This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2017.2681073, IEEE Communications Letters

Cloud Free Line of Sight Prediction Modeling for Optical Satellite Communication Networks

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***Abstract*—In this Letter, analytical models for the prediction of Cloud-Free Line-of-Sight (CFLOS) probability for a single optical satellite link and for multiple spatially separated optical satellite links are presented. The presence of clouds along the slant paths causes their blockage. As a result, an on/off channel with the presence of clouds is assumed. The proposed model for the calculation of CFLOS takes into account the elevation angle of the optical satellite links, the altitude of ground stations and the spatial variability of clouds. The methodology is based on the assumption that Integrated Liquid Water Content (ILWC) follows lognormal distribution and a well-defined relationship between ILWC and liquid water density. Moreover, joint CFLOS statistics are evaluated. In addition, CFLOS probability for simultaneously available optical links for the application of spatial multiplexing transmission techniques is estimated. The models are validated through simulated results and finally, the numerical results are devoted to optical satellite network examples with a view to achieving specific availability percentage.**

***Index Terms*—Satellite networks, optical communications, Cloud variability, CFLOS probability, multiple site diversity.**

I. Introduction

Frequency congestion and the demand for broadband and interactive satellite services are leading to the employment of even higher frequency bands. A promising solution to satisfy these requirements is the use of optical spectrum for Earth-space communications. To this end, several studies have already been conducted for the use of optical bands and especially the mitigation of feeder links from radio frequency (RF) to optical band [1]-[3]. Very recently DLR Institute of Communications and Navigation achieved a free space optical link at 1.72 Tbit/s over a 10.45 km link with propagation conditions similar to a GEO satellite worst-case uplink scenario [4]. Optical frequencies are attractive since they offer hundreds of times more spectral bandwidth than the RF bands, they are very difficult to be intercepted because of the very narrow beams and no frequency coordination is required [1], [2].

However, optical links are affected by several atmospheric phenomena like rain, snow, aerosols, turbulence. For optical communications, liquid water particles which are present in clouds are the most dominant fading mechanism [1]-[3]. The attenuation induced by clouds for optical links is so severe that even the presence of clouds is considered as blockage in the optical satellite link. Therefore an on/off channel with the occurrence of clouds is assumed for the evaluation of optical satellite communication networks [5], [6]. For the reliable design of optical satellite communication systems, the Cloud-Free Line-of-Sight (CFLOS) probability for a single link or multiple links must be taken into account and should be accurately estimated. In [7] a 3-D spatially correlated cloud fields model is introduced and can be used for the computation of CFLOS. Moreover, in [8] CFLOS is computed through the generation of time series from an integrated liquid water content (ILWC) synthesizer using multi-dimensional Stochastic Differential Equations (SDEs) taking into account the temporal and spatial variability of clouds for both single and multiple optical satellite links. In [9] a methodology for the computation of correlated ground stations availability for diversity scenarios is demonstrated while an optimization technique for ground station selection is introduced. Mathematical formulations for the estimation of ground station availability for single links and diversity scenarios for spatially correlated cloud occurrence values are given in [5]. More recently, in [6] a novel approach for the estimation of the availability of an optical ground station taking into account both the temporal and spatial correlation of clouds is reported.

The objective of this contribution is to present a new and simple physical and mathematical theoretical model for the prediction of CFLOS probability along a single slant path and for separated on spatial domain multiple optical satellite links. For the accurate evaluation of CFLOS the elevation angle of the slant path, the altitude of ground stations and the spatial variability of clouds are considered. In comparison to [7] and [8] in which these characteristics are also included, this paper proposes analytical expressions which effectively reduce the computational effort.

Now, the main assumptions of this contribution will be demonstrated: a) ILWC (L) can be described by lognormal distribution [10], [11], b) an explicit expression between ILWC and liquid water content is used, c) the correlation in spatial domain of ILWC is taken into account, d) statistical parameters of ILWC are used which are assumed constant along the slant path. Here, it must be noted that the input parameters to the model are susceptible to a measurement error. The numerical values of the statistical parameters contain an uncertainty, since they are obtained either from databases or measurements. An elegant analysis, on the effects of the errors in statistical modeling of the cloud fraction data sets, on the estimation of the availability of optical ground networks, is presented in [6].

The remainder of the paper is structured as follows: In Section II the methodology for the computation of CFLOS for single links is described. In Section III analytical formulas for the computation of CFLOS probability for multiple satellite links shaping a site diversity scenario are shown. Furthermore, CFLOS probability for a given number of simultaneously available links for spatial multiplexing transmission technique

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is presented. In Section IV the proposed methodology is validated with simulation results and various numerical results for different scenarios and cases are presented. Finally, Section V concludes the Letter.

