Fading mitigation coding techniques for space to ground free space optical communications

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Abstract—In this manuscript, a Geostationary satellite-to-ground Free Space Optics (FSO) downlink channel model has been implemented, which is able to predict temporal irradiance fluctuations caused by scintillation at a wide range of turbulence conditions and for different values of the zenith angle. In order to mitigate fading events that occur in FSO communications, we have also tested the performance of three different families of Rateless Codes (Luby Transform, Raptor and RaptorQ) into our model and found that RaptorQ is the best candidate to mitigate errors in FSO links.

Keywords— Optical Wireless Communications; Space-to-Ground FSO links, time-series, rateless codes; fading mitigation

I. INTRODUCTION

Until now, fiber optics technology has been and is largely employed within cities to ensure error-free and high data-rate linked communications, but it is not the most cost effective way to offer high-quality video and audio streaming services to end users. Another important technique that offers a new high-performance methodology and permits to connect cities to enter into a new age of communications is the Free Space Optical (FSO) technology. It is cost-effective and easy to deploy, also offering large bandwidth and, as in optical fibers, electromagnetic immunity. Moreover, FSO has wide practical applications and shows several advantages if compared to radio links, especially in terms of high transmission rates and security. In addition, it is employed in inter-satellite communications and/or satellites to earth links. Hence, the research in the field of optical communications for Smart Cities has increased considerably for over a decade now, since this topic represents the challenge of the near future.

In this scenario, our work uses FSO communications in a GEO-satellite downlink, thus offering the possibility to transmit digital data and information at a high rate, with reduced packet loss and fading thanks to the use of new coding techniques. For the above-mentioned features, FSO can be conveniently applied for applications that require ever greater bandwidth, such as high-definition Internet TV and videoconference services.

As well known, in Free Space Optics links, in order to transmit data through the free space, the optical carrier wavelengths (typically in the range 850 to 1550 nm) are intensity-modulated. An important advantage of FSO links is that any interference with Satellite broadcasting or any other Radio transmission apparatus is absent. However, the transmitted optical signals can be strongly affected by unfavorable atmospheric conditions, such as rain, fog, clouds, snow, smog, aerosol scattering and scintillations. Moreover, FSO links require “line of sight” between the receiver and the transmitter; any misalignment due to twisting, swaying and bending of structures can create serious difficulties for remote transmissions [1, 2].

In literature, different techniques have been implemented to mitigate the effects of signal-intensity fading caused by irradiance fluctuations due to atmospheric turbulence in ground to satellite FSO communication links.

In addition, FSO links performance can be further improved by adding more receivers and transmitters, increasing the receiver aperture diameter, and applying proper coding techniques, as the most recent rateless codes [3].

We highlight that it is of fundamental importance to study the propagation properties of laser beams through the atmosphere and to develop a proper mathematical channel model capable to simulate the FSO link features.

In [4, 5], we applied the rateless codes in a terrestrial FSO link, thus studying their error mitigation performance for an horizontal path. Instead, in this manuscript we focus on a slant path and, in particular, on Satellite to earth downlink. We first describe the used time-correlated channel model, which is able to predict random temporal irradiance fluctuations caused by optical turbulence. Subsequently, we report our simulation results on the error mitigation performances of three rateless code families (i.e., Luby-Transform, Raptor, and RaptorQ) taking into account the fading events predicted by using the above-mentioned channel model.

II. CHANNEL MODEL

As known, several impairments afflict FSO links producing a large number of communication problems, among which we remember, by way of example, fading and losses. The intensity of the latter is also heavily dependent on atmospheric conditions.
The work described in this paper focuses on impairments caused by the scintillation phenomena in a Satellite-to-Ground link (downlink). A typical FSO link apparatus exploits tracking systems, so that it is possible to consider beam wander effects negligible. Scintillation is caused by atmospheric turbulences, which arise local variations of the medium refractive index, and generate optical irradiance fluctuations. In a FSO link, irradiance variations, at the receiver, give rise to both fading losses and erasure errors during communications. In order to study these impairments, we have implemented a simulator that has permitted us to predict the temporal fluctuations of optical irradiance. The next few paragraphs will better explain the features of our simulator.

