Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Low-complexity joint transmit diversity and adaptive modulation schemes for OGS-satellite FSO uplink

To cite this article: E Elsaidy *et al* 2023 *J. Phys.: Conf. Ser.* **2616** 012043

View the article online for updates and enhancements.

You may also like

- A 100 m/320 Gbps SDM FSO link with a doublet lens scheme
Chung-Yi Li, Hai-Han Lu, Ting-Chien Lu et al.

- A comprehensive review of performance analysis of RF-FSO hybrid communication systems
Boyu Han

- MIMO optical wireless communication via monolithic or sparse apertures
Majid Safari and Shenjie Huang

This content was downloaded from IP address 195.43.0.86 on 12/03/2024 at 07:52

Low-complexity joint transmit diversity and adaptive modulation schemes for OGS-satellite FSO uplink

E Elsaidy [1], T Rakia [1], M Abdelaziz [1] and M H Abd El-azeem [2]

[1]Military Technical College , Cairo, Egypt
[2]Arab Academy for Science, Technology & Maritime Transport , Cairo, Egypt

E-mail: esmailelsaidy@mtc.edu.eg

Abstract. In this paper, we present two novel low-complexity transmission schemes for optical ground station (OGS)-satellite free space optical (FSO) uplink. Specifically, the TCAM-scheme which is a joint dual-branch threshold combining and adaptive modulation scheme and the SCAM-scheme which is a joint dual-branch selection combining and adaptive modulation scheme. In both schemes, the data rate is adjusted according to the instantaneous received combined SNRs at the satellite. We analyze the performance of the proposed schemes in terms of the outage probability, the average spectral efficiency and average bit error rate, while considering both subcarrirer intensity modulation/direct detection (SIM/DD) and coherent FSO detection techniques. Numerical results show that both TCAM and SCAM schemes provide better performance as compared to a single FSO uplink, while SCAM scheme enjoys better performance than TCAM scheme. This comes at the expense of increased complexity of the SCAM scheme. Also, coherent FSO detection technique shows better performance than the SIM/DD FSO detection technique for both schemes. The choice of which scheme and which FSO detection technique to use is a compromise of required quality of service and complexity.

1. Introduction

In recent years, providing end users with high data-rate services such as telecommunications, multimedia and high-speed Internet has gained an increased importance due to the growing demand on these services. This objective can be manipulated by transmitting huge amount of data from services providers to constellations of low earth orbit (LEO) satellites which in turn relay the data to vast number of customers over very wide geographical areas [1]. Free space optical (FSO) uplinks from an optical ground station (OGS) to LEO satellites have emerged as attractive candidates to be used in transmitting huge amount of data with high speed. This is because FSO uplinks are characterized by their wide unregulated spectrum with a significantly greater bandwidth as compared to their radio frequency (RF) links counterparts [2]. This leads to that many space agencies such as the European Space Agency, the National Aeronautics Agency and the Japan Aerospace to pay increased attention to FSO uplinks and to conduct many studies in this field (see [3] and references therein).

A transmitted optical beam from the OGS to the satellite is affected by turbulence eddies with different sizes and refractive indices because of the random variations in the atmosphere's temperature and pressure [4]. These atmospheric turbulences cause random

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

irradiance fluctuations. When the size of the turbulence eddies is bigger than the diameter of the transmitted optical beam, the the hot spot is randomly moved in the reception plane at the satellite causing beam wander-induced fading [4]. The misalignment between the OGS and the satellite due to building sway or satellite vibrations cause pointing error-induced fading which can also attenuates the transmitted optical beam [5]. Also, when the laser beam travels through the atmosphere towards the satellite, it can be affected by various weather conditions including clear air, fog, and cloud [6]. The quality of the FSO uplink can be greatly deteriorated by these fading effects.