II. CFLOS For Single Optical Satellite Link

Cloud masses can be defined knowing the following characteristics: the cloud base, the liquid water content and the vertical extent of clouds. For a vertical single link, CFLOS probability is the complementary probability of clouds occurrence, that is, 1 minus the probability of clouds presence (P_{CLW}). P_{CLW} is defined for a vertical link at the geographical location of interest and it can be derived from ITU-R P. 840-6 [12]. For slant paths, it is assumed that clouds impair the link if a cloud formation is present at the slant path. Considering a satellite slant path through the cloud layer (See Fig. 1) then the probability of CFLOS is equal to the probability that the line integral of the liquid water density (C) is equal to zero, i.e.:

$$P_{CFLOS} = P\left(\int_C \tilde{w} ds = 0\right) \tag{1}$$

where $\int_C \tilde{w} ds$ is the line integral of liquid water density over the line of slant path $C(x, y, z)$. The liquid water density on a point (x,y,z) is given by [8]:

$$\tilde{w}\left(x, y, z\right) = \begin{cases} \frac{L(x,y)(z-h_0)^{c_1-1} e^{-(z-h_0)/c_2}}{(c_2)^{c_1}\,\Gamma(c_1)} & \text{for } z \geq h_0 \\ 0 & \text{for } z < h_0 \end{cases}$$

$$\begin{aligned} c_1\left(L\right) &= 4.27\ e^{-4.93\,(L+0.06)} + 54.12\ e^{-61.25\ (L+0.06)} + 1.71 \\ c_2\left(L\right) &= 3.17\ c_1{}^{-3.04} + 0.074 \end{aligned} \tag{2}$$

where $L(x, y)$ is the integrated liquid water content on point (x, y), h_0 is cloud base height and $\Gamma()$ is the well-known gamma function. In this contribution, it is assumed that in an horizontal plane with an area of 1 km^2, i.e. the plane defined by a line of 1 km on x-axis and 1 km on y-axis, the ILWC is constant, as shown in Fig. 1. Then, the line integral of (1) can be written as:

$$P_{CFLOS} = P\left(\sum_{i=1}^{N} \int_{C_i} \tilde{w} ds = 0\right) \tag{3}$$

where C_i is the line of slant path in which the ILWC remains constant and N is the number of grids so as the whole slant path is taken into account. Therefore, LWC on every line C_i, depends only on height. In order to consider that a slant path is affected by clouds, the top height of the cloud (h_{top}) at every point must be higher than the lowest point of every line C_i. Considering the geometry of Fig.1, the lowest point above clouds on line C_i is given by:

$$h_{i,th} = dl_i \cdot \tan(\varphi) + h_{station} - h_0 \tag{4}$$

where dl_i is the distance on horizontal plane between the two lowest points of two lines, i.e. 1 km in our case, ϕ the elevation angle, $h_{station}$ the altitude above mean sea level of the station and h_0 is the height of cloud base. Therefore, (3) becomes:

$$P_{CFLOS} = P(\Delta h_1 < h_{1,th}, ..., \Delta h_i < h_{i,th}, ..., \Delta h_N < h_{N,th}) \tag{5}$$

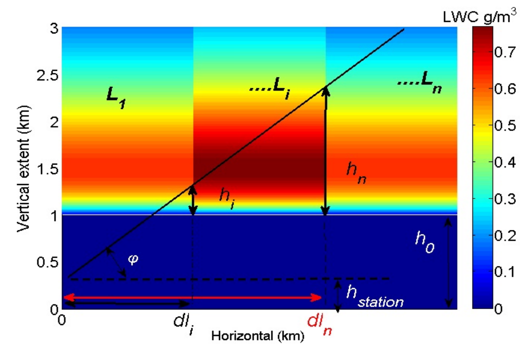

Fig. 1: Slant path configuration Cloud vertical extent snapshot

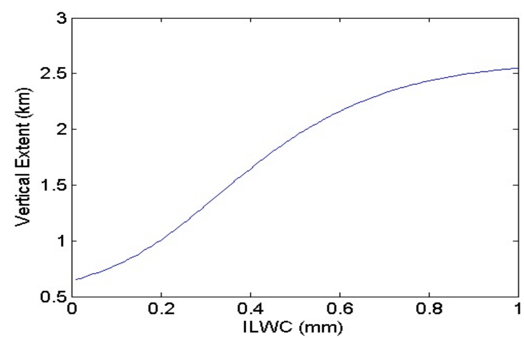

Fig. 2: Vertical extent vs ILWC

where $\Delta h_i = h_{i,top} - h_0$ for the line C_i.