### A. Irradiance Probability Distribution Function

Optical turbulence effects were extensively studied in literature and numerous distribution models (e.g., lognormal and negative exponential models) are developed in order to predict specific turbulence conditions, such as weak turbulence for lognormal model and very strong turbulence (saturate regime) for negative exponential model. Our model distribution allowed us to simulate irradiance fluctuations in a wide range of turbulence orders: the Gamma-Gamma model [1, 2] owns these properties and, hence, was suitable for our work.

Particularly, it provides the probability density function (PDF) of optical irradiance values at the receiver and depends on the Rytov variance that can be considered a measure of optical turbulence strength [1]. In order to compute the Rytov variance value, we used the following expression (valid under plane wave propagation condition):

$$\sigma_i^2 = 2.25 \mu_i k^{7/6} (H - h_0)^{5/6} \left[\sec(\zeta)\right]^{1/6} \tag{1}$$

where $k$ is the wavenumber, $H$ is the satellite altitude, $h_0$ is the ground station altitude, $\zeta$ is the zenith angle, $\mu_i$ is defined in Refs. [1, 2] and it is dependent on the refractive index structure parameter $C_n^2$ [m$^{-2/3}$]. The latter depends on altitude, in particular this parameter is important for distances from the ground-station to around 20 km. Over this altitude, $C_n^2$ can be considered negligible. In our studies, we used Hufnagel-Valley 5/7 model [1, 2] that describes $C_n^2$ as a function of altitude.

Herein, we have simulated a downlink between a Geostationary Earth Orbit (GEO) satellite and a terrestrial ground station: the turbulence path length increases with the zenith angle, and consequently the optical turbulence effects augment at the receiver. Therefore, we have computed Rytov variance values for different zenith angles at the conditions summarized in Table I. Results, reported in Table II, show that Rytov variance values are greater than 1 (under strong atmospheric turbulent conditions) at a zenith angle greater than or equal to about 73.8°, whereas, they are less than 1 (weak turbulence conditions) otherwise.

Using the expression (2) and starting from the determined Rytov variance values, we were able to produce Gamma-Gamma PDFs:

$$p(I) = \frac{2(\alpha\beta)^{n/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{n/2 - 1} K_{\alpha-\beta} \left(2\sqrt{\alpha\beta I} \right) \tag{2}$$

where $I$ is the normalized optical irradiance, $\Gamma(\cdot)$ is the Gamma function, $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second kind of order $n$. Instead, $\alpha$ and $\beta$ are two factors, defined in Refs. [1, 2], and valid for a point detector and under plane wave propagation condition. Given these assumptions, we can neglect the aperture averaging effects.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
<td>1.06 μm</td>
</tr>
<tr>
<td>$v$</td>
<td>Wind speed</td>
<td>21 m/s</td>
</tr>
<tr>
<td>$H$</td>
<td>Satellite altitude</td>
<td>35800 km</td>
</tr>
<tr>
<td>$h_0$</td>
<td>Ground station altitude</td>
<td>0 m</td>
</tr>
<tr>
<td>$A$</td>
<td>$C_n^2$ at ground level</td>
<td>$1.7 \times 10^{14}$ m$^{-2/3}$</td>
</tr>
</tbody>
</table>

### B. Irradiance covariance function

Temporal irradiance fluctuations can be predicted by determining the existing correlation between irradiance values. Supposing a plane wave propagation, for satellite-to-ground downlinks, we have expressed an irradiance covariance function [2] as follows:

$$B_i(\rho) = \exp \left\{ \frac{\sigma_i^2}{\sigma_{0i}^2} \left[ \frac{\mu_2(\rho)}{\mu_2(0)} \right] + 0.99 \frac{\sigma_i^2}{\sigma_{0i}^2} \left( \frac{k\rho^2 \eta_y}{L} \right)^{5/12} K_{5/6} \left( \frac{k\rho^2 \eta_y}{L} \right) \right\} - 1 \tag{3}$$

