Free Space Optical Wireless Communication Link Analysis for LEO Satellites based Future Generation Maritime Networks

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Abstract

The aim of future-generation networks is the global reach of the communication network. Terrestrial networks are expanding at the desired rate, but there is still no well-established maritime data traffic transmission infrastructure. Our proposal provides a heterogeneous network architecture of 6G communication systems for marine users' global connectivity and discusses optical light spectrum communication. However, the radio frequency (RF) is rapidly diminishing because of a considerable range of uses. Therefore, optical light communication is, thus, an effective candidate for the LEO satellite-based communication. The higher data rates, security, lower power consumption, and the LEO satellite mass reduction promise the advantages of free-space-optical communication. The findings of our calculations can be used to predict the possibilities of the LEO satellite equipment and assess space optical connectivity prospects in the future wireless networks.

I. Introduction

The connected world is the agenda of 6G, which needs to ensure worldwide connectivity. Therefore, humans' activities will expand dramatically from space to air, ground, and sea environment in this era. To ensure the 6G networks' worldwide wireless coverage, it is necessary to integrate marine users to form a multi-dimensional space-air-ground-sea network. Moreover, 6G networks will differ from the current network setups because of zero-touch and intent-based to enhance network efficiency, improve maintenance, and reduce operating costs [1]. This network consists of a huge number of diverse and vertical applications that will be convoluted and multi-dimensional, i.e., imaging, radar, positioning, navigation [2], sensing [3], control, caching, computing, and communication [4]. Moreover, its framework will consider integrating networks with extremely low latency in wireless communication with super-high throughput demands [1].

However, to provide the application mentioned above, it is difficult for the existing radio frequency spectrum (RF). With the ever-growing demand for wireless communication, the RF spectrum is pumped by a new paradigm, i.e., artificial intelligent networks, autonomous vehicles, augmented reality, and virtual reality; these trends make the RF spectrum inefficient to fulfill the quality of service (QoS) demands of wireless networks. Therefore, it is necessary to investigate the optical spectrum for the wireless network's communication. The optical spectrum is now a key enabler for the Internet worldwide. In addition to linking all continents, optical fiber communication networks form the core of modern communication networks that provide high-speed data connectivity to metropolises, villages, towns, and, increasingly, homes. Extending the optical fiber medium for last-mile networking and smartphone communication to include the free-space medium not only seems to be a natural step but also one that is reasonably easy to take [5].

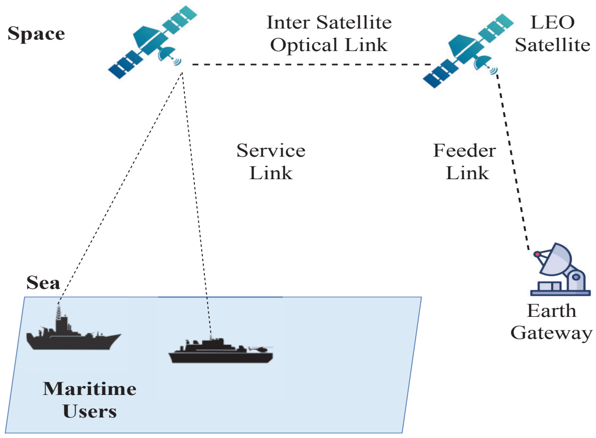

Fig. 1: Illustration of Maritime Communication Network

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II. Inter-Satellite Link Analysis

Inter-satellite link (ISL) is a link between satellites, and this type of link is important because ISL allows direct communication and sharing of information between satellites and can be a ground-based data relay. RF communication is the most common type of communication for this scenario. However, for the future, the interest in another form of communication, namely free-space optical (FSO) communication, is growing. FSO communication can offer many advantages over RF. We assumed that the transmission power and signal wavelength are very generic parameters mentioned in table I. We consider the On-Off Keying (OOK) scheme for the modulation of the FSO signal, which can be stated as follows;

$$P_{\text{TX}}(t) = \sum 2P_{\text{TX}} b_n \operatorname{rect}\left(\frac{t - nT_b}{T_b}\right), \tag{1}$$

where $P_{\text{TX}}(t)$, P_{TX} indicates the instantaneous and average optical power, respectively. Moreover, T_b represents the reciprocal of datarate (C_b) and $b_n \in \{0, 1\}$ indicate each bit which need to transmit. Moreover, $rect$ is used to obtain the rectangular waveform in pulses. The energy need to require for the transmission of per bit in FSO can be given as;