Many methods had been presented in the literature to mitigate these effects and improve the reliability of the FSO uplink. One method was using the transmit diversity technique [7, 8] in which a number of received laser beams are combined at the receiver by using linear combining techniques such as maximal ratio combining (MRC), equal gain combining (EGC), and selection combining (SC). The main idea of this method is that multiple transmitted laser beams that are separated by distances greater than the spatial coherence radius are less likely to be affected by the same amount of channel fading and less likely to be all in bad conditions. The MRC technique was adopted in [7,8] for the FSO uplinks, while the EGC and SC techniques were used for FSO downlinks in [9]. This transmit diversity technique had shown a noticeable performance improvement of the OGS-satellite FSO transmission system at the expense of an increased hardware complexity at the receiver side. Another method is adopting the adaptive modulation technique in which a target bit error rate (BER) is maintained while adjusting the parameters of the modulation scheme, such as the constellation size according to the channel state information (CSI) [10, 11]. This technique aims to use the FSO channel more efficiently in adverse channel conditions as the FSO channel experiences slow-fading [5]. In [10], the capacity of the FSO uplink was improved through changing the modulation order of an M-phase shift keying (M-PSK) modulation scheme. In [11], the spectral efficiency of the FSO uplink was improved by changing the modulation order of an M-amplitude shift keying (M-ASK) modulation scheme.

In this work, we present two new low-complexity joint transmit diversity and adaptive modulation schemes for the OGS-satellite FSO uplink in order to mitigate the fading effects and increase the reliability of the FSO uplink. Specifically, the TCAM-scheme which is a joint dual-branch threshold combining (TC) and adaptive modulation scheme and the SCAM-scheme which is a joint dual-branch selection combining (SC) and adaptive modulation scheme. The proposed schemes discretely adjust the data rate on the two FSO uplinks in accordance with the instantaneous received combined signal-to-noise ratio (SNR) at the satellite where different sizes of an M-quadrature amplitude modulation (M-QAM) scheme are used. The proposed schemes are based on TC and SC schemes which are less complex as compared to other transmit diversity techniques as the MRC and EGC schemes.

The rest of the paper is organized as follows. The OGS-satellite FSO uplink model is presented in section 2. The proposed TCAM and SCAM schemes are introduced in section 3. The performance of the TCAM and SCAM schemes is analyzed in section 4, followed by the numerical results in section 5. Finally, section 6 concludes the work in this paper.

2. OGS-to-Satellite FSO Uplink Modelling

The FSO uplink is assumed to experience modulated-Gamma fading due to the combined effects of the atmospheric turbulence and beam wander along with pointing error impairments due to the misalignment between the OGS and the LEO satellite. The modulated-Gamma distribution fits well the experimental data as well as the simulation results from the Lincoln laboratory numerical wave optics code [4]. In the modulated-Gamma distribution, the received irradiance with Gamma distribution is assumed to be modulated by a beam-wander factor with Beta distribution [4]. Thus, considering subcarrier intensity modulation/direct detection (SIM/DD) and coherent FSO detection techniques, a unified probability density function (PDF) of the received SNR, denoted by γ_{FSO}, is given by [12, Eq. (16)]

$$f_{\gamma_{FSO}}(\gamma_{FSO}) = \frac{\delta^2\mu}{r\Gamma(\nu)}\gamma_{FSO}{}^{-1}G_{2,3}^{3,0}\left[\frac{\delta^2\mu\nu\left(\gamma_{FSO}/\mu_r\right)^{\frac{1}{r}}}{(1+\mu)(1+\delta^2)}\,|_{\delta^2,\mu,\nu}^{1+\mu,1+\delta^2}\right], \tag{1}$$

where $r = 1$ for coherent FSO detection technique with $\mu_r = \bar{\gamma}_{FSO}$ and $r = 2$ for SIM/DD FSO detection technique with $\mu_r = \bar{\gamma}_{FSO}\nu\mu(2+\mu)(2\delta^2+\delta^4)/(1+\delta^2)^2(1+\nu)(1+\mu)^2$, where $\bar{\gamma}_{FSO}$ is the statistical average of instantaneous received SNR for both detection techniques. ν is the shape parameter of the Gamma distribution, μ is the beam-wander parameter, δ is the severity parameter of the pointing error-induced fading (small values of δ means large pointing errors-induced fading effects and the vice-versa) and $G[.]$ is the Meijer G-function as defined in [13, Eq.(9.301)]. The shape parameter is calculated as $\nu = [\exp\left(\sigma^2_{\ln X}+\sigma^2_{\ln Y}\right)-1]^{-1}$ [4] where $\sigma^2_{\ln X} = 0.49\sigma^2_{Bu}/\left(1+(1+\Theta)0.56\sigma_{Bu}^{12/5}\right)^{7/6}$ and $\sigma^2_{\ln Y} = 0.51\sigma^2_{Bu}/\left(1+0.69\sigma_{Bu}^{12/5}\right)^{5/6}$ with σ^2_{Bu} is calculated by

