let R be the rain rate in mm/h, the specific attenuation of wireless optical link is given by [15]:

$$\alpha_{rain} = 1.076 R^{0.67} \text{ dB/km}$$

(4)

If S is the snow rate in mm/h then specific attenuation in dB/km is given by [16, 17] as:

$$\alpha_{snow} = a S^b$$

(5)

If $\lambda$ is the wavelength, the parameters a and b for dry snow are given as the following:

$$a = 5.42 \times 10^{-4} \lambda, b = 1.38$$

(6)

The maximum propagation distance (L) for meeting the high visibility requirements is given by [18, 19]:

$$L = 10^{-\alpha/20}$$

(7)

The main objective of wireless optical link design is to get as much light as possible from one end to the other in order to receive a stronger signal that would result in higher link receive a stronger signal that would result in higher link margin and greater link availability. The basic formula for a typical optical link is an exponential decaying as function of the path length $L_{\text{opt}}$ as the following expression [19]:

$$P_R = P_T \frac{D_I^2}{(D_s + (L_{\text{div}} + L)^2) e^{-\alpha L}}$$

(8)

Where $P_R$ is the received power after traveling the path length L through the losssy medium, $P_T$ is the initial transmitted power, $D_s$ is the diameter of the receiver aperture, $\alpha$ is the total attenuation coefficient of the medium, $D_t$ is the diameter of the transmitter lens, $L_{\text{div}}$ is the transmitter divergence of the beam, and $L_{\text{div}}$ is the transmitter divergence of the beam can be given by:

$$L_{\text{div}} = \frac{720 \lambda}{\pi^2 D_t}$$

(9)

Along with the beam size there is the problem of collecting enough light to receive the signal. The larger the beam is at the receiver the lower the photon density that is collected through the receiving aperture. Since line of sight is so critical, the system would need to make use of a beam divergence or diffused beam approach, which involves a large field of view that toleration substantial line of sight interference without significant impact on overall signal quality. Link design parameters consists of two parts link design parameters consists of two parts: internal system parameters (system related parameters), and external system parameters (link related parameters). These parameters collectively form link margin (LM) which mathematically is given by:

$$LM = P_R - S_R$$

(10)

Where $S_R$ is the receiver sensitivity. Link margin (LM) is a ratio of the available received power on a clear day (at it is a ratio of the available received power on a clear day (at a given range) to the receiver power sensitivity required to meet the bit error rate (BER) specification. The SNR requirements for modulation scheme at a fixed data rate of one Gbit/sec is obtained from the following formula [20]:

$$SNR = P_T - 30 + G_T + G_R - 20 \log \left( \frac{4\pi}{\lambda} \right) - 10 \log (k_B \cdot B \cdot W \cdot T) - a - NF - F_m$$

(11)

Where $P_T$ is the transmitter power, $G_T$ is the transmitter antenna gain, $G_R$ is the receiver antenna gain, $\lambda$ is the optical signal wavelength, $k_B$ is the Boltzmann’s constant (1.38x10^{-23} J/K), Receiver Bandwidth (BW= 1 MHz), T is the ambient temperature in K., Receiver Noise Figure, $F_m$ is the Fade margin, and a is the total attenuation in dB/km. The
transmitter and receiver antenna gains can be expressed as the following formulas:

\[ G_T = \frac{32}{L_{div}} \]  
(12)

\[ G_R = \left( \frac{\pi D_r}{\lambda} \right)^2 \]  
(13)

For most PIN receivers, the noise is generally thermally limited, which independent of signal current. The bit error rate (BER) is related to the signal to noise ratio as follows [24]:

\[ BER = \left( \frac{2}{\pi \cdot SNR} \right) \exp \left( -\frac{SNR}{8} \right) \]  
(14)

### III. SIMULATION RESULTS AND DISCUSSIONS

We have investigated the high quality and best performance of wireless optical communication networks for high visibility line of sight between transmitter and receiver to upgrade signal to noise ratio, received power, link margin, transmission bit rate and decreased BER and then to upgrade the transmission bit distance product.

