

Link Budget Analysis for Free-Space Optical Satellite Networks

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Abstract—Free-space optical satellite networks (FSOSNs) will employ free-space optical links between satellites and between satellites and ground stations, and the link budget for optical inter-satellite links and optical uplink/downlink is analyzed in this paper. The satellites in these FSOSNs will have limited energy and thereby limited power, and we investigate the effect of link distance and link margin on optical inter-satellite link transmission power, and the effect of slant distance, elevation angle, and link margin on optical uplink/downlink transmission power. We model these optical links and compute the results for various parameters. We observe that the transmission power increases when the link distance increases for inter-satellite and uplink/downlink communications, while the transmission power decreases when the elevation angle increases for uplink/downlink transmission. We also observe an inverse relationship between link margin and link distance. Furthermore, we highlight some practical insights and design guidelines gained from this analysis.

Index Terms—Free-space optical satellite networks, link budget, optical inter-satellite link, optical uplink/downlink, transmission power.

I. INTRODUCTION

Free-space optical communication is receiving more and more attention these days as it is a promising and rapidly developing technology for wireless communication between satellites due to its larger link bandwidth, license free spectrum, higher link data rate, better security, smaller antenna size, lower terminal mass, and lower terminal power consumption compared to radio frequency-based satellite communication [1]. The free-space optical satellite networks (FSOSNs) based on upcoming low Earth orbit (LEO) satellite constellations, such as SpaceX's Starlink [2], and Telesat's Lightspeed [3], are expected to employ optical or laser inter-satellite links while optical or laser uplink and downlink communications are envisioned for future FSOSNs [4], [5].

A satellite harvests solar energy via its solar panels and stores it in its battery. The lifetime of a satellite's battery is determined by the number of charging and recharging cycles, and a satellite's working lifetime is equal to its battery's lifetime. If the transmission power of a link between satellites or between a satellite and a ground station is high, the satellite needs more energy from the battery, which results in more frequent discharging/charging and leads to shorter battery lifetime and thereby shorter satellite lifetime. Once the battery is depleted, the satellite will lose power, become inoperative,

and need to be replaced and de-orbited. In this way, the analysis and design of link budget for FSOSNs is important.

In this work, we analyze the link budget for communication over optical inter-satellite links and optical uplink and downlink communications. Since satellites are orbiting around the Earth in space, the propagation medium for inter-satellite communication is vacuum of space, and the optical beams propagate without attenuation and fading due to the propagation medium. For uplink and downlink, the optical beams must go through the atmosphere, which causes multiple attenuation and fading due to scattering and scintillation, and the required transmission power should be adjusted accordingly to compensate for the loss caused by the atmosphere.

In the link budget analysis of FSOSNs, we first vary the link distance and set the required received power as -35.5 dBm, data rate as 10 Gbps, and bit error rate as 10^{-12} [6]. We observe that the link transmission power increases with the increase in link distance. Then, we vary the elevation angle for uplink/downlink and fix the altitude of the satellite. We find out that the atmospheric attenuation increases when the elevation angle decreases. We also investigate the relationship between link margin and link distance for both optical inter-satellite link and optical uplink/downlink, and the results show an inverse relationship between the two. Furthermore, some practical insights and design guidelines that emerge from this analysis are discussed. To the best of our knowledge, for the first time in literature we investigate transmission power in terms of link distance, link margin, and elevation angle for both optical inter-satellite link and optical uplink/downlink.

The rest of the paper is organized as follows. The related work is discussed in Section II. Section III presents the system model, including the link budget modelling for optical inter-satellite link and optical uplink/downlink. Section IV provides the results and analysis of various factors affecting link transmission power. Section V discusses practical insights and design guidelines. Conclusions and future work are summarized in Section VI.

II. RELATED WORK

In the literature, there are various studies that consider link budget analysis for optical satellite communications as can be seen in [6]–[10] and the references therein. Different from the current literature, we investigate both optical inter-satellite link between LEO satellites and optical uplink/downlink between

LEO satellites and ground stations that can establish FSOSNs in space. In [6], the authors study the bit error rate vs. received power for optical inter-satellite links, while we focus on examining the factors affecting link transmission power for optical inter-satellite link and optical uplink/downlink in LEO FSOSNs. In [7], the authors investigate the optical inter-satellite link with data rate of 10 Gbps and the relationship between link margin and link distance, while in this work we also study the link margin and slant distance for optical uplink/downlink.

