Received 11 September 2023, accepted 4 October 2023, date of publication 6 October 2023, date of current version 12 October 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3322649

RESEARCH ARTICLE

Multiple Transmitters for Gain Saturated Pre-Amplified FSO Communication Systems Limited by Strong Atmospheric Turbulence and Pointing Error

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ABSTRACT The use of multiple transmitters in a turbulent free-space optical (FSO) communication link can enhance the systems performance because greater received power can improve receiver sensitivity. Nevertheless, the effect of having more power at the receiver can be severe. This paper investigates the impact of using multiple transmitters in preamplified FSO communication links limited by strong atmospheric turbulence (AT), amplified spontaneous emission noise, fixed path loss and pointing errors (PEs) using different preamplifier operating modes and different decision thresholding schemes. Results obtained show that regardless of the number of transmitters used, the best bit error rate (BER) performances are obtained with normalised decision threshold levels of about 0.2 and 0.5 when the decision thresholding scheme at the receiver is non-adaptive and adaptive, respectively. Also, in the strong AT regime, an additional transmitted power of about 7dB is required for the FSO communication systems under minimal PE effects to have the same performance as FSO communication systems without PE. The results also show that when the effects of PE are absent or minimal, a larger receiver would require about 15dB less transmitted power to record the same performance as a smaller receiver. However, with a non-adaptive decision threshold, smaller receivers perform better than larger receivers when the PE effects are severe. Additionally, it is shown in this paper that when the effects of PE is severe, the BER performances consistently get better with more transmitters regardless of the decision thresholding scheme employed at the receiver. However, in the absence of PEs, increasing the number of transmitters indefinitely will not always guarantee improved BER performances when the receiver decision threshold is non-adaptive. The use of multiple transmitters is particularly advantageous for applications where it is either necessary or unavoidable to use lower transmitted power.

INDEX TERMS Atmospheric turbulence, optical amplifier, spatial diversity, pointing error, free space optical communication, optical receiver, decision threshold.

The associate editor coordinating the review of this manuscript and approving it for publication was Tae Wook Kim.

I. INTRODUCTION

Free-space optical (FSO) communication involves transmitting data using optical signals through the atmosphere, typically over short to medium distances. Due to the significant detrimental effects of limitations such as atmospheric turbulence (AT) on the optical signal traversing the atmosphere in a FSO communication system [1], [2], various techniques such as using multiple receivers and/or transmitters to enhance spatial diversity have been used to mitigate these undesirable effects [2], [3]. The use of multiple receivers and/or transmitters offers advantages such as increased data rates due to simultaneous transmission across multiple channels, redundancy and reliability, improved robustness, extended coverage and higher availability. Also, FSO communication systems using multiple receivers and/or transmitters can be used for applications such as urban communication networks, disaster recovery and temporary networks, indoor wireless networks, aerospace and satellite communication, data centers and high-performance computing, military and security applications and last-mile connectivity. Pointing errors (PEs) also occur in FSO communication links, especially over long distances, where it is difficult to ensure that the receiver and the transmitter are perfectly aligned [4], [5]. In addition to the AT induced received signal fluctuations and PEs, the optical signal power also reduces along the propagation path as a result of geometric spread (GS) and other impairments such as rain, haze and snow [6], [7]. While the use of an optical amplifier (OA) as a preamplifier in a FSO communication system ensures an increase in the received signal power and an improvement in the optical receiver sensitivity, it also generates amplified spontaneous emission (ASE) which produces beat noises that can further limit system performance [8], [9].

By considering gain saturated and fixed gain operating modes of an OA and also considering non-adaptive and adaptive decision thresholds at the receiver, this paper will examine the performance of FSO communication systems impaired by AT, ASE noise characterized by statistical properties following a Gaussian distribution, GS and PE using multiple transmitters and a preamplified receiver. By analyzing different FSO communication system configurations, optimal normalized decision threshold levels and bit error rate (BER) results are obtained. Many recent literature [10] on the use of multiple transmitters with a preamplified receiver have based their analysis on the small signal (fixed) OA gain. However, the OA can be driven into saturation (which will lead to a reduction in the OA small signal gain) when the input power of the OA is large enough [8], [10]. Additionally, while most literature have focused on a receiver decision threshold that constantly adapts to the turbulence level [7], [11], practical FSO systems make use of a decision threshold that is non-adaptive due to the complexity involved in the practical fabrication of an adaptive decision threshold [12]. The major contributions of this paper to the body of knowledge on FSO communication system consisting of multiple transmitters are shown below.

- Performance evaluation of fixed gain and gain saturated preamplifiers using various decision thresholding schemes
- Performance evaluation of non-adaptive and adaptive decision thresholding schemes using various preamplifier operating modes
- Determination of the optimal normalized decision threshold levels for various decision thresholding schemes and preamplifier operating modes
- Implications of choosing particular receiver diameter sizes in the presence of GS, AT and PE for various decision thresholding schemes and preamplifier operating modes

After the introductory section, the review of related works is presented in section II. Section III presents the system model and BER analysis where the gamma-gamma (GG), AT and PE models are also described. The results obtained from the analysis are presented and discussed in section IV. A conclusion is provided in section V.