$$\begin{aligned}\sigma^2_{Bu} &= 8.70\mu_u k^{7/6}(H-h_0)^{5/6}\sec^{11/6}(\zeta),\\ \mu_u &= \mathrm{Re}\left\{\int_{h_0}^{H} C_n^2(h)\left\{\xi^{\frac{5}{6}}\left[\Lambda\xi+i(1-\overline{\Theta}\xi)\right]^{\frac{5}{6}}-\Lambda^{\frac{5}{6}}\xi^{\frac{5}{3}}\right\}dh\right\},\end{aligned} \tag{2}$$

where $k = 2\pi/\lambda$ is the optical wave number with λ is the wavelength of the optical beam beam, H is the altitude of the satellite, h_0 is the altitude of the ground station and ζ is the zenith angle measured from the vertical direction, $\xi = 1-(h-h_0)/(H-h_0)$, $i = \sqrt{-1}$ and $\overline{\Theta} = 1-\Theta$. Assuming a Gaussian-beam wave model, $\Theta = \Theta_0/(\Theta_0^2+\Lambda_0^2)$ is the refraction parameter at the satellite side with Θ_0 and Λ_0 are the curvature parameter and Fresnel ratio respectively. $\Theta_0 = 1-L/F_0$, where F_0 is the phase front radius of curvature of the laser beam at the OGS and $L = (H-h_0)\sec(\zeta)$ is the slant distance between the OGS and the satellite. $\Lambda_0 = 2L/kW_0^2$, where W_0 is the radius of the laser beam at the OGS. $\Lambda = \Lambda_0/(\Theta_0^2+\Lambda_0^2) = 2L/kW^2$ is the diffraction parameter at the satellite side, where W is the radius of the laser beam at the satellite. For a collimated laser beam, $F_0 = \infty$ which leads to $\Theta = 1/(1+\Lambda_0^2)$ and $\Lambda = \Lambda_0/(1+\Lambda_0^2)$. The beam-wander parameter is calculated by [4]

$$\mu = \left[\sqrt{\frac{\exp\left(\sigma^2_{\ln X}+\sigma^2_{\ln Y}\right)}{34.29(\Lambda L/kr_0{}^2)^{\frac{5}{6}}(\sigma^2_{pe}/W^2)}+1}\right]-1, \tag{3}$$

where σ^2_{pe} is the variance of the pointing error that is resulted from the effects of the beam-wander and is given by [4]

$$\sigma^2_{pe} \cong 0.54L^2\left(\frac{\lambda}{2W_0}\right)^2\left(\frac{2W_0}{r_o}\right)^{\frac{5}{3}}\left[1-\left(\frac{\pi^2W_0^2/r_0^2}{1+\pi^2W_0^2/r_0^2}\right)^{\frac{1}{6}}\right], \quad H \gg 20\ \mathrm{Km}, \tag{4}$$

where r_0 is the atmospheric coherence width that is given by [14]

$$r_0 = \left[0.423\ k^2\sec(\zeta)\int_{h_0}^{H} C_n^2(h)dh\right]^{-3/5}. \tag{5}$$