In [8], the authors mention the link budget model for optical inter-satellite link and simulate links using QPSK modulation to find relationship between link distance and data rate, while in this work we assume on-off keying (OOK) and simulate the optical links with more practical parameters. In [9], the authors give the model for optical link budget and link margin, but their analysis is based on simulation of LEO-to-GEO and GEO-to-ground optical links, while we focus on LEO-to-LEO and LEO-to-ground optical links. In [10], Mie scattering, and geometrical scattering are considered in atmospheric attenuation for optical uplink/downlink, while in this work we also investigate the effect of slant distance and elevation angle on atmospheric attenuation for optical uplink/downlink.

III. SYSTEM MODEL

This section introduces the system model for optical links in FSOSNs, which includes optical inter-satellite link model and optical uplink/downlink model as well as link margin model.

The geometrical expression of the parameters in the inter-satellite link and uplink/downlink can be found in Fig. 1. In this figure, the blue circular bound around the surface of the Earth refers to the troposphere layer of the atmosphere with height h_A km and O refers to the center of the Earth. The ground station is located at h_E km above the mean sea level, and the elevation angle (i.e., the angle between the tangential line to the surface of the Earth, shown as dashed line in Fig. 1, and the link between the ground station and the satellite Sat A) is θ_E degrees. R_E is the radius of the Earth and is considered as 6,378.1 km, and h_S is the altitude of the satellites Sat A and Sat B. The distance from O to Sat A is $R_E + h_S$ and the distance from O to ground station is $R_E + h_E$, d_A represents the distance that the optical laser beam propagates through the troposphere layer of the atmosphere, and d_{GS} is the slant distance for the uplink and downlink between satellite Sat A and ground station. d_{SS} is the distance between the two satellites Sat A and Sat B.

A. Optical Inter-Satellite Link Model

For FSOSNs, the optical links between transmitters and receivers can be classified as uplink, inter-satellite link and downlink. An optical inter-satellite link is the link between two satellites, and the propagation medium is the vacuum of space since these links exist between satellites located in space. For an optical inter-satellite link, the received power is given as

$$P_R = P_T \eta_T \eta_R G_T G_R L_T L_R L_A L_{PG}, \quad (1)$$

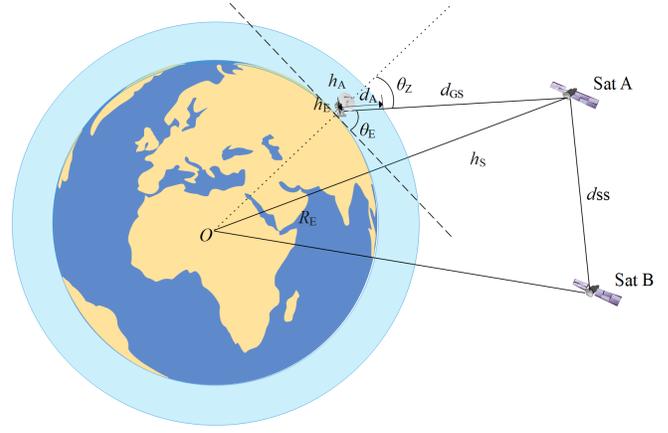


Fig. 1. Geometrical representation of parameters for inter-satellite link and uplink/downlink optical communication.

where P_R is the received power in Watts, P_T is the transmitted power in Watts, η_T is the optics efficiency of the transmitter, η_R is the optics efficiency of the receiver, G_T is the transmitter gain, G_R is the receiver gain, L_T is the transmitter pointing loss, L_R is the receiver pointing loss, and L_{PS} is the free-space path loss for the optical link between satellites [11]. The transmitter gain G_T in (1) is expressed as $G_T = 16/(\Theta_T)^2$, where Θ_T is the full transmitting divergence angle in radians [12]; the receiver gain G_R is expressed as $G_R = (D_R \pi / \lambda)^2$, where D_R is the receiver's telescope diameter in mm [12]; the transmitter pointing loss L_T is given as $L_T = \exp(-G_T(\theta_T)^2)$, where θ_T is the transmitter pointing error in radians [11]; the receiver pointing loss L_R is written as $L_R = \exp(-G_R(\theta_R)^2)$, where θ_R is the receiver pointing error in radians [11]; and the free-space path loss L_{PS} is given as

$$L_{PS} = (\lambda / 4\pi d_{SS})^2, \quad (2)$$

where λ is the operating wavelength in nm, and d_{SS} is the distance between satellites in km [11].

