Optimised Gain Saturated Pre-Amplified Free-Space Optical Communication Systems

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Abstract: The performance of a fixed and saturated gain preamplified free-space optical communication system in a turbulent atmosphere is investigated, in the presence of amplified spontaneous emission noise. Bit error rate (BER) analysis of both non-adaptive decision and adaptive decision threshold schemes are considered and the effects of using both fixed and saturated gain preamplified receivers are investigated for different turbulence regimes. Results obtained in this paper showed, as expected, that the lognormal distribution gives a better performance than the gamma-gamma distribution in the weak turbulence regime and that the BER performances reaches an optimal level when the power at the preamplifier input is comparable with the internal saturation power of the preamplifier. Also, it is shown that the optimal non-adaptive decision threshold in a gain saturated preamplified receiver will have a decision threshold level between 0.2 and 0.3.

Keywords: Free-space optical communication, atmospheric turbulence, optical amplifier, gain saturation, decision threshold.

1. INTRODUCTION

Free-space optical (FSO) communication has attracted significant interest in research and development activities because of the advantages it offers compared to radio frequency (RF) and optical fibre communication systems [1-7]. Despite all the possible benefits of deploying FSO systems, their capabilities are limited by atmospheric conditions [8-10]. A major impairment to seamless signal transmission through the atmosphere is thermal inhomogeneity. These thermal inhomogeneities cause random temporal and spatial refractive index changes which results in large-scale and small-scale eddies (i.e. atmospheric turbulence) that haphazardly interacts with the transmitted optical signal [8, 11]. Atmospheric turbulence causes scintillation (i.e. fluctuations of the optical signal transmitted through the atmosphere) and it significantly affects system performance [11]. These undesirable effects are even more pronounced when an FSO system is required for longer distances [12]. Specifically, the effect of atmospheric turbulence is highly significant at communication distances greater than 1 km [6, 13]. In order to obtain the desired performance especially over long distances, suitable turbulence alleviation methods are required such as using error correcting codes with interleaving [14], aperture averaging [15] and spatial diversity [6].

As shown in an earlier work [16], the ability of an optical amplifier (OA) to adapt its gain to new power levels by providing lower gain to higher input powers and higher gains to lower input powers makes it suitable for scintillation mitigation in a FSO communication system. These saturation characteristics of the OA gain was also shown to enhance acceptable bit error rate (BER) performances where channel state information is not known and a non-adaptive decision threshold is used at the receiver [16].

Using the Gaussian Approximation (GA) technique, the performance evaluation of fixed and saturated gain preamplified receivers in a non-return-to-zero (NRZ) on-off keying (OOK) FSO communication system is considered in this work. Results are shown for various threshold settings and various statistical models are used to model the different atmospheric turbulence levels. Also, the optimum non-adaptive decision threshold when a saturated gain preamplifier is deployed at the receiver is presented. Note that only single wavelength FSO communication systems are considered in this paper. After this introductory part, the turbulence models used to represent the FSO link is described in section 2. Section 3 describes an optically preamplified FSO receiver model. In Section 4, effects of gain saturation in the preamplifier and the bit error rate (BER) analysis are presented. Results of the numerical analysis are discussed in section 5 and a conclusion is given in section 6.

2. CHANNEL STATISTICS

Various statistical channel models have been used to describe atmospheric-induced turbulence fading. The lognormal (LN) distribution is commonly used to characterise the weak turbulence regime and the K
distribution (which is consistent with experimental results) is used to characterise the strong turbulence regime. Compared to the LN distribution, the gamma-gamma (GG) distribution used to characterise the weak to strong turbulence regimes shows better agreement between experimental and theoretical data. In a saturated turbulence regime, the negative exponential (NE) distribution has proved to give a better fit when compared with theoretical data. The probability density functions (PDFs) of the various atmospheric turbulence distributions are given in Table 1 [17, 18].