From [7], it is considered that $\tilde{w}_i\left(h_i, L_i\right) \to 0$ for $\tilde{w}_i(h_i) \leq 0.06L_i$ and the top cloud height on the 3-D plane defined in line C_i where L is constant, can be calculated through the solution of the following transcendental equation:

$$\begin{aligned} &\int_{h_0}^{h_{i,th}} \tilde{w}_i(h_i, L_i) dh_i = 0.94L_i \Leftrightarrow \\ &\gamma\left(c_{1,i}, (h_{i,top} - h_0)/c_{2,i}\right)/\Gamma\left(c_{1.i}\right) = 0.94 \end{aligned} \tag{6}$$

where $\gamma()$ is the incomplete gamma function.

Using (6), the explicit relation between the vertical extent of the cloud ($h_{top} - h_0$) and the integrated liquid water content can be calculated and it is numerically evaluated in Fig. 2. Vertical extent is an increasing function of ILWC and so (6) has a single and unique solution. Therefore, (5) can be written in terms of ILWC through (6).

$$P_{CFLOS} = P\left(L_1 < L_{1,th}, L_2 < L_{2,th}, ..., L_N < L_{N,th}\right) \tag{7}$$

As presented in [8], [11] ILWC can be modeled as a Lognormal distribution, truncated to a threshold to match the cloud probability occurrence. Thus using the normally distributed random variables $u_i = \left(\ln(L_i) - m_i\right)/\sigma_i$ where, m_i, σ_i are the mean value and standard deviation of $\ln(L_i)$ at grid point i respectively [12], CFLOS probability is given:

$$\begin{aligned} P_{CFLOS} &= P\left(u_1 < a_{1,th}, .., u_N < a_{N,th}\right) = \\ &= \int_0^{a_{1,th}} .. \int_0^{a_{N,th}} f_{u_1..u_N}\left(u_1, .., u_N\right) \cdot du_1 \cdot \cdot du_N \end{aligned} \tag{8}$$

where $f_{u_1..u_N}$ is the pdf (Probability Distribution Function) of the multivariate normal distribution [13]. The elements of

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the correlation matrix for the random variables u_i can be calculated using the following correlation factor [7]:

$$\rho_C(d) = 0.35\, e^{-\frac{d}{7.8}} + 0.65\, e^{-\frac{d}{225.3}} \quad (9)$$

where d(km) is the distance between the grid points of the slant path. Finally, $\alpha_{i,th}(i = 1, ..., N)$ are the truncation thresholds [11]:

$$a_{i,th} = Q^{-1}\left(P_{CLW_i} \cdot Q\left(\ln\left(\left(\frac{L_{i,th}}{\exp(m_i)}\right)\frac{1}{\sigma_i}\right)\right)\right) \quad (10)$$

where Q is found in [12]. P_{CLWi} is the probability that L exceeds 0 mm for a single grid. The statistical parameters can be derived from databanks like ITU-R P.840-6 [12] or ERA-40 database of ECMWF, European Centre for Medium-Range Weather Forecasts, etc. for the place of interest. For the cloud base h_0(km) local available statistics may be used. Otherwise, cloud base values can be derived from a proposed distribution in [7] and then the mean value of P_{CFLOS} is calculated. h_0 can be considered constant along the slant path [7].

III. CFLOS for Multiple Optical Satellite Links

In this Section, the above methodology is extended for the prediction of joint CFLOS probability P_{CFLOS}^{joint} for multiple spatially separated optical links in a site diversity scenario. The joint CFLOS probability for n links is the probability that at least one station is not affected by clouds, i.e. using (1):

$$P_{CFLOS}^{\text{joint}} = 1 - P\left(\int_{SL^1} \tilde{w}ds > 0, ..., \int_{SL^n} \tilde{w}ds > 0\right) \quad (11)$$

where SL^i is the line of the slant path on link i, $i = 1, \ldots, n$. Using (1), the probability that clouds are present through a single satellite slant path is:

$$P_{NCFLOS}^i = P\left(\int_{SL^i} \tilde{w}ds > 0\right) = 1 - P_{CFLOS}^i \quad (12)$$