B. Optical Uplink/Downlink Model

Optical uplink and downlink communications between satellites and ground stations experience attenuations because of the atmosphere. Scattering is generally defined as the redirection of beam energy by particles present along the beam propagation path. In this work, we consider Mie scattering and geometrical scattering to model atmospheric attenuation as these two are the primary sources of beam scattering and thereby beam fading in the atmosphere.

To model optical uplink and downlink, atmospheric attenuation must be considered and the received power is given as

$$P_R = P_T \eta_T \eta_R G_T G_R L_T L_R L_A L_{PG}, \quad (3)$$

where L_A is the atmospheric attenuation loss, L_{PG} is the free-space path loss for links between ground stations and satellites [9] and other parameters are like the optical inter-satellite link model in (1). The slant distance (i.e., the distance between

a ground station and a satellite) for uplink/downlink d_{GS} is given as

$$d_{GS} = R(\sqrt{((R+H)/R)^2 - (\cos(\theta_E))^2} - \sin(\theta_E)), \quad (4)$$

where $R = R_E + h_E$ and $H = h_S - h_E$ [13]. The free-space path loss L_{PG} can be expressed based on slant distance as

$$L_{PG} = (\lambda/4\pi d_{GS})^2. \quad (5)$$

We consider the altitude of the ground station in (4) to model practical scenarios as in real cases the ground stations are mostly located at high places on the surface of the Earth.

1) Atmospheric Attenuation due to Mie Scattering:

Mie scattering occurs when the diameter of atmospheric particles is equal to or greater than the wavelength of the optical beam. It mainly occurs in the lower part of the atmosphere where larger particles are more abundant, and it is primarily caused by microscopic particles of water. The following expression, which can precisely model the Mie scattering effect, is appropriate for ground stations located at altitudes between 0 and 5 km above the mean sea level:

$$\rho = a(h_E)^3 + b(h_E)^2 + ch_E + d, \quad (6)$$

where ρ denotes the extinction ratio, h_E is the height of the ground station above the mean sea level in km, and a , b , c and d are the wavelength dependent empirical coefficients, which can be expressed as $a = -0.000545\lambda^2 + 0.002\lambda - 0.0038$, $b = 0.00628\lambda^2 - 0.0232\lambda + 0.00439$, $c = -0.028\lambda^2 + 0.101\lambda - 0.18$, $d = -0.228\lambda^3 + 0.922\lambda^2 - 1.26\lambda + 0.719$, and the atmospheric attenuation due to Mie scattering can be expressed as

$$I_m = \exp(-\rho/\sin(\theta_E)), \quad (7)$$

where θ_E is the elevation angle of the ground station in degrees [14].

2) Atmospheric Attenuation due to Geometrical Scattering:

Geometrical scattering is used to model the attenuation due to atmosphere that is close to the surface of the Earth and is caused by fog or dense clouds. In this model, the following expression shows the effect of geometrical scattering:

$$V = 1.002/(L_W N)^{0.6473}, \quad (8)$$

where V is the visibility in km, L_W is the liquid water content in g/m^{-3} and N is the cloud number concentration in cm^{-3} . The attenuation coefficient θ_A can be expressed as

$$\theta_A = (3.91/V)(\lambda/550)^{-\varphi}, \quad (9)$$

where φ is the particle size related coefficient given according to Kim's model [15]. The Beer-Lambert law is given as $I(z) = \exp(-\mu z)$, where μ is the attenuation coefficient that depends on wavelength and z is the distance of the transmission path [16]. For geometrical scattering, the atmospheric attenuation can be expressed using the Beer-Lambert law as