### Table 1: Atmospheric turbulence distributions

<table>
<thead>
<tr>
<th>Model</th>
<th>PDF</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma-gamma (GG)</td>
<td>[ f_{GG}(h_t) = \frac{2(\alpha\beta)^{\alpha+\beta/2}}{\Gamma(\alpha)\Gamma(\beta)} h_t^{\alpha+\beta/2} K_{\alpha-\beta}(2\sqrt{\alpha\beta} h_t) ]</td>
<td>[ \alpha = \exp \left[ \frac{0.49\sigma_R^2}{1 + [0.1\sigma_R^{12/5}]/5^{1/6}} \right]^{-1} ]</td>
</tr>
<tr>
<td>Lognormal (LN)</td>
<td>[ f_{LN}(h_t) = \frac{1}{h_t \sqrt{2\pi\sigma_t^2}} \exp \left{ -\frac{\ln(h_t) + \frac{1}{2}\sigma_t^2}{2\sigma_t^2} \right} ]</td>
<td>[ \beta = \exp \left[ \frac{0.51\sigma_R^2}{1 + [0.069\sigma_R^{12/5}]/5^{1/6}} \right]^{-1} ]</td>
</tr>
<tr>
<td>K</td>
<td>[ f_K(h_t) = \frac{2\alpha}{\Gamma(\alpha)} (\alpha h_t)^{\alpha-1} K_{\alpha-1}(2\sqrt{\alpha h_t}) ]</td>
<td>[ \sigma_t^2 = \exp \left[ \frac{0.49\sigma_R^2}{1 + [0.1\sigma_R^{12/5}]/5^{1/6}} \right]^{-1} ]</td>
</tr>
<tr>
<td>Negative exponential (NE)</td>
<td>[ f_{NE}(h_t) = \exp(-h_t) ]</td>
<td>[ \sigma_R^2 = 1.23C_n^2 k^{7/6} D^{1/6} ]</td>
</tr>
</tbody>
</table>

In Table 1, the parameter \( h_t \) is used to describe the varying channel loss (or gain) due to atmospheric turbulence. \( \alpha \) and \( \beta \) are the number of large and small scale eddies due to the scattering process respectively, \( \Gamma(\cdot) \) is the Gamma function and \( K_u(\cdot) \) is the modified Bessel function of the second kind with order, \( u \). \( \sigma_t^2 \), the Rytov variance is used to describe the different turbulence regimes. \( D \) is the length of the FSO link and \( k = 2\pi/\lambda \) represents the optical wave number where \( \lambda \) is the optical wavelength. \( C_n^2 \) is the refractive index structure parameter [17, 18].

3. **OPTICALLY PREAMPLIFIED FSO RECEIVER MODEL**

A FSO link with an optically preamplified FSO receiver model using a direct detection scheme with NRZ-OOK modulation is shown in Figure 1. The amplified spontaneous emission (ASE) noise produced is reduced with an optical band pass filter (OBPF). A photodiode (PD) of responsivity \( R = h\eta/q \) where \( h \) is the Planck constant, \( \eta \) is the quantum efficiency, \( q \) is the electronic charge and \( v \) is the frequency of the optical carrier is used for optical-to-electrical (O/E) conversion of the transmitted signal before electrical amplification, filtering and the recovery of the transmitted data bit at the decision circuit [18, 19].

![Figure 1: Single wavelength FSO link with an optically preamplified FSO receiver model](image-url)
4. GAIN SATURATION AND BER ANALYSIS

The instantaneous signal power at the input of the OA is unconditionally related to its gain and the relation is given as [20]

\[ P_{in} = \frac{P_{out}}{G - 1} \ln \left( \frac{G_{in}}{G} \right) \]  

(1)

where \( P_{in} = P_{OA_{in}h_i} \), \( P_{OA_{in}} \) is the turbulence-free average power at the OA input. \( G_{in} \) is the fixed (small signal) gain of the OA. \( P_{sat} \) is the internal saturation power of the OA and \( G \) is the operating (non-fixed) gain of the OA. In a FSO link where it is assumed that atmospheric fluctuations are appropriately tracked by the gain dynamics, this relationship between the gain and instantaneous input signal power of the OA describes a gain adjustment process where lower input powers receive higher gains and higher input powers receive lower gains leading to a more stable average power at the output of the OA given as [16]

\[ P_{out}(P_{in}) = G(P_{in})^2 \]  

(2)

Therefore, when a gain saturated OA is placed after the FSO link, a non-adaptive decision threshold can be easily used at the receiver since a more stable power is obtained at the photodiode, is obtained by averaging the OA output power over the turbulence PDF and it is given as [16]

\[ I_D(P_{OA_{in}}) = R \int_0^\infty P_{out}(P_{OA_{in}}, h_i) f_{atm}(h_i) dh_i \]  

(3)

where \( atm \) refers to the statistical channel model. The adaptive decision threshold is given as [16].