II. RELATED WORK

In [13], a FSO communication system with hybrid OAs (consisting of two erbium-doped fiber amplifiers (EDFAs)) used to improve reach by a factor of 5 was proposed. In [13], where the lognormal distribution was used to model the weak AT regime and the GG distribution was used to model the moderate to strong AT regimes, the hybrid OA configuration substantially improved the quality factor (Q-factor) and BER. Note that the limiting impact of ASE beat noises was not considered in [13]. In [14], the performance of FSO communication systems limited by atmospheric turbulence, pointing errors and amplified spontaneous emission using non-return-to-zero (NRZ) on–off keying (OOK) modulation and chi-square statistics were analysed. Closed-form expressions were derived for the average BER and results in [14] showed the significant detrimental effects of PEs on system performance. Also, [14] showed that system with preamplifiers performed better than systems without preamplifiers. In [15], a switching system was used to switch transmission between the use of multiple FSO transmitters and multiple RF transmitters and theoretical expressions were derived for the outage probability and symbol error rate. It was shown in [15] that over longer distances and in strong AT regimes, systems based on switching between the multiple FSO transmitters and multiple RF transmitter performed better than systems based on using only multiple FSO transmitters.

Using the OptiSystem simulation package and a hardware prototype, the performance of a FSO communication system consisting of an array of transmitters was investigated in [16] and results were obtained for the BER, eye diagram (for the link distance), received power and Q-factor. The use of multiple transmitters to reduce the susceptibility of FSO communication systems (impaired by PE and AT) to interception and eavesdropping was shown in [17]. It was shown in [17] that using multiple transmitters can improve the average secrecy capacity (ASC) of FSO communication system even when PE effects are substantial. Authors in [17] also showed that no significant ASC improvement was noticed when the transmitters are more than 4 and that increasing the normalized beam width will reduce the possibility of eavesdropping. In [3], experimental and theoretical investigations were carried out on FSO communication systems with repetition coding using parallel multiple transmitters and an EDFA at the receiver over a correlated turbulent channel. While other works on FSO communication systems using multiple transmitters and receivers [18], [19] have carried out various analysis based on assumptions of an identical distribution of the turbulent channel over parallel links, authors in [3] showed that the turbulent channel in feasible FSO communication systems is largely not distributed identically. The advantage of using a preamplifier was also shown in [3] as systems with a preamplifier performed better than systems without a preamplifier by about 6dB at the same target BER.

In [20], the author used evaluation methods such as the gaussian approximation (GA), saddle point approximation (SPA) and modified Chernoff bound (MCB) to analyse the performance of FSO communication system consisting of a single receiver and a single transmitter. In [20], BER results were obtained while considering AT, GS, PE and ASE noise effects. Also, [20] dealt with various OA operating modes and decision thresholding schemes. However, since only a single transmitter was considered in [20], the advantage of using multiple transmitters in an atmosphere limited by AT and PE was not considered.

III. SYSTEM MODEL AND BER ANALYSIS

A FSO communication system with multiple transmitters and an optical receiver (having a preamplifier) is shown in Fig. 1, where N_{tx} represents the number of transmitters. The system uses NRZ OOK modulation at each transmitter and direct detection at the receiver. Even though it is assumed that all the transmitters maintain a 'line of sight' configuration with the receiver, they are not in perfect alignment with the receiver. Each transmitter directs its optical signal towards the preamplifier, where all the optical signals are cumulatively collected. After optical preamplification, processes such as filtering with an optical band pass filter (OBPF), photodetection with a photodiode, electrical amplification and filtering and the retrieval of the sent information by a decision circuit takes place. Note that the responsivity of the photodiode $R = \eta q / hv$ where h and η represents the Planck constant and quantum efficiency respectively. Also, v and q represents the optical carrier frequency and electronic charge respectively [1], [8].

A. ATMOSPHERIC TURBULENCE AND POINTING ERROR MODELS

Different statistical models have been used to represent the random fluctuations present in the intensity of the optical signal traversing an atmosphere limited by AT. The GG distribution, which is known to adequately represent various AT regimes, is used to describe the strong AT regime considered in this paper. The GG distribution has a conditional probability density function (PDF) given as [1], [21].

$$f_{h_t}(h_t) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} h_t^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_t}\right) h_t > 0 \tag{1}$$

where Γ, h_t and $K_u(.)$ represents the Gamma function, AT induced loss/gain of the fluctuating channel and order u modified Bessel function (second kind) respectively. Note that h_t has a mean of 1. Also, $h = h_t h_p$ represents the AT, PE and GS induced loss/gain of the fluctuating channel where h_p represents the PE and GS induced loss/gain of the fluctuating channel. Also, α and β represents the large scale eddies and small scale eddies produced by the scattering process respectively and they are given as [1].

$$\alpha = 1 \Bigg/ \left\{ \exp\left[\frac{0.49\sigma_R^2}{\left(1+\left(1.11\sigma_R^{12/5}\right)\right)^{7/6}} \right] - 1 \right\} \tag{2}$$

$$\beta = 1 \Bigg/ \left\{ \exp\left[\frac{0.51\sigma_R^2}{\left(1+\left(0.69\sigma_R^{12/5}\right)\right)^{5/6}} \right] - 1 \right\} \tag{3}$$