where $\sigma_{0i}^2$, $\sigma_i^2$, $\mu_2(\cdot)$, and $\eta_y$ are parameters depending on the Rytov variance, while $\mu_2(\cdot)$ is a function of $H$, $h_0$ and $C_n^2$. The previous expression is a function of spatial variable $\rho$. Under Taylor’s frozen eddies hypothesis [1, 2] we have this equation:
\[ \rho \equiv \rho_T \]  

where \( t \) is the time and \( \rho_T \) is the average transverse wind speed (orthogonal to the propagation direction). At this point, we are now able to convert the spatial covariance into a time function by setting \( \rho_T \) in expression (4), and substituting it into (3). The irradiance covariance becomes a function of the only independent variable \( t \) and, for this reason, it could be implemented in our model. In order to simulate our channel, we have fixed \( \rho_T = 1 \) m/s, obtaining irradiance correlation times close to those experimentally and theoretically reported [6].

C. Irradiance fluctuation simulations

We calculated irradiance time series by means of the PDF expression (2) and the temporal covariance expression (3) in order to predict irradiance fluctuations at different turbulence conditions, but we have noticed that, when we try to correlate a non-Gaussian distribution using only a correlation filter, the output distribution converges to a Gaussian one. Anyway, we overcame this problem via a suitable algorithm [7], which is composed by a correlation filter and a nonlinear memory-less block function.

For our study, we considered two input parameters: the double side Fourier Transform of the temporal irradiance covariance - obtained employing the FFT of \( B(t) \) - and a random irradiance sequence that followed a Gamma-Gamma distribution. The temporal spacing between two adjacent samples was the reciprocal of the FFT sampling frequency (\( f_c \)). We were, in this way, able to choose the time series resolution according to our needs.

Fig. 1 reports an example of irradiance fluctuation simulation for a GEO satellite downlink when we suppose 45° zenith angle, 1.06 \( \mu \)m wavelength, \( h_0 = 0 \) m, 0.2 s time interval and 10\( \mu \)s temporal spacing. Fig. 2 shows a comparison between the theoretical input sample distribution (solid line) and the output one, as extracted from the irradiance time series (dashed line).

In Fig. 3 we report a comparison between the theoretical temporal covariance function (solid line) and the output one, as extracted from the irradiance time series (dashed line).

The irradiance covariance functions own a plateau that has been considered during simulations and it is not shown in Fig. 3. It is worth noting that the two mentioned input functions are very similar to the output ones. Hence, the channel we have implemented is able to predict, with a good approximation, temporal irradiance fluctuations at the receiver employing a correlation filter and a nonlinear memory-less block function.

III. RATELESS CODES AND SIMULATIONS

During FSO communications, the optical irradiance can drop below a given threshold due to the presence of turbulence. In this case, the receiver is not anymore able to distinguish between signal and noise and, therefore, erasure errors can occur (i.e., packets are lost). In order to mitigate these impairments, it is possible to apply coding techniques, such as
rateless codes, that were appositely designed for erasure channels.

Hence, we tested three rateless code typologies on the previously described channel model and investigated on their capabilities to eventually improve the quality of the FSO GEO downlink.

A. Rateless codes

Rateless codes have been used for over a decade in FSO communications, being effectively adaptable to any channel, even with unknown statistics. They add a redundant coding to the source data, allowing the receiver to recover the whole original payload, even if erasure errors have occurred. These features make rateless codes ideal for applications where relatively short packets are either received correctly or not at all (such as broadcast and multicast transmissions) [3].

In this work, we applied Fountain codes (FCs) which are rateless in the sense that the number of encoded packets that can be generated from the source message is potentially limitless and have been widely used for q-ary erasure channel.

In FCs, a file is divided into K packets (i.e., the elementary unit that is either transmitted intact or erased by the erasure channel), each composed of a whole number of bits. At each clock cycle, the encoder generates a new set of N packets by carrying out a linear combination (bitwise sum, modulo-2) of the K source packets by means of a binary pseudo-random G matrix (K × N). Each encoded packet will be linked to one or more source packets. The number of such links is called “degree” (δ).

If the channel erases some transmitted packets, the receiver will collect Nr packets. Now, there are two possible situations: if Nr < K, data are not sufficient to recover the whole file; otherwise, the receiver can recover the file if, and only if, invertible G matrix exists, by performing Gaussian elimination. In particular, if Nr=K, the receiver has a probability of 0.289 to recover the file, while, if Nr > K, the probability increases; in fact, if K+h encoded packets (where h is the received overhead) are collected, the recovery capabilities improve as h increases [3].