\[ BER(P_{OA_{in}}) = \frac{1}{2} \left[ 1 - \text{erfc} \left( \frac{i_D - i_0(P_{OA_{in}})}{2\sigma_0} \right) \right] + \frac{1}{2} \left[ 1 - \text{erfc} \left( \frac{i_0(P_{OA_{in}}) - i_D}{2\sigma_1} \right) \right] \]  

(5)

The average BER obtained by averaging the conditioned BER over the turbulence PDF is given as [18]

\[ BER_{avr}(P_{OA_{in}}) = \int_0^\infty BER(P_{OA_{in}}, h_i) f_{atm}(h_i) dh_i \]  

(6)

The non-adaptive decision threshold shown in (3) is equivalent to when the decision threshold level, \( D_{rel} \) is fixed midway between \( i_0 \) and \( i_D \). This decision threshold can be regarded as corresponding to \( D_{rel} = 0.5 \). The optimum non-adaptive decision threshold can then be obtained as

\[ i_{D_{opt}} = \Lambda(BER_{avr,ot}(P_{OA_{in}})) \]  

(7)

where \( \Lambda(\_\_\_\_\_) \) is an abbreviation for the mathematical minimum.

5. RESULTS AND DISCUSSIONS

Table 2 shows the parameters used for the numerical analysis. The saturated operation uses complete saturation characteristics and integrates the effect of ASE noise. An OA that cannot be driven into gain saturation (\( P_{sat} \rightarrow \infty \)) is referred to as a fixed gain OA and an OA that can be driven into gain saturation (\( P_{sat} = 5 \) dBm) is referred to as a saturated gain OA.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>optical wavelength</td>
<td>( \lambda )</td>
<td>1550 nm</td>
</tr>
<tr>
<td>bit rate</td>
<td>( B_b )</td>
<td>2.5 Gb/s</td>
</tr>
<tr>
<td>OBPF bandwidth</td>
<td>( B_{opt} )</td>
<td>70 GHz</td>
</tr>
<tr>
<td>noise figure</td>
<td>( NF )</td>
<td>5 dB</td>
</tr>
<tr>
<td>quantum efficiency</td>
<td>( \eta )</td>
<td>0.8</td>
</tr>
<tr>
<td>extinction ratio</td>
<td>( r )</td>
<td>10 dB</td>
</tr>
</tbody>
</table>

The receiver thermal noise (i.e. \( 7 \times 10^{-7} \) A) is obtained with a baseline receiver sensitivity of \(-23 \) dBm corresponding to a BER of \( 10^{-12} \) [18]. The values used to
model the weak to strong turbulence regimes in Figure 2 are shown in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Atmospheric turbulence regimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^2_R$</td>
<td>Weak</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\beta$</td>
<td>21.59</td>
</tr>
</tbody>
</table>

Table 3: Parameters used to model the turbulence regimes

Figure 2 shows the BER curves for different turbulence regimes in a single wavelength FSO link. In Figure 2(a) where a fixed gain preamplified receiver with an adaptive decision threshold is used, the LN distribution is used to describe the weak turbulence regime and the GG distribution is used to describe the weak, moderate, strong and saturated turbulence regimes. As mentioned in [8, 18, 22] and shown in Figure 2(a), the LN distribution (BER of $10^{-12}$ achievable with a received optical power of about 36dBm) gives a better performance when compared to the GG distribution (BER of $10^{-12}$ achievable with a received optical power of about 34dBm) in the weak turbulence regime. However, the GG distribution has been shown to be more accurate when both are compared with experimental results [8, 18, 22, 23]. Also, as the turbulence strength decreases from the saturated turbulence regime to the weak turbulence regime, the BER performance becomes better. This increase in BER performance occurs because when the turbulence strength reduces, there is a proportional decrease in the fluctuation of the received optical signal at the receiver.

![BER curves for different turbulence regimes](image)

Figure 2: Average BER against average received power for different turbulence regimes ($G_{eff} = 25$ dB)

(a) Fixed gain preamplified receiver with an adaptive decision threshold
(b) Fixed gain preamplified receiver with an adaptive decision threshold
(c) Fixed gain preamplified receiver with non-adaptive decision threshold
(d) Saturated gain preamplified receiver with a non-adaptive decision threshold

In Figure 2(b) where a fixed gain preamplified receiver with an adaptive decision threshold is used, the GG distribution is used to describe the strong and saturated turbulence regimes, the K turbulence distribution is used to describe the strong turbulence regime and the NE turbulence distribution is used to describe the saturated turbulence regime. In the strong turbulence regime, the GG distribution is shown to perform better than the K distribution.
distribution at higher received optical power values ($<\cdot-35$dBm) and in the saturated turbulence regime, the NE distribution is shown to perform better than the GG distribution for all the received optical power values considered. It should however be noted that the overall BER performance ($<10^{-3}$) is not good enough for a reliable communication link. In order to have a more reliable communication link in the strong and saturated turbulence regimes, other performance optimising measures such as a forward error correction (FEC) technique with interleaving can be introduced [14, 18].