The Rytov variance $\sigma_R^2 = 1.23 z^{11/6} k^{7/6} C_n^2$ where C_n^2, z, $k = 2\pi/\lambda$ and λ represents the structure parameter of the refractive index, link length, number of the optical wave and wavelength respectively. By considering AT and diffraction effects, the Gaussian beam width at z, is given as [21].

$$w_z \approx w_{z_d}\sqrt{1 + 1.33\sigma_R^2 \left(2z/kw_{z_d}\right)^{5/6}} \tag{4}$$

where $w_{z_d} = w_0\sqrt{1+\left(z/z_R\right)^2}$ represents the width of the beam as a result of diffraction alone. $z_R = \pi w_0^2/\lambda$ and w_0 represents the Raleigh range and the beam waist when $z = 0$ respectively. By assuming that the aperture of the optical receiver is circular and that a Raleigh distribution model (used to represent PE, AT and GS) adequately represents the radial displacement from the beam center axis r, h_p can be represented by a PDF given as [22] and [23]

$$f_{h_p}\left(h_p\right) = h_p^{\varsigma^2-1}\frac{\varsigma^2}{a_0^{\varsigma^2}}, a_0 \geq h_p \geq 0 \tag{5}$$

where $\varsigma = w_{z_{eq}}/2\sigma_{PE}$. $w_{z_{eq}} = w_z\sqrt{\sqrt{\pi}\, erf\,(\upsilon)\,/2\upsilon exp\left(-\upsilon^2\right)}$ represents the equivalent beam and the PE displacement at the receiving end has a standard deviation, σ_{PE}. The power accumulated at the receiving lens (for $r = 0$) has a fraction, $a_0 = [erf\,(\upsilon)]^2$ and $\upsilon = \sqrt{\pi} r_{rx}/\sqrt{2} w_z$. By combining (1) and (5), the PDF representing AT, PE and GS is

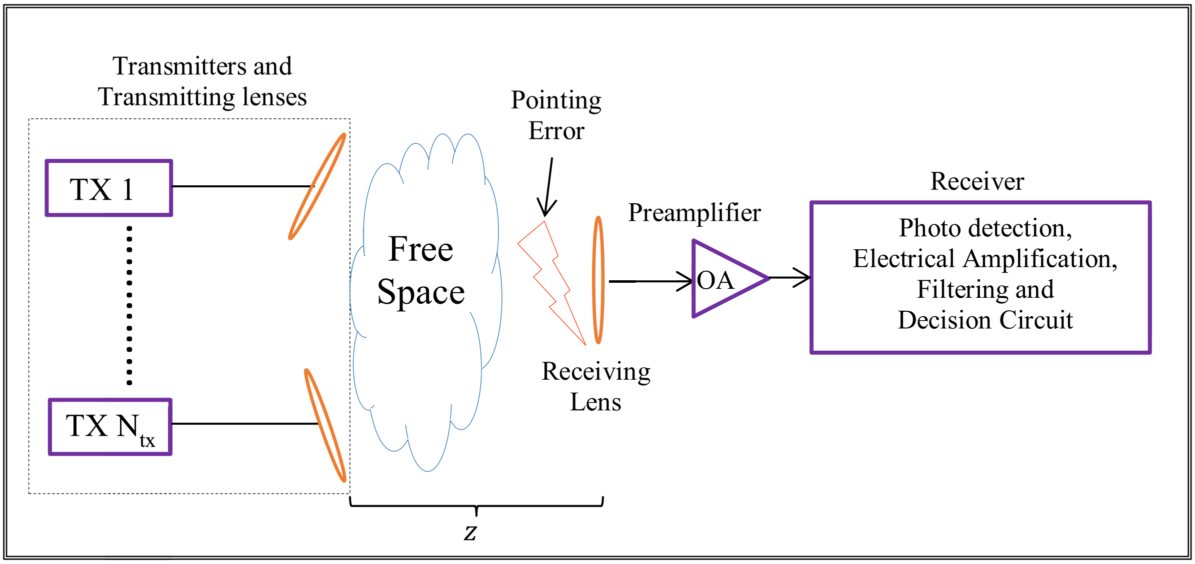


FIGURE 1. FSO link with multiple transmitters (System model).

given as [24].

$$f_h(h) = \frac{2\varsigma^2 (\alpha\beta)^{(\alpha+\beta)/2}}{a_0^{\varsigma^2}\Gamma(\alpha)\Gamma(\beta)} h^{\varsigma^2-1} \int_h /a_0^{\infty} h_t^{\left(\frac{\alpha+\beta}{2}\right)-1-\varsigma^2} \times K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_t}\right) dh_t \quad (6)$$

Note that while a closed form of (6) exists [10], (6) is used in this work because, in addition to (6) being an established method for solving similar problems [18], [19], (6) is also computationally convenient.