$$I_g = \exp(-\theta_A d_A), \quad (10)$$

where d_A is the distance of the optical beam through the troposphere layer of the atmosphere over which it encounters

geometrical scattering, and it can be expressed based on the zenith angle (i.e., the angle between the perpendicular to the surface of the Earth, shown as dotted line in Fig. 1, and the link between the ground station and the satellite Sat A) θ_Z as $d_A = (h_A - h_E) \sec(\theta_Z)$ [17], and it can also be calculated using the elevation angle θ_E as $d_A = (h_A - h_E) \csc(\theta_E)$, where h_A is the height of the troposphere layer of atmosphere in km, h_E is the altitude of the ground station in km, and $\theta_E = 90^\circ - \theta_Z$.

The atmospheric attenuation loss considering both Mie scattering and geometrical scattering [10] can then be calculated as

$$L_A = I_m I_g = \exp(-\rho/\sin(\theta_E)) \exp(-\theta_A d_A). \quad (11)$$

C. Link Margin Model

The performance of an optical communication system is commonly evaluated in terms of link margin, bit error rate and etc. The link margin is defined as the ratio of the received signal power and the required signal power that is needed to achieve a specific bit error rate at a given data rate. The link margin is needed to counter unexpected losses and noises, and it should be always positive to guarantee that the received signal can be received properly. The link margin can be modelled as

$$LM = P_R/P_{req}, \quad (12)$$

where P_R is the received power in mW and P_{req} is the receiver sensitivity in mW [9]. In this work, we are interested in the link transmission power. Thereby, we have to find the received power, which can be expressed based on the link margin as $P_R = LM \times P_{req}$.

We first investigate the impact of link distance and elevation angle on link transmission power with fixed link margin, and then study the relationship between link margin and link distance for fixed transmission power.

IV. RESULTS

In this section, we present the numerical results obtained for link transmission power based on link distance, link margin, and elevation angle to analyze the performance of optical uplink/downlink and optical inter-satellite link. Furthermore, we investigate the relationship between link margin and link distance for these links.

A. Transmission Power vs. Link Distance for Optical Inter-Satellite Link

We consider the optical link model parameters summarized in Table 1 to evaluate the optical inter-satellite links and uplink/downlink. These parameters are used in practical and realized optical satellite communication systems. We consider OOK as the optical link's modulation scheme. We use curve fitting technique to find the receiver sensitivity as -35.5 dBm for OOK modulation with 10 Gbps data rate and 10^{-12} bit error rate from [7]. We consider P_{req} as -35.5 dBm and set the LM as 3 dB. Based on the parameters in Table 1, we use (1) and (2) to compute the link transmission power P_T for

TABLE 1
OPTICAL LINK MODEL PARAMETERS.

Parameter	Symbol	Units	Value
Laser wavelength [6]	λ	nm	1550
Transmitter optical efficiency [8]	η_T		0.8
Receiver optical efficiency [8]	η_R		0.8
Data rate [7]	R_{data}	Gbps	10
Receiver telescope diameter [6]	D_R	mm	80
Transmitter pointing error [8]	θ_T	μrad	1
Receiver pointing error [8]	θ_R	μrad	1
Full transmitting divergence angle [6]	Θ_T	μrad	15
Receiver sensitivity [7]	P_{req}	dBm	-35.5
Bit error rate [7]			10^{-12}

TABLE 2
TRANSMISSION POWER VS. LINK DISTANCE FOR OPTICAL INTER-SATELLITE LINK.

d_{SS} (km)	L_{PS} (dB)	P_T (dBm)	P_T (W)
1000	-258.18	15.32	34.05×10^{-3}
2000	-264.20	21.34	136.20×10^{-3}
3000	-267.74	23.87	306.46×10^{-3}
4000	-270.24	27.36	544.81×10^{-3}
4500	-271.24	28.39	689.53×10^{-3}
5000	-272.18	29.30	851.27×10^{-3}
5500	-272.98	30.13	1.03
6000	-273.76	30.88	1.23
7000	-275.10	32.22	1.67
8000	-276.26	33.38	2.18
9000	-277.26	34.41	2.76
10000	-278.18	35.32	3.41

different link distances between satellites as shown in Table 2. As the table indicates, when d_{ss} increases, P_T increases as expected.