$C_n^2(h)$ in (2) and (5) is the the structure parameter which is usually modelled by the H–V$_{5/7}$ model with a nominal value of $C_n^2(0) = 1.7\times10^{-14}m^{-2/3}$ at the ground level and an rms wind speed value of 21 m/s [14]. The unified cumulative distribution function (CDF) of the received SNR γ_{FSO} is given by [12, Eq. (17)]

$$F_{\gamma_{FSO}}(\gamma_{FSO}) = \frac{\delta^2 \mu r^{\nu-2.5}}{(2\pi)^{\frac{r-1}{2}}\Gamma(\nu)} G^{3r,1}_{2r+1,3r+1}\left[\mathcal{A}\frac{\gamma_{FSO}}{\mu_r}\,\Big|^{1,\kappa_1}_{\kappa_2,0}\right], \tag{6}$$

where $\mathcal{A} = \left(\delta^2\mu\nu/r(1+\mu)(1+\delta^2)\right)^r$, $2r$-terms κ_1 defined as $\kappa_1 = \frac{\mu+1}{r}, ..., \frac{\mu+r}{r}, \frac{\delta^2+1}{r}, ..., \frac{\delta^2+r}{r}$, and $3r$-terms κ_2 defined as $\kappa_2 = \frac{\delta^2}{r}, ..., \frac{\delta^2+r-1}{r}, \frac{\mu}{r}, ..., \frac{\mu+r-1}{r}, \frac{\nu}{r}, ..., \frac{\nu+r-1}{r}$.

3. Joint Transmit Diversity and Adaptive Modulation Schemes Modelling

The OGS is equipped with two laser sources which provide dual FSO uplinks to the LEO satellite, denoted by FSO_1 and FSO_2 where the corresponding received SNRs are denoted by γ_{FSO1} and γ_{FSO2}, respectively. The two sources are assumed to be separated by a distance that is greater than the atmospheric coherence width r_0. It is feasible to satisfy this condition as there are no space limitation at the OGS. Thus, the two FSO uplinks are considered to be statistically independent from each other. It is worth to mention here that the two FSO uplinks will have the same statistical distribution as defined by (1) and (6). A data symbol can be transmitted over any one of the two FSO uplinks according to a threshold combining (TC) technique or a selection combining (SC) technique while adopting the M-QAM scheme on both uplinks. M-QAM is widely adopted in the high data-rate FSO systems due to the ease of its modulation and demodulation processes and its high spectral efficiency [15]. The OGS can use any one of N constellation sizes of the M-QAM scheme according to the instantaneous received SNR at the satellite which is assumed to be sent to the OGS via an error-free feedback link. The main target is to maintain the instantaneous bit-error-rate (BER) less than a targeted value of BER_0 (to satisfy the required quality of service (QoS)) while achieving the maximum possible spectral efficiency. Let $\gamma_{th1}, \gamma_{th2}, ..., \gamma_{thN}$ be the SNR thresholds that are corresponding to N constellation sizes of $M = 4, 16, ..., 2^{2N}$, respectively such that $\gamma_{th1} < \gamma_{th2} < ... < \gamma_{thN}$. Note that $\gamma_{thN+1} = \infty$. These thresholds can be calculated according to the target value BER_0 by using [16]

$$\gamma_{th_n} = (2^{2n} - 1)\left[-\frac{2}{3}\ln(5\ \text{BER}_0)\right], \quad 2^{2n} \geq 4, \tag{7}$$

where the instantaneous BER of the M-QAM scheme of size 2^{2n} is well approximated by [16]

$$BER_n(\gamma) = 0.2\exp\left(\frac{-1.5}{2^{2n}-1}\gamma\right), \quad 2^{2n} \geq 4,\ 0 \leq \gamma \leq 30\text{dB}. \tag{8}$$

It is worth to mention here that the FSO uplink is considered a slow fading channel where the correlation time of the atmosphere is in the order of 10 millisecond or more [14] which ensures that the OGS will change its constellation size according to the instantaneous CSI before the FSO uplink changes.