B. PREAMPLIFIER MODEL

The use of a preamplifier to reduce turbulence-induced scintillation relies on exploiting the way OAs respond when their gain becomes saturated. This scintillation reduction technique assumes that the OA gain can quickly adjust to turbulence fluctuations [25], [26]. Now, the OA gain G, is related to its input optical signal power, P_{in}, as shown below [8]

$$P_{in} = \frac{P_{sat}}{G-1} \ln \frac{G_{ss}}{G} \quad (7)$$

where P_{sat} and G_{ss} are the OA's internal saturation power and small signal gain respectively. Thus, OAs help to suppress scintillation by giving more gain to lower input power and less gain to higher input power. Note that when the preamplifier is operating in the fixed gain mode, $G = G_{ss}$. However, when the preamplifier is operating in the gain saturation mode, $G \leq G_{ss}$.

C. BER ANALYSIS

By assuming that the noise (including ASE noise) present in the received signal is Gaussian and by taking multiple transmitters into consideration, the BER can be modified from [8] and given as

$$BER = \frac{1}{2}\left[\frac{1}{2}\text{erfc}\left(\frac{i_{D_{NA/A}}(P_{OAin_i}) - i_0(P_{OAin_i})}{\sqrt{2\sigma_0^2(P_{OAin_i})}}\right) + \frac{1}{2}\text{erfc}\left(\frac{i_1(P_{OAin_i}) - i_{D_{NA/A}}(P_{OAin_i})}{\sqrt{2\sigma_1^2(P_{OAin_i})}}\right)\right] \quad (i = 1 \ldots\ldots N_{tx}) \quad (8)$$

where i_D represents the receiver decision threshold. $i_0(P_{OAin_i}) = 2RG\sum_i^{N_{tx}} P_{OAin_i}/(r+1)$ and $i_1(P_{OAin_i}) = 2e_r RG\sum_i^{N_{tx}} P_{OAin_i}/(r+1)$ represents the average levels of the signal at the sampling instant for the '0' and '1' bits sent respectively. e_r represents the extinction ratio. $P_{OAin_i}(P_{tx_i}) = P_{tx_i}L_i$ is the OA input power from the ith transmitter where P_{tx_i} and $L_i = L_{nt_i}h_i$ represents the transmitted power of the ith transmitter and total link loss of the ith link respectively. h_i is the h of the ith link. $L_{nt_i} = (d_{rx}/\varphi_i z)^2 \epsilon_i$ represents the turbulence free path loss of the ith link where d_{rx}, φ_i and $\epsilon_i = e^{-\vartheta_i z}$ represents the diameter of the receiving lens, beam divergence angle of the ith transmitter and the atmospheric attenuation of the ith link respectively. ϑ_i represents the scattering and absorption induced attenuation coefficient of the ith link. $\sigma^2_{(0/1)}(c) = \sigma^2_{s(0/1)-sp}(P_{OAin_i}) + \sigma^2_{sp-sp} + \sigma^2_{sh,(0/1)}(P_{OAin_i}) + \sigma^2_{th}$, $\sigma^2_{sh,(0/1)}(P_{OAin_i}) = 2qR(G\sum_i^{N_{tx}} P_{OAin_i} + m_t N_0 B_{opt})B_e$, σ^2_{th}, $\sigma^2_{s(0/1)-sp}(P_{OAin_i}) = 4GR^2\sum_i^{N_{tx}} P_{OAin_i} N_0 B_e$ and $\sigma^2_{sp-sp} = 2m_t R^2 N_0^2 B_{opt} B_e \left(1 - B_e/2B_{opt}\right)$ represents the noise current variance, the shot noise, variance of the receiver thermal noise, the signal-spontaneous and the spontaneous-spontaneous beat noises respectively. Note that

TABLE 1. Numerical analysis parameters.

Parameter	Symbol	Value
Optical wavelength	λ	1550 nm [8], [27]
Bit rate	R_b	2.5 Gb/s [27]
OBPF bandwidth	B_{opt}	76 GHz [28]
Quantum efficiency	η	0.8 [29]
Receiver thermal noise	σ_{th}	7×10^{-7} A [11]
Noise figure	NF	5 dB [11]
OA small signal gain	G_{ss}	30 dB [27]
Extinction ratio	e_r	10 dB [11]

the signal-spontaneous and spontaneous-spontaneous beat noises are due to the preamplification process [9], [11]. $N_0 = 0.5\,(NFG-1)\,hv$, B_{opt}, $B_e = 0.7R_b$, R_b, m_t and noise figure (NF) are the ASE noise power spectral density, OBPF bandwidth, bandwidth (equivalent) of the receiver noise, bit rate, polarisation states parameter number and the noise figure, respectively [10]. The decision threshold (non-adaptive) is given as [10]

$$i_{D_{NA}}\left(P_{OAin_i}\right) \cong 2\mathrm{D}_{rel}R\int_0^{\infty}\sum_{i}^{N_{tx}}P_{OAin_i}f_h\,(\mathrm{h})\,d\mathrm{h}\,(i=1\ldots\ldots N_{tx}) \quad (9)$$

where D_{rel} represents the decision threshold level and it is usually normalized to values ranging from 0 to 1. Note that a D_{rel} value of 0.5 means that the decision threshold is placed halfway between the 0 and 1 bits. The decision threshold (adaptive) is given as [8].