where P_{CFLOS}^i is calculated from the methodology presented in the previous section. Considering the random variable that clouds are present in a single slant path is a binary variable, the following may be assumed for P_{NCFLOS}^i [8]:

$$P_{NCFLOS}^i = Q\left(\alpha_{sp,th}^i\right) \quad (13)$$

Therefore, the threshold value of zero mean and unity variance Gaussian random variable (u_{sp}^i) over which clouds are present in a single link is:

$$\alpha_{sp,th}^i = Q^{-1}\left(P_{NCFLOS}^i\right) \quad (14)$$

The joint CFLOS probability, i.e. the probability of at least one station is free of clouds, is given by:

$$P_{CFLOS}^{\text{joint}} = 1 - P\left(u_{sp}^1 \geq a_{sp,th}^1, ..., u_{sp}^n \geq a_{sp,th}^n\right) \quad (15)$$

The joint Complementary Cumulative Distribution Function (CCDF), for the n variables can be calculated from the joint CDFs according to [12] and based on (14) we have:

$$P_{CFLOS}^{\text{joint}} = \int_0^{\alpha_{sp,th}^1} f_{u_{sp}^1} du_{sp}^1 + ... + \int_0^{\alpha_{sp,th}^n} f_{u_{sp}^n} du_{sp}^n + ... +$$
$$+(-1)^{n-1} \int_0^{\alpha_{sp,th}^1} .... \int_0^{\alpha_{sp,th}^n} f_{u_{sp}^1 u_{sp}^2 \ldots u_{sp}^n} \cdot du_{sp}^1 du_{sp}^2 \cdots du_{sp}^n \quad (16)$$

where $f_{u_{sp}^i}$ are the pdfs of normal distribution for $i = 1, .., n$ links while $f_{u_{sp}^1 u_{sp}^2 \ldots u_{sp}^n}$ are the pdfs of multivariate normal distribution of all the combinations of n optical slant paths [13]. The use of (16) eases the calculation of the joint probabilities due to the fact that the integrals are calculated in defined limits excluding the infinity. The values of correlation matrix are calculated through the well-defined correlation expression proposed in [7] and given in (9). The distances (d) used in (9) are the distances between the slant paths i.e. the Euclidean distances of the ground terminals.

In case that two or more stations are simultaneously under cloud-free line-of-sight conditions, then spatial multiplexing technique [14] can be used in order to increase the transmitted capacity. The probability that clouds are not present for 2 or more stations from n total is given by [15]:

$$P_{SA}(m) = 1 - \sum_{v=0}^{m-1} P(v) \quad (17)$$

where m is the number of ground stations that we want to be at least active, $P(0)$ is the probability that no station is available, i.e. 1-P_{CFLOS}^{joint} and $P(v)$ is the probability that exactly v stations are available and can be calculated by [14]:

$$P(v) = \sum_{k=0}^{n-v} (-1)^k \begin{pmatrix} v+k \\ v \end{pmatrix} S_k$$
$$S_k = \sum \sum_{1 \leq i_1 < i_2 < \ldots < i_{v+k}}^{v+k} \cdots \sum P\left(\bigcap_{j=1}^{v+k} u_{sp}^{i_j} < a_{sp,th}^{i_j}\right) \quad (18)$$

IV. Numerical Results AND Discussion

The expressions of the analytical formulas presented previously are applied for the prediction of both single link and multiple links CFLOS probability. The expressions (8) and (16) can be easily calculated numerically since the integrand functions are monotonically decreasing. Numerical calculation software has been developed in MATLAB. The statistical parameters for the corresponding vertical links are taken from ITU-R P.840-6 [12]. For h_0, 3000 values have been derived as a random draw from the pdf of h_0 [7]. The methodology is executed for each h_0, separately and then the mean value of P_{CFLOS} is calculated.

Firstly, we validate the proposed methodology for the prediction of CFLOS for the single slant path using simulated data from the analytical model presented in [8]. The comparison results are shown in Fig.3, where the CFLOS probability for 4 single links is given vs. the elevation angle.

The solid lines are the predicted results of the simulation model in [8] and the symbols are coming from the proposed methodology. The results coincide thus leading to the validation of the CFLOS model. Moreover, the order of the magnitude of the variation of P_{CFLOS} with elevation angle comes from the spatial correlation of ILWC along the slant path. Now, numerical results for a site diversity scenario with hypothetical links placed in Greece are presented. The ASTRA satellite at 23.5 deg E is considered as space segment. In the Table I, a pool of 10 hypothetical stations located in Greece is given. CFLOS probability of single links is computed taking into account the elevation angle and the altitude of the stations using (8) for each single station.