3.1. Joint Dual-branch Threshold Combining and Adaptive Modulation Scheme (TCAM-scheme)

In this scheme, the OGS will first use the FSO uplink FSO_1 for data transmission. The constellation size 2^{2N} will be used over FSO_1 as long as $\gamma_{FSO1} \geq \gamma_{thN}$ in order to grantee the maximum spectral efficiency. If γ_{FSO1} decreases beyond γ_{thN}, the satellite checks another SNR threshold γ_{th_n} in a descending order until one threshold satisfies $\gamma_{FSO1} \geq \gamma_{th_n}$. Then, the satellite transmits a feedback signal to the OGS in order to use the corresponding M-QAM scheme in its data transmission. If $\gamma_{FSO1} < \gamma_{th1}$, the satellite transmits a feedback signal of 1-bit to the OGS in order to use the FSO_2 uplink for data transmission. When the OGS uses the FSO_2 uplink, the satellite will repeat the same threshold checking process as was done with the FSO_1 uplink aiming to maximize the spectral efficiency through the usage of the largest possible constellation size 2^{2N}. This is done by sending a feedback signal to the OGS in order to use the chosen 2^{2N}-QAM scheme. If $\gamma_{FSO2} < \gamma_{th1}$, the satellite transmits a feedback signal to the OGS in order to suspend data transmission over both FSO uplinks[1]. The average feedback load of the proposed TCAM-scheme can be calculated as $\lceil \log_2(N+1) \rceil \left(1 + \mathrm{P_r}[\gamma_{FSO1} < \gamma_{th1}]\right)$ bits. Considering the operational modes of this transmission scheme, the received SNR at the satellite, denoted by γ_c, is given by

$$\gamma_c = \begin{cases} \gamma_{FSO1}, & \text{if } \gamma_{FSO1} \geq \gamma_{th1} \\ \gamma_{FSO2}, & \text{if } \gamma_{FSO1} < \gamma_{th1}. \end{cases} \tag{9}$$

Under the assumption of independent and identically distributed (I.I.D.) FSO uplinks, the CDF of γ_c is given by

$$\begin{aligned} F_{\gamma_c}(\gamma_{FSO}) &= \mathrm{P_r}[\gamma_{FSO1} < \gamma_{FSO}, \gamma_{FSO1} \geq \gamma_{th1}] + \mathrm{P_r}[\gamma_{FSO2} < \gamma_{FSO}, \gamma_{FSO1} < \gamma_{th1}] \\ &= \begin{cases} F_{\gamma_{FSO}}(\gamma_{th1}) F_{\gamma_{FSO}}(\gamma_{FSO}) + F_{\gamma_{FSO}}(\gamma_{FSO}) - F_{\gamma_{FSO}}(\gamma_{th1}), & \text{if } \gamma_{FSO} \geq \gamma_{th1} \\ F_{\gamma_{FSO}}(\gamma_{th1}) F_{\gamma_{FSO}}(\gamma_{FSO}), & \text{if } \gamma_{FSO} < \gamma_{th1}, \end{cases} \end{aligned} \tag{10}$$

where $F_{\gamma_{FSO}}(\gamma_{FSO})$ is given by (6). By differentiating (10) with respect to γ_{FSO}, the PDF of γ_c in this case is given by

$$f_{\gamma_c}(\gamma_{FSO}) = \begin{cases} F_{\gamma_{FSO}}(\gamma_{th1}) f_{\gamma_{FSO}}(\gamma_{FSO}) + f_{\gamma_{FSO}}(\gamma_{FSO}), & \text{if } \gamma_{FSO} \geq \gamma_{th1} \\ F_{\gamma_{FSO}}(\gamma_{th1}) f_{\gamma_{FSO}}(\gamma_{FSO}), & \text{if } \gamma_{FSO} < \gamma_{th1}, \end{cases} \tag{11}$$

where $f_{\gamma_{FSO}}(\gamma_{FSO})$ is given by (1). Based on the operational modes of the TCAM scheme, the average number of FSO uplink's CSI estimations needed can be calculated as $1 + [F_{\gamma_{FSO}}(\gamma_{th1})]$.