$$i_{D_A}(P_{OAin_i}) \cong 2\mathrm{D}_{rel}\frac{i_1(P_{OAin_i})\sigma_0(P_{OAin_i})+i_0(P_{OAin_i})\sigma_1(P_{OAin_i})}{\sigma_1(P_{OAin_i})+\sigma_0(P_{OAin_i})}\quad (i=1\ldots\ldots N_{tx}) \quad (10)$$

Also, the optimal decision threshold level can be given as

$$D_{rel_{opt}}\left(i_{D_{\frac{NA}{A}}}\right) = \Lambda\left(BER_{av,D_{rel}}\left(P_{OAin_i}\right)\right)D_{rel} \in \left\langle 0,\ldots,0.5,\ldots,1 \,\middle|\, P_{OAin_i}\right\rangle,\quad (i=1\ldots\ldots N_{tx}) \quad (11)$$

where $D_{rel_{opt}}$ represents the optimal decision threshold level; the decision threshold level that gives the lowest average BER value over a range of received power.

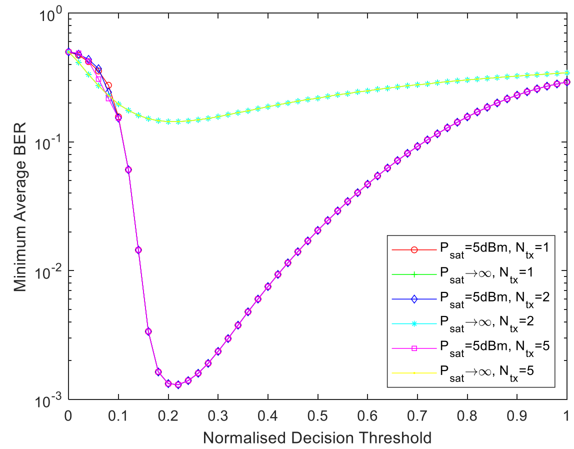
IV. RESULTS AND DISCUSSION

Table 1 contains the numerical analysis parameters. The FSO commuication systems considered are those with PE (WPE) and those without PE (WoPE) using single and multiple transmitters with different σ_{PE}, normalised beam width (W_z/r) and OA internal saturation power (P_{sat}) values. Note that gain saturated ($P_{sat} = 5$ dBm) and fixed gain ($P_{sat} \rightarrow \infty$) OAs refer to OAs that are not restrained from experiencing gain saturation and OAs restrained from experiencing gain saturation respectively. Also, acceptable BER results are BER results that fall within forward error correction limits. The strong AT regime ($\sigma_R^2 = 3.5$) considered in this work results from $C_n^2 = 8.36\times10^{-14}m^{-2/3}$ and $z = 1500m$. Also, with $w_0 = 0.002$ and a 1.5×10^{-4} rad beam divergence angle, normalised beam widths $W_z/r = 25$ and $W_z/r = 5$ are obtained from $0.03m$ and $0.15m$ receiver diameters respectively.

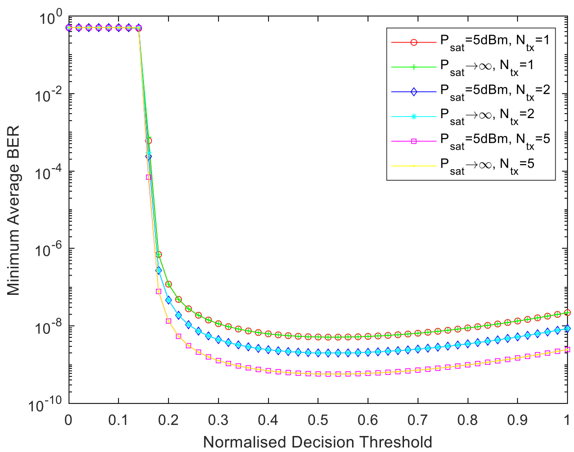
Minimum average BER results obtained for FSO communication systems WPE ($N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$, $\sigma_{PE} = 0.1$, $W_z/r = 5$) for different normalised decision threshold levels are shown in Fig. 2. Note that the minimum average BERs were obtained from BER results covering a selected range of transmitted power (-10dBm to 20dBm). In Fig. 2(a), minimum average BER results for FSO communication systems using a non-adaptive decision threshold show that in gain saturated and fixed gain preamplified FSO communication systems using single or multiple transmitters, the best average BER performances were observed with D_{rel} values of about 0.2.