B. Transmission Power vs. Slant Distance for Optical Up-link/Downlink

For the computation of the optical uplink/downlink transmission power, the parameters related to the atmospheric attenuation are summarized in Table 3. We use (6) and (7) to compute Mie scattering I_m , which depends upon ground station altitude h_E , elevation angle θ_E , and wavelength λ . We find geometrical scattering I_g according to (8)–(10). Thereafter, we obtain the atmospheric attenuation loss L_A by using (11) and compute P_T for optical uplink/downlink as shown in Table 4 when θ_E is fixed as 40° , and LM is fixed as 3 dB. In this table, we vary the altitude of the satellite h_S and get corresponding slant distance d_{GS} using (4). With increase in h_S and thereby d_{GS} , P_T increases as shown in this table.

TABLE 3
ATMOSPHERIC ATTENUATION PARAMETERS.

Parameter	Symbol	Units	Value
Ground station height [10]	h_E	km	1
Thin cirrus cloud concentration [15]	L_W	cm^{-3}	0.5
Liquid water content [15]	N	g/m^{-3}	3.128×10^{-4}
Partial size coefficient [10]	φ		1.6
Elevation angle [2]	θ_E	degree	40
Troposphere layer height [17]	h_A	km	20

C. Transmission Power vs. Elevation Angle for Optical Up-link/Downlink

Since both Mie and geometrical scatterings are related to elevation angle θ_E between the satellite and the ground station, we further compute P_T for various elevation angles from 10° to 90° and fix the altitude of the satellite h_S as 550 km. The satellite is right above the ground station when θ_E reaches 90° , and the slant distance $d_{GS} = h_S - h_E$. We show the corresponding results in Table 5, which indicate that P_T decreases with increase in θ_E .

D. Transmission Power vs. Link Margin for Optical Inter-Satellite Link

As shown in Table 6, we compute P_T for different values of LM and d_{SS} . For a certain value of d_{SS} in this table, P_T increases with increase in LM . We also investigate the value for LM with a given P_T based on different link distances. For optical inter-satellite link, we find the value of LM that is available for establishing an optical link between satellites with 1 W P_T at different values of d_{SS} . Note that P_T of Mynaric's laser communication terminal is limited to 1 W [6]. In this table, when d_{SS} is 4,000 km, 4,500 km, 5,000 km, and 5,500 km, the value for LM that is available with 1 W P_T is 5.6 dB, 4.6 dB, 3.7 dB, and 2.9 dB, respectively, and these results are shown in red in the table.

E. Transmission Power vs. Link Margin for Optical Up-link/Downlink

Table 7 shows that P_T increases with increase in LM for a certain value of d_{GS} when θ_E is fixed at 40° . For optical uplink/downlink, we also find LM for 1 W P_T at different satellite altitudes and thereby different slant distances. In this table, when h_S is 600 km, 700 km, 800 km, and 900 km, the LM that can be achieved with 1 W P_T is 18.3 dB, 17 dB, 15.9 dB, and 15 dB, respectively, and these results are highlighted in red in the table.

V. PRACTICAL INSIGHTS AND DESIGN GUIDELINES

In this section, we provide important practical insights and design guidelines that can be helpful for practical satellite communication.

Practical Insights

- For optical inter-satellite link and optical uplink/downlink, L_{PS} and L_{PG} and thereby P_T increase as d_{SS} and d_{GS} increase. Thereby, the deployment of satellites is of critical importance to maximize their lifetime.

- The P_T needed for optical uplink/downlink is larger compared to the one required for optical inter-satellite link with same link distance. For example, for 2,000 km link distance, P_T needed for optical inter-satellite link and optical uplink/downlink is 136.20 mW and 152.05 mW, respectively.

- When θ_E is fixed at 40° , I_m and I_g remain the same irrespective of h_S . This is because both scatterings are independent of d_{GS} at a fixed θ_E and this indicates that these two attenuations only happen in the atmosphere near the Earth's surface.