<table>
<thead>
<tr>
<th>Table 1: Proposed operating parameters for wireless optical link design [3, 5, 8, 12, 20].</th>
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<tbody>
<tr>
<td><strong>Operating parameter</strong></td>
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<tr>
<td>-----------------------------------------------</td>
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<tr>
<td>Ambient temperature (T)</td>
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<tr>
<td>Transmitted power (P_T)</td>
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<tr>
<td>Operating signal wavelength (λ)</td>
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<tr>
<td>Fade margin (F_m)</td>
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<tr>
<td>Transmitting antenna diameter (D_t)</td>
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<tr>
<td>Receiving antenna diameter (D_r)</td>
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<td>Receiver Sensitivity (S_R)</td>
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<tr>
<td>Snow rate, S</td>
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<td>Boltzmann’s constant (K)</td>
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<td>Noise Figure (F)</td>
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<td>Visibility, V</td>
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Based on the modeling equations analysis and the assumed set of the operating system parameters as shown in Table 1, the following facts are assured as shown in the series of Figs. (1-11):

i) As shown in the series of Figs. (1-3) have assured that maximum propagation distance increases with increasing both operating optical signal wavelength and visibility range. While it is observed that with increasing visibility range leads to the decreased of both received signal power and link margin.
Fig. 2. Received power in relation to visibility and different optical transmission windows at the assumed set of the operating parameters.

Fig. 3. Link margin in relation to visibility and different optical transmission windows at the assumed set of the operating parameters.

Fig. 4. Signal to noise ratio in relation to ambient temperature and different high visibility ranges at the assumed set of the operating parameters.
Fig. 5. Signal to noise ratio in relation to ambient temperature and different low visibility ranges at the assumed set of the operating parameters.

Fig. 6. Signal to noise ratio in relation to ambient temperature and different high visibility ranges at the assumed set of the operating parameters.

Fig. 7. Signal to noise ratio in relation to ambient temperature and different low visibility ranges at the assumed set of the operating parameters.
Fig. 8. Bit error rate in relation to ambient temperature and different high visibility ranges at the assumed set of the operating parameters.

Fig. 9. Bit error rate in relation to ambient temperature and different low visibility ranges at the assumed set of the operating parameters.

Fig. 10. Bit error rate in relation to ambient temperature and different high visibility ranges at the assumed set of the operating parameters.
As shown in Figs. (4-11) have indicated that signal to noise ratio increases and bit error rate decreases with increasing operating optical signal wavelength and decreasing ambient temperature for both low and high visibilities range. It is observed that high visibility region has presented higher SNR and lower BER compared to low visibility region.

IV. CONCLUSIONS

In a summary, high visibility optical wireless communication links in optical wireless communication networks have presented higher propagation distances, SNR, transmission bit rate, bit rate distance product, and lower BER and link margin. It is theoretically found that the increased operating optical signal wavelength and the decreasing ambient temperature, this lead to the increased propagation distance, SNR, bit rate distance product, and the decreased link margin and BER.

REFERENCES


Author's Profile

Dr. Ahmed Nabih Zaki Rashed was born in Menouf city, Menoufia State, Egypt country in 23 July, 1976. Received the B.Sc., M.Sc., and Ph.D. scientific degrees in the Electronics and Electrical Communications Engineering Department from Faculty of Electronic Engineering, Menoufia University in 1999, 2005, and 2010 respectively. Currently, his job carrier is a scientific lecturer in Electronics and Electrical Communications Engineering Department, Faculty of Electronic Engineering, Menoufia university, Menouf.

Postal Menouf city code: 32951, EGYPT. His scientific master science thesis has focused on polymer fibers in optical access communication systems. Moreover his scientific Ph. D. thesis has focused on recent applications in linear or nonlinear passive or active in optical networks. His interesting research mainly focuses on transmission capacity, a data rate product and long transmission distances of passive and active optical communication networks, wireless communication, radio over fiber communication systems, and optical network security and management. He has published many high scientific research papers in high quality and technical international journals in the field of advanced communication systems, optoelectronic devices, and passive optical access communication networks. His areas of interest and experience in optical communication systems, advanced optical communication networks, wireless optical access networks, analog communication systems, optical filters and Sensors. As well as he is editorial board member in high academic scientific International research Journals. Moreover he is a reviewer member in high impact scientific research international journals in the field of electronics, optical communication systems, optoelectronics, information technology and advanced optical communication systems and networks.