In Fig. 2(b), minimum average BER results for FSO communication systems using an adaptive decision threshold show that in gain saturated and fixed gain preamplified FSO communication systems using single or multiple transmitters, optimal performances are observed with D_{rel} values of about 0.5. These results for FSO communication systems with increased number of transmitters align with earlier works [20], [30] with a single transmitter, where it was shown that to obtain optimal average BER performances, D_{rel} should have values of about 0.2 and 0.5 when a non-adaptive decision threshold and an adaptive decision threshold is used at the receiver respectively. Note that based on these results, the D_{rel} used for the adaptive and non-adaptive decision thresholds in Figs. 3 and 4 are 0.5 and 0.2 respectively. Also, regardless of the number of transmitters, a consistency is noticed in the BER performance for each normalised decision threshold levels for the FSO communication systems using a non-adaptive decision threshold as shown in Fig. 2(a). However, the FSO communication systems using an adaptive decision threshold in Fig. 2(b) show while the normalised decision threshold levels obtained from using different number of transmitters follow the same patten, the BER performance gets better as the number of transmitters increase. Specifically, N_tx values of 1, 2 and 3 produced optimal BER performances of around 10^{-8}, 5×10^{-9} and 10^{-9} respectively.

Using adaptive and non-adaptive decision thresholds, the average BER results obtained for different transmitted power are shown in Fig. 3. In Fig. 3(a), average BER results for FSO communication systems WoPE ($N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$, $W_z/r \in \{5, 25\}$ using a non-adaptive decision threshold show that for $N_{tx} \in \{1, 2, 5\}$, an average BER of about 10^{-3} is obtained when



(a)



(b)

FIGURE 2. Minimum average BER against normalised decision thresholds where $N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$ for systems WPE ($\sigma_{PE} = 0.1$, $W_z/r = 5$). (a) Non-adaptive decision threshold (b) Adaptive decision threshold.

$P_{sat} = 5dBm$ for $W_z/r \in \{5, 25\}$. However, an error floor is observed at an average BER of about 10^{-1} when $P_{sat} = \infty$ for $W_z/r \in \{5, 25\}$. This further confirms the assertion in [10] that OA saturation is only useful for AT suppression when the receiver uses a non-adaptive threshold. Fig. 3(a) also shows that while increasing the number of transmitters in the FSO communication systems under consideration did not improve the best average BER performance, FSO communication systems having more transmitters will need lower transmitted power to achieve the same average BER results as FSO communication systems with fewer transmitters. This advantage is particularly useful for applications where it is either necessary or unavoidable to use lower transmitted power. Average BER results in Fig. 3(a) also show that FSO communication systems WoPE using a larger receiver ($W_z/r = 5$) performed better (an improvement of about 15dB at the same target BER) than those using a smaller receiver ($W_z/r = 25$).

In Fig. 3(b), average BER results for FSO communication systems WoPE ($N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$, $W_z/r \in \{5, 25\}$ using an adaptive decision threshold show that unlike in Fig. 3(a) where different average BER performances were observed for the different P_{sat} values, Fig. 3(b) shows similar performances for $P_{sat} = 5dBm$ and $P_{sat} = \infty$ regardless of the number of transmitters. This is so because with an adaptive decision threshold where $D_{rel} = 0.5$, the adaptive decision threshold responds to the AT fluctuations and always ensure that the threshold level is always approximately midway between the 1 and 0 bits. Average BER results obtained in Fig. 3(c) for FSO communication systems WPE ($N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$, $W_z/r \in \{5, 25\}$, $\sigma_{PE} = 0.1$) using a non-adaptive decision threshold and in Fig. 3(d) for FSO communication systems WPE ($N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$, $W_z/r \in \{5, 25\}$, $\sigma_{PE} = 0.1$) using an adaptive decision threshold are similar to those obtained in Figs. 3(a) and 3b respectively. This is due to the fact that since the PE effects considered in Figs. 3(c) and 3(d) are not severe ($\sigma_{PE} = 0.1$), the only performance impairment noticed when compared with systems WoPE is a transmitted power deficiency of about 7dB at the same target BER across all the corresponding FSO communication systems. This means that for the strong AT regime under consideration, an additional transmitted power of about 7dB is required for the FSO communication systems under minimal PE effects to have the same performance as FSO communication systems WoPE. The effect of increasing the severity of PE effects is shown in Fig. 3(e) for FSO communication systems WPE ($N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$, $W_z/r \in \{5, 25\}$, $\sigma_{PE} = 4$) using a non-adaptive decision threshold and in Fig. 3(f) for FSO communication systems WPE ($N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$, $W_z/r \in \{5, 25\}$, $\sigma_{PE} = 4$) using an adaptive decision threshold. While average BER results in Figs. 3(a) to 3(d) consistently show that using a larger receiver ($W_z/r = 5$) is preferable to using a smaller receiver ($W_z/r = 25$) because a larger receiver achieved same BER performances with a smaller receiver while using less transmitted power, average BER results Figs 3(e) and 3(f) lacked such consistency. In Fig. 3(e) where a non-adaptive decision threshold is used, FSO communication systems using smaller receivers performed better than FSO communication systems using larger receivers when the transmitted power are increased (> −30dBm). It is also noteworthy that increasing the number of transmitters indefinitely might not guarantee improved BER performance because at further increased transmitted power (> 15dBm), FSO communication systems using 5 transmitters performed worse than FSO communication systems using less number of transmitters. In Fig. 3(f) where an adaptive decision threshold is used, the average BER results obtained also follow the same trajectory as those in Fig. 3(e) because it can also be observed that using smaller receivers is better than using larger receivers when the transmitted power are high.