3.2. Joint Dual-branch Selection Combining and Adaptive Modulation Scheme (SCAM-scheme)

In this scheme, the satellite checks the received γ_{FSO1} and γ_{FSO2} and then sends a feedback signal of 1-bit to tell the OGS to use the FSO uplink that supports the maximum SNR for data transmission. Thus, the received SNR at the satellite, denoted by γ_c, is given by

$$\gamma_c = \mathrm{Max}\{\gamma_{FSO1}, \gamma_{FSO2}\}. \tag{12}$$

In order to achieve the maximum spectral efficiency, the OGS will use the constellation size 2^{2N} over the chosen FSO uplink as long as $\gamma_c \geq \gamma_{thN}$. If γ_c decreases beyond γ_{thN}, the satellite checks another threshold γ_{thn} in a descending order until one threshold satisfies $\gamma_{thn} \leq \gamma_c$. In this case, the satellite sends a feedback signal to the OGS in order to use the corresponding M-QAM scheme in its data transmission. If the thresholds checking process reaches γ_{th1} and γ_c is less than γ_{th1}, the satellite sends a feedback signal to the OGS in order to suspend data transmission over both FSO uplinks. The average feedback load of the proposed SCAM-scheme can be calculated as $\lceil \log_2(N+1) \rceil \left(1 + \mathrm{P_r}[\gamma_c < \gamma_{th1}]\right)$ bits. Under the assumption of I.I.D. FSO uplinks, the CDF of γ_c is given by

$$F_{\gamma_c}(\gamma_{FSO}) = \mathrm{P_r}[\gamma_{FSO1} < \gamma_{FSO}] \mathrm{P_r}[\gamma_{FSO2} < \gamma_{FSO}] = \left[F_{\gamma_{FSO}}(\gamma_{FSO})\right]^2, \tag{13}$$

where $F_{\gamma_{FSO}}(\gamma_{FSO})$ is given by (6). By differentiating (13) with respect to γ_{FSO}, the PDF of γ_c in this case is given by

$$f_{\gamma_c}(\gamma_{FSO}) = 2F_{\gamma_{FSO}}(\gamma_{FSO}) f_{\gamma_{FSO}}(\gamma_{FSO}), \tag{14}$$

where $f_{\gamma_{FSO}}(\gamma_{FSO})$ is given by (1). Based on the operational modes of the SCAM scheme, the average number of FSO uplink's CSI estimations needed is equal to 2.

[1] When data transmission is suspended, pilot signal is assumed to be continuously transmitted over both FSO uplinks to examine their qualities.

4. Performance Analysis of the Proposed Transmission Schemes

4.1. Outage Probability

When the combiner SNR γ_c falls below γ_{th1}, the transmission scheme can't support the target BER and thus it goes into outage state. Thus, the outage probability P_{out} of the transmission scheme can be calculated as

$$\mathrm{P}_{out} = F_{\gamma_c}(\gamma_{th1}), \tag{15}$$

where $F_{\gamma_c}(\gamma_{FSO})$ is the CDF of γ_c given by either (10) or (13) according to the used scheme.

4.2. Average Spectral Efficiency

The average spectral efficiency η of the transmission schemes is defined as the average number of bits transmitted over each symbol period [16]. Thus, η can be calculated as

$$\eta = \sum_{n=1}^{N} 2n[F_{\gamma_c}(\gamma_{th\,n+1}) - F_{\gamma_c}(\gamma_{th\,n})], \tag{16}$$

where $F_{\gamma_c}(\gamma_{FSO})$ is given by either (10) or (13) according to the used transmission scheme.

4.3. Average Bit Error Rate

The average BER P_e of the transmission schemes is defined as the ratio of the average number of erroneously received bits over the total average number of transmitted bits [16]. Thus, P_e can be calculated as

$$P_e = \frac{1}{\eta}\sum_{n=1}^{N} 2n\overline{BER}_n, \tag{17}$$

where $\overline{BER}_n$ is the average BER of using constellation size 2^{2n}, given by

$$\overline{BER}_n = \int_{\gamma_{th\,n}}^{\gamma_{th\,n+1}} BER_n(\gamma_{FSO}) f_{\gamma_c}(\gamma_{FSO}) d\gamma_{FSO}, \tag{18}$$

with $BER_n(\gamma_{FSO})$ is given by (8) and $f_{\gamma_c}(\gamma_{FSO})$ is given by either (11) or (14) according to the used transmission scheme. Numerical methods can be used to evaluate (18).