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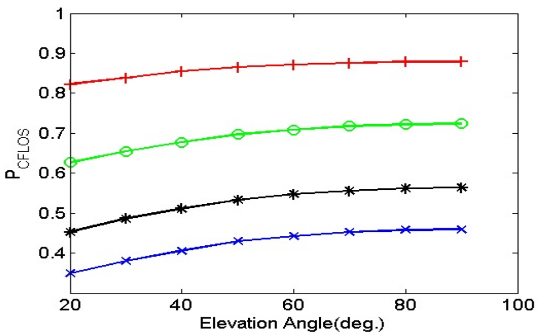

Fig. 3: CFLOS probability vs. elevation angle for single links: + Karachi, o Athens NTUA Campus, * Toulouse, x Berlin. The solid lines are from [8]

TABLE I: CFLOS Of The 10 Stations

Area (lat. ^{o}N, long. ^{o}E)	Elev. Angle (deg)	Altitude (m)	P_{CFLOS} (%)
Athens (37.98, 23.78)	43.19	300	69.2
Kea (37.613, 24.3198)	46.39	250	72.3
Taygetos (36.95, 22.35)	47.12	1700	71.38
Korinthos (37.94, 22.9)	46.15	350	68.2
City of Rhodes (36.4, 28.2)	47.47	200	82.0
Larissa (39.64, 22.42)	44.1	300	63.8
City of Limnos(39.92, 25.14)	43.78	320	67.4
Lefkada (38.66, 20.63)	45.1	330	67.5
Psiloritis Crete (35.23, 24.77)	49.0	1900	79.2
Skopelos (39.11, 23.71)	44.72	250	68.4

Now, using the above stations we want to compute the joint CFLOS in order to achieve a 99.8% availability. In Table II, the joint CFLOS is computed using (16). The joint CFLOS values in the last column are the corresponding ones for double, triple etc. multiple site diversity schemes. e.g., the first row presents the probability that the 1st station is available, the second row presents the probability at least one of the 1st and 2nd station is available, the third row presents the probability at least one of the 1st, the 2nd and the 3rd is available etc. Moreover the optimized selection technique which was presented in [9] has been employed for the optimum combination of the available stations.

Considering an uncertainty in the input statistical parameters (+/-5%, +/-10%), the predicted joint CFLOS probability for the 4 stations of Table II are: a) for -5% 99.3% and for +5% 99.17% and b) for -10% 99.35% and for +10% 99.08%. With this simple sensitivity example, we show the variability of the numerical output of the CFLOS model using hypothetical uncertainties in the input parameters. The impact of the uncertainties of the databases to CFLOS modeling is beyond the scope of our contribution. The errors in the satellite network availability based on the inputs from data sets are examined in [6].

TABLE II: Joint CFLOS

Area (lat. ^{o}N, long. ^{o}E)	Elev. Angle (deg)	Altitude (m)	P_{CFLOS}^{joint} (%)
City of Rhodes (36.4, 28.2)	47.47	200	82.0
Psiloritis Crete (35.23, 24.77)	49	1900	95.12
Lefkada (38.66, 20.63)	45.1	330	98.21
City of Limnos(39.92, 25.14)	43.78	320	99.22
Taygetos (36.95, 22.35)	47.12	1700	99.61
Kea (37.613, 24.3198)	46.39	250	99.76
Larissa (39.64, 22.417)	44.1	300	99.87

Finally, for a hypothetical scenario with the first 4 stations of Table II the probability of having simultaneously available at least 2 or 3 stations out of 4 is calculated using the expression (17). For 2 available stations the $P_{SA}(2) = 93.16\%$ and for 3 available stations $P_{SA}(3) = 71.63\%$. The corresponding predicted values with an uncertainty of +/- 10% vary from 92.21% to 93.63% for the 2 stations and from 69.04% to 74.06% for the 3 stations. The simultaneous available probabilities can be used in order to evaluate various joint transmission techniques [14].

V. Conclusion

In this Letter, a methodology for the calculation of CFLOS probability for single satellite slant paths and for multiple slant paths are presented. This model takes into account the spatial variability of clouds, the elevation angle and the altitude of the ground station. The CFLOS prediction of a slant path has been validated using an analytical model for the simulation of cloud occurrence of a satellite link. In addition, numerical results for single links and spatial diversity schemes are demonstrated while the joint CFLOS probabilities of all the terminals are presented. Finally, the probability that multiple ground stations are cloud-free simultaneously is calculated.

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