$$J_b = nhf, \tag{2}$$

where n is the average photons detected per bit, h indicates Planck's constant, and f represents the signal's frequency. Therefore, the minimum threshold power at the receiver is stated as;

$$P_{\text{th}} = \frac{J_b}{T_b} = nhfC_b. \tag{3}$$

In this link architecture, we consider path loss and gain linearly to get the actual receiver power, which is;

$$P_{\text{RX}} = \xi_{\text{RX}} g_{\text{TX}} P_{\text{TX}}, \tag{4}$$

where ξ_{RX} indicate the path loss and g_{TX} represents the gain of the link. FSO is based on a laser beam that is specifically guided. Thus, the divergence angle (ϕ_{di}) is one of the most important parameters in FSO communication. Therefore, the gain of transmuting and loss of receiving side, both are dependent upon divergence angle can be stated as;

$$g_{\text{TX}} = \frac{e}{e_o}, \tag{5}$$

where e indicate the intensity of radiant and e_o is stated as;

$$e_o = \frac{P_{\text{TX}}}{4\pi},$$

$$e_o = \frac{P_{\text{TX}}}{2\pi}(m + 1),$$

$$m = \frac{ln2}{ln(\cos\phi_{di})},$$

where m indicate the Lambertian order [6], which defines the divergence of signal beam. Therefore, the pathloss experienced by receiver is given by;

$$\xi_{\text{RX}} = \frac{A_{\text{RX}}}{4\pi r^2}, \tag{6}$$

where $A_{\text{RX}} = \frac{\pi}{4d_{\text{RX}}^2}$ represents the area where the beam target the receiver (assuming the angle of incidence is equal to 0), which inturn provides the gain. This area is dependent upon the the diameter d_{RX} of receiving side, and r is the distance between satellites. The actual receive power at the receiver can be stated as [7];

$$\begin{aligned} P_{\text{RX}} &= \frac{P_{\text{TX}}}{4\pi r^2} \cdot \frac{1}{e_o} \cdot \frac{A_{\text{RX}}}{r^2} \\ &= \frac{A_{\text{RX}}}{2\pi r^2}\left(1 - \frac{ln2}{ln(\cos\phi_{\text{di}})}\right) P_{\text{TX}}. \end{aligned} \tag{7}$$

Therefore, to trigger the receiver, this power equation can be used to calculate the minimum threshold.

III. Link Sensitivity, Error Probability, and Noise Analysis

The photon energy can be represented as;

$$E = hf, \tag{8}$$

where h is Planck constant and f is the optical frequency. As mentioned earlier, the minimum energy on the receiver side to detect anything per bit can be stated as;

$$E_{\text{th}} = N_{\text{ph}} hf, \tag{9}$$

where N_{ph} is the average number of photons that needed to detect 1 bit of information. Therefore, minimum required receive power (maximum sensitivity):

$$P_{\text{th}} = 10\log_{10}\left(\frac{E_{\text{th}}B}{10^{-3}}\right), \tag{10}$$

where B is the channel bandwidth. The Bit Error Rate (BER) depends on the type of the modulation, received power, noise and responsivity of the detector system. We assume Gaussian noise and represents BER of the On-off keying (OOK) in PIN case:

$$\begin{aligned} P_b &= \frac{1}{2}\operatorname{ercf}\left(\sqrt{\frac{\zeta}{2}}\right) \\ &= \frac{1}{2}\operatorname{ercf}\left(\sqrt{\frac{P_{\text{th}}^2\gamma^2}{2\sigma^2}}\right), \end{aligned} \tag{11}$$

where ζ is the Signal-to-Noise ratio, σ^2 is the noise variance (noise power) and γ is the photodiode, and the operator $\operatorname{erfc}(\cdot)$ is the complimentary error function which can be stated as;

$$\operatorname{erfc}(x) = \frac{1}{\pi}\int_x^\infty e^{-t^2} dt. \tag{12}$$

The bit error rate (BER) for the p-intrinsic-n (PIN) diode can be stated as;

$$P_b = \frac{1}{2}\operatorname{erfc}\left(\frac{\gamma P_{\text{th,PIN}}}{\sqrt{2\sigma^2}}\right), \tag{13}$$