5. Numerical Results

In this section we introduce several numerical examples to study the proposed schemes' performance. The parameters of the FSO uplinks that are used in the numerical results are taken from [4] where we assume $H = 300$ Km, $h_0 = 100$ m and $\lambda = 1550$ nm. Three different constellation sizes 2^{2n} of values 4, 16 and 64 are assumed to be used. Assuming target BER_0 of 10^{-6}, the corresponding thresholds $\gamma_{th\,n}$, $n = 1, 2$, and 3 are calculated by using (7). It can be observed from Figs. $1-3$ that coherent FSO detection technique gives better outage and BER performances and higher spectral efficiency than SIM/DD FSO detection technique. However, this comes at the cost of more complexity of the coherent FSO detection technique as compared to the SIM/DD detection technique.

In figure 1, we plot P_{out} of the proposed TCAM and SCAM schemes and a single FSO uplink as a function of $\bar{\gamma}_{FSO}$ with $\delta = 7$ and $\zeta = 0^0$. It can be observed that the proposed TCAM and SCAM schemes provide an outage performance much better than that of a single FSO uplink with the same adaptive modulation scheme. Also, it can be observed that both schemes show the same outage performance for both coherent and SIM/DD detection techniques. This is because both schemes have an outage probability of $[F_{\gamma_{FSO}}(\gamma_{th1})]^2$ which corresponds that both schemes

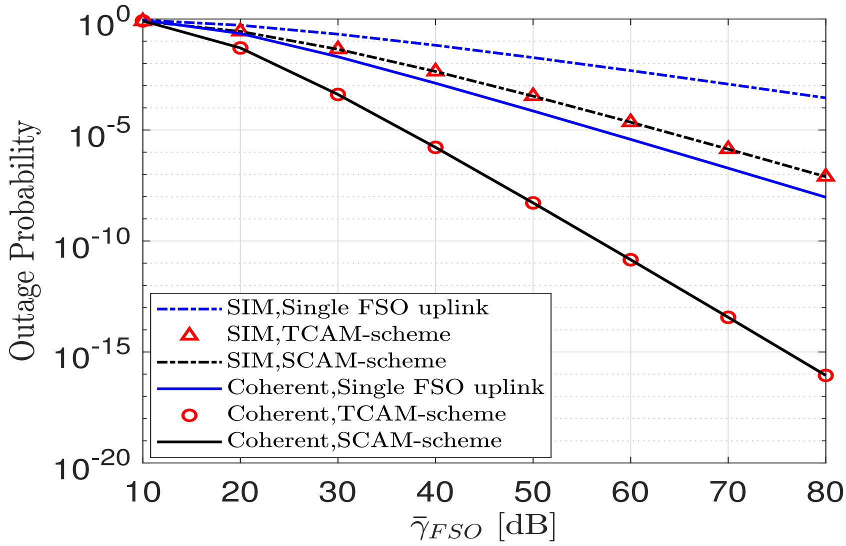

Figure 1. Outage probability of the proposed TCAM and SCAM schemes and a single FSO uplink.

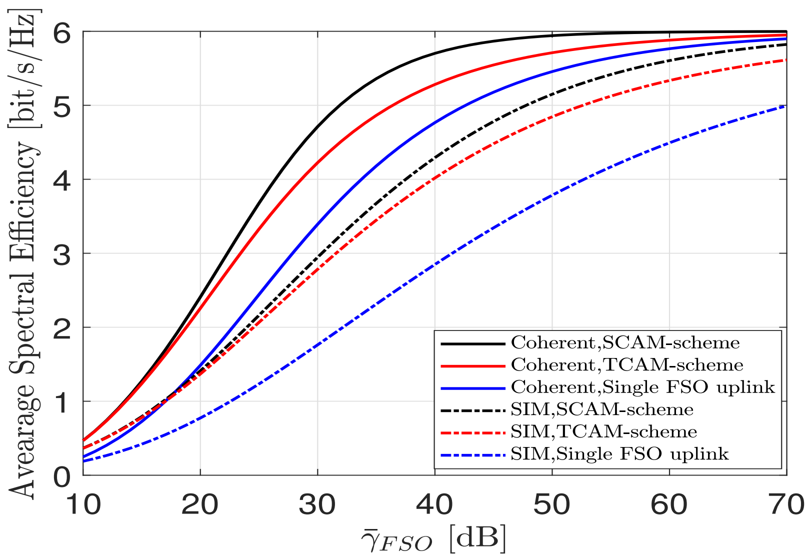

Figure 2. Average spectral efficiency of the proposed TCAM and SCAM schemes and a single FSO uplink.