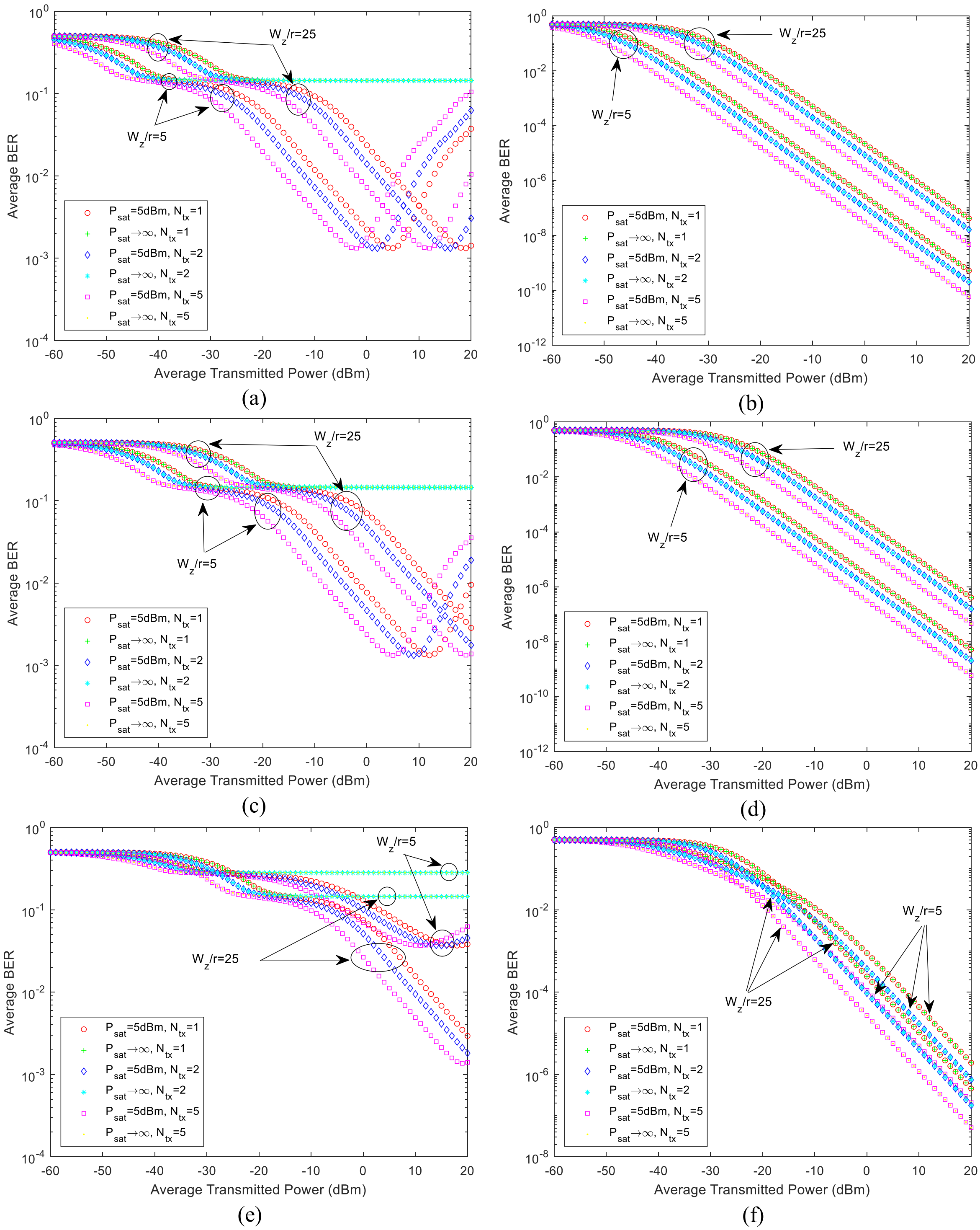
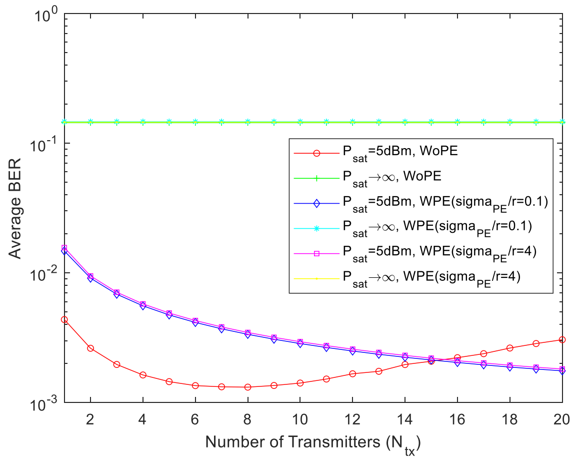
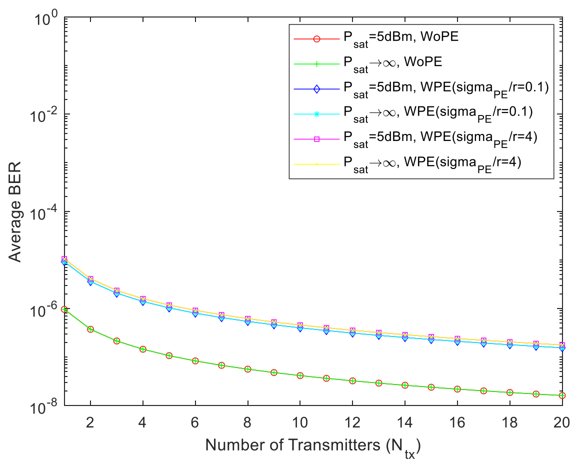