TABLE I: Simulation Parameters

Parameters	Values
h	$6.62607004e-34\ \ m^2$ kg/s
T	290 K
k	$1.38064852e-23$
C_d	$2 \times 1e-12$ F
q	$1.60217662 \times 1e-19$ C
P_{TX}	1 W = 30 dBm
r	100 km
λ	1550×10^-9 m
C_b	1 Mbps

which can be modified by making $P_b = 10^-9$ as;

$$P_{\text{th}} = \frac{\text{erfcinv}\left(2P_b\right)\sqrt{2\sigma^2}}{\gamma} \quad [W], \tag{14}$$

Similarly, The bit error rate (BER) for the avalanche photodiode (APD) can be stated as;

$$P_b = \frac{1}{2}\,\text{erfc}\left(\frac{\gamma M P_{\text{th,APD}}}{\sqrt{2\sigma^2}}\right), \tag{15}$$

which can be simplified as;

$$P_{\text{th}} = \frac{\text{erfcinv}\left(2P_b\right)\sqrt{2\sigma^2}}{\gamma M}, \tag{16}$$

where M is the gain of APD. We need to observe the thermal noise effect on this link for PIN, which can stated as;

$$\begin{aligned} \chi^2_{\text{PIN}} &= \left(\frac{4kT}{R_f} + 2qI_{\text{BE}}\right) I_2 R_b \\ &= N_0 + 2qI_{\text{BE}} I_2 C_b, \end{aligned} \tag{17}$$

where T represents the absolute temperature, k indicate the Boltzmann constant, $R_f = \frac{100}{2\pi c_d C_b}$ represents the forward resistance, c_d indicate the capacitance of photodiode, q represents the charge on electron, $I_{\text{BE}} = \frac{I_c}{\beta}$ indicate the base-emitter current, I_2 is the Personick integral for thermal noise, R_b indicate the bit rate, and N_o represents the noise spectral density. Similarly, the thermal noise for APD

$$\begin{aligned} \chi^2_{\text{APD}} &= \frac{4kT}{R_f} I_2 R_b + 2qI_d M^2_{\text{Si}} F_{\text{Si}} I_2 C_b \\ &= N_0 + 2qI_2 C_b\left(I_{\text{BE}} + M^2_{\text{Si}} F_{\text{Si}} I_d\right) \\ &\approx N_0 + 2qI_2 I_d C_b M^2_{\text{Si}} F_{\text{Si}}, \end{aligned} \tag{18}$$

where I_d indicate the dark current, M_{Si} is the silicon gain, and F_{Si} represents the excess noise factor.

IV. Simulation Results and Discussion

To depict the link analysis in the simulation results, we deployed the link model in the Python environment. We consider the dependence between divergence angle, lower power, and receiver aperture size. The main parameters which are considered for this simulation are given in table I. We consider that two LEO satellites need to relay the communication data for maritime traffic by using the optical light spectrum. Our simulation result is given in Fig. 2, which deduced that for

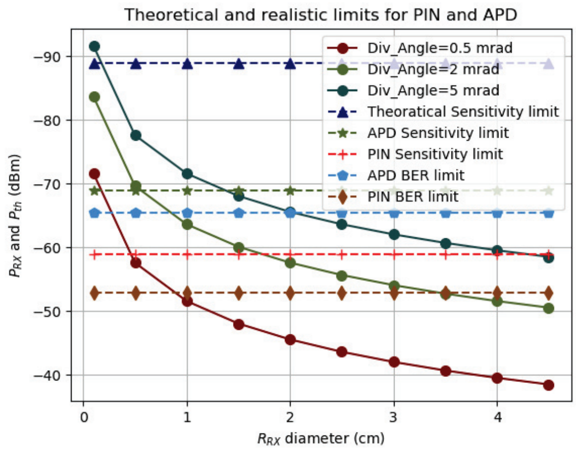

Fig. 2: Received Power vs Receiver Diameter

the certain C_b, the most appropriate parameters of angle and aperture are laying below realistic receive power limit.

V. Conclusion

This paper studied the fundamental analysis of an LED optical light communication device in a maritime communication with the LEO satellite-based system. It is necessary to comply with optical lighting and optical transmission requirements in an optical light communication system. These specifications were addressed in this study, and an example of architecture was presented. Parameters that mostly affect the efficiency of the communications system were also presented.

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