TABLE 4
TRANSMISSION POWER VS. SLANT DISTANCE FOR OPTICAL UPLINK/DOWNLINK.

h_S (km)	d_{GS} (km)	L_{PG} (dB)	I_m (dB)	I_g (dB)	L_A (dB)	P_T (dBm)	P_T (W)
300	451.2	-251.27	-0.15	-0.33	-0.48	8.89	7.75×10^{-3}
400	596.7	-253.69	-0.15	-0.33	-0.48	11.32	13.55×10^{-3}
500	739.9	-255.56	-0.15	-0.33	-0.48	13.19	20.83×10^{-3}
600	881.0	-257.08	-0.15	-0.33	-0.48	14.70	29.54×10^{-3}
700	1020.1	-258.35	-0.15	-0.33	-0.48	15.98	39.60×10^{-3}
800	1157.5	-259.45	-0.15	-0.33	-0.48	17.07	50.98×10^{-3}
900	1293.2	-260.41	-0.15	-0.33	-0.48	18.04	63.64×10^{-3}
1000	1427.4	-261.27	-0.15	-0.33	-0.48	18.90	77.54×10^{-3}
1100	1560.2	-262.04	-0.15	-0.33	-0.48	19.67	92.63×10^{-3}
1200	1691.7	-262.74	-0.15	-0.33	-0.48	20.37	108.90×10^{-3}
1300	1821.9	-263.39	-0.15	-0.33	-0.48	21.01	126.31×10^{-3}
1400	1951.0	-263.98	-0.15	-0.33	-0.48	21.61	144.85×10^{-3}
1500	2079.0	-264.53	-0.15	-0.33	-0.48	22.16	164.48×10^{-3}

TABLE 5
TRANSMISSION POWER VS. ELEVATION ANGLE FOR OPTICAL UPLINK/DOWNLINK.

θ_E (°)	d_{GS} (km)	d_A (km)	L_{PG} (dB)	I_m (dB)	I_g (dB)	L_A (dB)	P_T (dBm)	P_T (W)
10	1813.4	109.4	-263.35	-0.57	-1.22	-1.79	22.28	168.96×10^{-3}
20	1291.8	55.6	-260.40	-0.29	-0.62	-0.91	18.45	70.02×10^{-3}
30	991.2	38.0	-258.10	-0.20	-0.42	-0.62	15.87	38.60×10^{-3}
40	810.7	29.6	-256.35	-0.15	-0.33	-0.48	13.98	25.01×10^{-3}
50	697.7	24.8	-255.05	-0.13	-0.26	-0.41	12.60	18.20×10^{-3}
60	625.8	21.9	-254.11	-0.11	-0.24	-0.36	11.61	14.48×10^{-3}
70	581.2	20.2	-253.47	-0.11	-0.22	-0.33	10.94	12.41×10^{-3}
80	556.8	19.3	-253.09	-0.10	-0.21	-0.32	10.55	11.35×10^{-3}
90	549.0	19.0	-252.97	-0.10	-0.21	-0.31	10.42	11.02×10^{-3}

TABLE 6
TRANSMISSION POWER VS. LINK MARGIN FOR OPTICAL INTER-SATELLITE LINK.

d_{SS} (km)	LM (dB)	P_R (dBm)	P_T (dBm)	P_T (W)
4000	4	-31.5	28.36	0.686
	5	-30.5	29.36	0.863
	5.6	-29.9	29.96	0.991
	6	-29.5	30.36	1.087
	7	-28.5	31.36	1.369
4500	3	-32.5	28.39	0.690
	4	-31.5	29.39	0.868
	4.6	-30.9	29.99	0.997
	5	-30.5	30.34	1.093
	6	-29.5	31.39	1.376
5000	2	-33.5	28.30	0.676
	3	-32.5	29.30	0.851
	3.7	-31.8	30.00	1.000
	4	-31.5	30.30	1.072
	5	-30.5	31.30	1.349
5500	1	-34.5	28.13	0.650
	2	-33.5	29.13	0.818
	2.9	-32.6	30.03	1.007
	3	-32.5	30.13	1.030
	4	-31.5	31.13	1.297

TABLE 7
TRANSMISSION POWER VS. LINK MARGIN FOR OPTICAL UPLINK/DOWNLINK.