In Figure 2(c) where a fixed gain preamplified receiver with a non-adaptive decision threshold is used, the LN distribution is used to describe the weak turbulence regime and the GG distribution is used to describe the weak, moderate, strong and saturated turbulence regimes. Also, the K and the NE turbulence distributions were used to describe the strong and saturated turbulence regimes respectively. Unlike the BER values ($\approx10^{-12}$) obtained in Figure 2(a) where an adaptive decision threshold is used, BER floors at high BER values ($>10^{-2}$) are obtained in all the turbulence regimes in Figure 2(c). The BER floors are obtained because of the inability of a non-adaptive decision threshold to adapt to fluctuations in the received optical signal. However, a non-adaptive decision threshold can be used to obtain better BER performances as shown in Figure 2(d).

In Figure 2(d) where a saturated gain preamplified receiver with a non-adaptive decision threshold is used, the LN distribution is used to describe the weak turbulence regime and the GG distribution is used to describe the weak, moderate, strong and saturated turbulence regimes. Unlike the poor BER performances shown in Figure 2(c) where a non-adaptive decision threshold was also used at the receiver, the introduction of a saturated gain preamplifier allows for improved BER performances shown in Figure 2(d). While all the BER results shown in Figure 2(c) were more than $10^{-2}$, better BER results ($<10^{-10}$ for LN and GG) are shown in Figure 2(d). It is also noticed that the merits of using a saturated gain preamplified receiver is mainly evident in the weak turbulence regime as shown by the LN and GG distributions. A noticeable similarity between the results for a non-adaptive and an adaptive decision threshold is the better BER performance observed with the LN distribution compared to the GG distribution in the weak turbulence regime. As mentioned in earlier results and shown in Figure 2(d), when a saturated gain preamplified receiver with a non-adaptive decision threshold is used, optimal BER performances are obtained when the $P_{sat}$ value of the preamplifier is comparable to the received optical power.

Figure 3 shows the BER curves for different $G_{ss}$ values using a saturated gain preamplified receiver with a non-adaptive decision threshold. As shown in [16], Figure 3 clearly also shows that the BER performances reaches an optimal level when the power at the preamplifier input is comparable with the $P_{sat}$ values. This attribute can also be seen to be consistent for the different $G_{ss}$ values as shown in Figure 3. Also, the BER performance improves as the $G_{ss}$ value increases since an increase in the $G_{ss}$ value allows wider range of powers to be received while providing more gain to the input signal.

While Figure 3 shows results for $D_{rel} = 0.5$, Figure 4 shows the minimum BER values that can be obtained at different threshold levels using a saturated gain preamplified receiver. As expected, the BER performance increases as the $G_{ss}$ value increases. It is also observed that for all the various $G_{ss}$ values, the best performances are obtained at $0.2 < D_{rel} < 0.3$.

**6. CONCLUSION**

This paper examined the performance of a fixed and saturated gain preamplified FSO communication system in a turbulent atmosphere. Results obtained in this paper showed that the LN distribution gives a better performance than the GG distribution in the weak turbulence regime. Also, as expected, the BER performance becomes better as the turbulence strength decreases. In the strong turbulence regime, the GG distribution is shown to perform better than
the K distribution at higher received optical power values and the NE distribution is shown to perform better than the GG distribution in the saturated turbulence regime. While the BER floors observed for a fixed gain preamplifier results shows that a non-adaptive decision threshold is unable to adapt to fluctuations in the received optical signal, the introduction of a saturated gain preamplifier allows for improved BER performances. In all the cases considered in this paper, the BER performances reaches an optimal level when the power at the preamplifier input is comparable with the internal saturation power of the preamplifier. It has also been shown that a gain saturated preamplified receiver performs optimally when the threshold level of the non-adaptive decision threshold is between 0.2 and 0.3.

REFERENCES