FIGURE 3. **Average BER against average transmitted power where $N_{tx} \in \{1, 2, 5\}$, $P_{sat} \in \{5dBm, \infty\}$ and $W_z/r \in \{5, 25\}$.(a) Non-adaptive decision threshold and WoPE ($D_{rel} = 0.2$) (b) Adaptive decision threshold and WoPE ($D_{rel} = 0.5$) (c) Non-adaptive decision threshold and WPE ($\sigma_{PE} = 0.1$, $D_{rel} = 0.2$) (d) Adaptive decision threshold and WPE ($\sigma_{PE} = 0.1$, $D_{rel} = 0.5$) (e) Non-adaptive decision threshold and WPE ($\sigma_{PE} = 4$, $D_{rel} = 0.2$) (f) Adaptive decision threshold and WPE ($\sigma_{PE} = 4$, $D_{rel} = 0.5$).**

The impact of further increasing the number of transmitter is shown in Fig. 4 where FSO commucation systems ($W_z/r = 25$, $P_{tx} = 10dBm$) using adaptive and non-adaptive decision thresholds are considered. In Fig. 4(a), average BER results for FSO communication systems using a non-adaptive decision threshold further confirms the earlier assertion in Fig. 3(a) that OA gain saturation is only advantageous when the receiver uses a non-adaptive decision



(a)



(b)

FIGURE 4. Average BER against number of transmitters for FSO communication systems ($W_Z/r = 25$, $P_{tx} = 10dBm$). (a) Non-adaptive decision threshold ($D_{rel} = 0.2$) (b) Adaptive decision threshold ($D_{rel} = 0.5$).

threshold because while fixed gain OAs recorded very poor performances ($> 10^{-1}$) even with 20 transmitters, gain saturated OAs performed better ($< 10^{-2}$). Also, average BER results in Fig. 4(a) align with the average BER results obtained in Fig. 3(e) that showed that for FSO communication systems, WoPE using a non-adaptive decision threshold, increasing the number of transmitters indefinitely will not always guarantee improved BER performances.

However, the use of more transmitters is shown to mitigate the effect of severe PE in Fig. 4(a) where FSO communication systems WPE consistently performed better with more transmitters. When an adaptive decision threshold is used in Fig. 4(b), a continual improvement (though less significant as the number of transmitters increase) is noticed with more transmitters in all the FSO communication systems considered, regardless of the operating mode of the preamplifier.

V. CONCLUSION

The performance of preamplified FSO communication systems using multiple transmitters in a communication link impaired by strong AT, ASE noise and pointing errors was considered in this paper. Results are obtained for cases where the preamplifier is operated in different modes (gain saturated and fixed gain) and for when the receiver is employing different decision thresholding schemes (adptive and non-adaptive). Results from this paper showed that regardless of the number of transmitters used, the best BER performances are obtained with normalised decision threshold levels of about 0.2 and 0.5 when the decision thresholding scheme at the receiver is non-adaptive and adaptive respectively. Results from this paper also showed that increasing the number of transmitters when a non-adaptive decision threshold is used did not improve the best average BER performance. However, FSO communication systems having more transmitters will need less transmitted power to achieve the same average BER as FSO communication systems with fewer transmitters. Results from this paper showed that when pointing error effects are either absent or minimal, a larger receiver can achieve the same performance as a smaller receiver using less transmitted power (an improvement of about 15dB at the same target BER). However, smaller receivers performed better then larger receivers at higher transmitted power when a non-adaptive decision threshold is used. As expected, the use of more transmitters in FSO communication systems using an adaptive decision threshold resulted in improved BER performances. However, this improved performance becomes less significant as the number of transmitters increase. It is also noteworthy that when PE is absent in FSO communication systems using a non-adaptive decision threshold, increasing the number of transmitters indefinitely will not always guarantee improved BER performances. However, the use of more transmitters is shown to mitigate the effect of severe PE as the BER performance consistently got better with more transmitters regardless of the decision threshholding scheme used at the receiver when PE effects are severe. Since this work focussed on spatial diversity at the transmitting side, a natural progression of this work is to also study spatial diversity at the receiving side by placing an OA before each receiver (using various decision thresholding schemes) and considering the impact of gain saturation on each preamplifier. Also, the pulse position modulation (PPM) format can be used with preamplified FSO communication systems (with or without spatial diversity) limited by AT, GS and PE with emphasis on how gain saturation of the preamplifier(s) will affect system performance and how the PPM system compares with the OOK results in this paper.

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