h_S (km)	d_{GS} (km)	LM (dB)	P_R (dBm)	P_T (dBm)	P_T (W)
600	881.0	17	-18.5	28.70	0.742
		18	-17.5	29.70	0.934
		18.3	-17.2	30.00	1.001
		19	-16.5	30.70	1.176
		20	-15.5	31.70	1.480
700	1020.1	15	-20.5	27.98	0.628
		16	-19.5	28.98	0.790
		17	-18.5	29.98	0.995
		18	-17.5	30.98	1.252
		19	-16.5	31.98	1.577
800	1157.5	14	-21.5	28.07	0.642
		15	-20.5	29.07	0.808
		15.9	-19.6	29.97	0.994
		16	-19.5	30.07	1.017
		17	-18.5	31.07	1.281
900	1293.2	13	-22.5	28.04	0.636
		14	-21.5	29.04	0.801
		15	-20.5	30.04	1.009
		16	-19.5	31.04	1.270
		17	-18.5	32.04	1.599

- For optical uplink/downlink, I_m and I_g and thereby L_A vary with θ_E . However, the relationship between θ_E and L_A is not linear. L_A changes significantly when θ_E is small and for large values of θ_E , the change in L_A becomes very small. For example, L_A changes significantly when θ_E increases from 10° to 20° but changes slightly from 70° to 80° .

- With the increase of θ_E , d_{GS} and d_A decrease and reduce

L_{PG} and I_g , respectively; I_m also decreases with increase in θ_E as according to (7) the larger the θ_E the lower the I_m ; and this results in a decrease in P_T for optical uplink/downlink with increase in θ_E .

- The LM decreases when d_{SS} and d_{GS} increase at a fixed P_T , which indicates an inverse relationship. This is because L_{PS} and L_{PG} increase with increase in d_{SS} and d_{GS} ,

which degrades LM that is available with a fixed P_T . The LM for optical inter-satellite link that is available with 1 W P_T decreases when d_{SS} increases. A higher LM is available at lower h_S and thereby lower d_{GS} with 1 W P_T , and the available LM decreases with increase in h_S and d_{GS} for optical uplink/downlink.

Design Guidelines

- With 1 W P_T and 3 dB LM available to establish a 10 Gbps optical link in an FSOSN, d_{SS} is limited to 5,419 km for reliable optical inter-satellite link performance, and h_S is restricted to 4,062 km and d_{GS} is constrained to 5,125 km for reliable optical uplink/downlink performance.

- For a 10 Gbps optical inter-satellite link limited by 1 W P_T , LM reaches zero when d_{SS} is 7,654 km. The 10 Gbps optical communication link between two satellites can no longer be sustained when LM falls below zero as P_R falls below P_{req} .

- For a 10 Gbps optical uplink/downlink with a limitation of 1 W on P_T , LM reaches zero when d_{GS} is 7,240 km and h_S is 5,970 km. The satellites in an FSOSN should have h_S less than 5,970 km when θ_E is 40° and P_T is limited to 1 W, as the satellites located at a higher h_S will not be able to maintain 10 Gbps optical uplink/downlink communication.

VI. CONCLUSION

In this work, we investigated the link budget for optical inter satellite link and optical uplink/downlink in FSOSNs. We use appropriate system models for these links and study the link transmission power at different link distances, different elevation angles for uplink/downlink, and different link margins. It is observed that with the increase in link distance, the link transmission power increases due to increase in free-space path loss. The results show that the atmospheric attenuation depends upon the elevation angle between the satellite and the ground station for optical uplink/downlink, and this loss increases when the elevation angle decreases. We also investigate the relationship between link margin and link distance for a given link transmission power and link data rate. We observe that the link margin and link distance have an inverse relationship. Furthermore, some practical insights and design guidelines are provided.

In FSOSNs, satellites have an optical inter-satellite link (or laser inter-satellite link (LISL)) range for connectivity. The LISL range is a range within which a satellite can successfully establish an LISL with any other satellite that is within this range. The larger the LISL range, the more the possible connectivity, and the longer the links between satellites. In this way, fewer satellites and LISLs are needed on the path between source and destination ground stations over the FSOSN, which will reduce the latency but will result in an increase in satellite transmission power. In future, we plan to analyze this tradeoff between satellite transmission power and network latency in FSOSNs arising from different LISL ranges.

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