Luby Transform (LT) codes [3] are a first implementation of the FCs theory. In order to successfully complete the decoding process, they require two conditions: a number of received coded packets Nr=K and an encoded packet with degree equal to 1 at each decoding step. LT codes computational performance can be improved by using a proper management of sparse graphs. However, the degree distribution does not always guarantee a decoding sparse graph and, thus, a good decoding speed.

This issue is solved with the aid of Raptor Codes (RCs). They are, substantially, LT codes having a pre-coding step added to reduce the expected degree. In details, RCs show an expected degree equal to three. In this way, the decoding graph is always sparse thus obtaining lower decoding computational costs. Moreover, RCs are “systematic codes”, i.e., codes in which the original source symbols are transmitted prior to the output symbols produced by the coding system [8]. In addition, RCs operate on Galois Field 2 (GF(2)) and the number of source symbols is limited to 8192.

An evolution of RCs is represented by RaptorQ codes (RQ). They are “systematic codes”, too, but they also use a much larger alphabet, i.e., GF(256), in addition to GF(2), in order to reduce the failure probability at a specific overhead, thus demonstrating better recovering capability. They also permit to easily find good systematic indices [8] hence supporting a number of source symbols much larger than RCs.

B. Performance tests

In this work, in order to test the rateless codes mentioned in the previous section, we considered a GEO satellite-to-ground FSO downlink operating at 1 Gbps (OOK modulation and 1518 bytes frame size), taking into account several values of the zenith angle. Moreover, we supposed that additional losses (due to scattering and absorption) are present in the simulated FSO GEO downlink. For this reason, we assumed that the receiver was not able to detect the useful signal at fading below a -6dB threshold level. Therefore, on the other hand, we considered that the receiver was capable to correctly carry out the detection process for a signal drop up to -6dB. The other configuration parameters are shown in Table I.

In Fig. 4 we show the results of LT codes performance analysis considering: a zenith angle of 80° (corresponding to a strong optical turbulence), different K and overhead values. It is worth noting that an overhead of 15% is needed to avoid a failure probability of 100%. In fact, LT codes are non-systematic and they also need a minimum received overhead to perform the decoding process. We also note in Fig. 4 that, with increasing source symbol numbers and at high values of overhead, the recovery probability improves.

Subsequently, we have tested Raptor and RaptorQ codes. In Fig. 5 and Fig. 6 the test results of, respectively, Raptor and RaptorQ codes are depicted, at 80° zenith angle. In both diagrams, with increasing K, the slopes of linear regression (l.r.) augment. Therefore, the higher are the values of overhead and the higher is the number of source packets, the better is the
performance of the codes. We highlight that, conversely to LT codes, the failure probability of Raptor and RaptorQ codes decreases already at low overhead values. Moreover, RaptorQ has slightly better recovery capabilities than Raptor, while they show great improvements if compared to LT codes. In fact, if we consider $K = 1000$ and overhead 30%, the failure probability decreases from 50% (in LT) to 35% (in Raptor) and to 25% (in RaptorQ).

Hence, RaptorQ codes should be preferred when optical turbulence conditions are worse.

**CONCLUSION**

During this work, we implemented a FSO channel model that, by taking into account the temporal covariance function of irradiance, is able to predict time irradiance fluctuations at the receiver with a high resolution. The irradiance time series predicted by the above-mentioned model has been used to test the performance of LT, Raptor and RaptorQ codes. These codes are usually adopted to mitigate all the erasure errors caused by scintillation. Our simulations showed that, for a zenith angle of 80°, LT codes had good recovery capabilities only considering high values of $K$ (source symbols) and of the overhead. In general, Raptor and especially RaptorQ codes are, instead, able to drastically mitigate erasure errors already for lower values of $K$ and overhead (such as $K = 1000$, overhead 20%). We highlight that RQ codes provide the best recovering performance if compared to the other rateless codes, in particular when a high number of $K$ packets is required.

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