will be in outage when both FSO uplinks are in outage. As expected, the outage performance of both schemes is improved as the quality of both FSO uplinks is improved.

In figure **??**, we plot η of the proposed TCAM and SCAM schemes and a single FSO uplink as a function of $\bar{\gamma}_{FSO}$ with $\delta = 1$ and $\zeta = 60$. It can be seen that the average spectral efficiency of both proposed schemes increases by increasing $\bar{\gamma}_{FSO}$ for both SIM/DD and coherent detection schemes. This is because higher modulation constellation size is used as the quality of the FSO uplinks improves. Also, both schemes provide average spectral efficiency much higher than that of a single FSO uplink with the same adaptive modulation scheme. It can observe also that the SCAM scheme has an average spectral efficiency higher than that of the TCAM scheme.

In figure 3, we plot P_e of the proposed TCAM and SCAM schemes and a single FSO uplink as a function of $\bar{\gamma}_{FSO}$ with $\delta = 1$ and $\zeta = 60$. It can be observed that the SCAM-scheme can

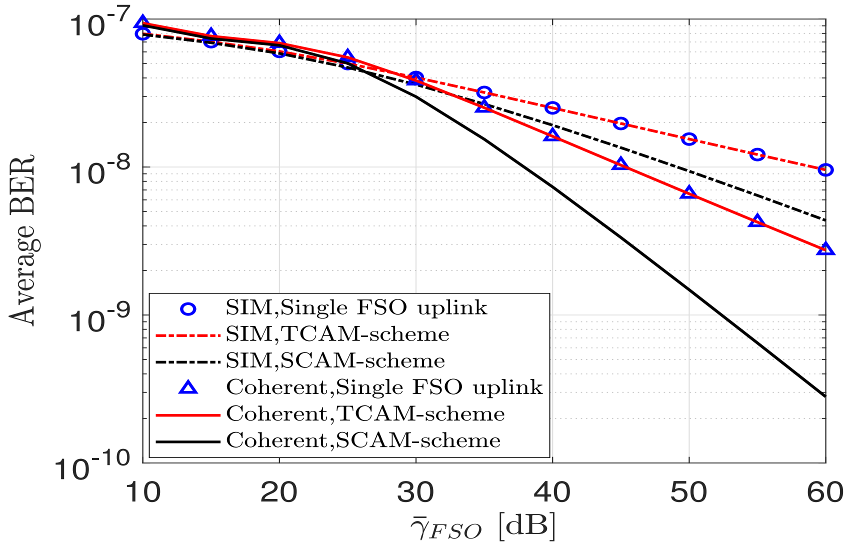

Figure 3. Average BER of the proposed TCAM and SCAM schemes and a single FSO uplink.

achieve BER performance better than that of TCAM-scheme and a single FSO uplink. Also, it can be observed that the TCAM-scheme shows almost the same BER performance as the single FSO uplink. As expected, the average BER decreases as the quality of both FSO uplinks is improved.

6. Conclusion

In this work, we presented two novel low-complexity transmission schemes for OGS-satellite FSO uplink, named as TCAM and SCAM schemes. The two proposed schemes had shown a superior performance improvement in terms of outage probability, average spectral efficiency while enjoying good BER performance as compared to a single FSO uplink. This is owing to their increased ability to mitigate the fading effects that encounter over the FSO uplink which in turn had improved the reliability of the data transmission system. Also, numerical results had shown that the SCAM scheme had better performance than the TCAM scheme at the expense of higher complexity in terms of the average number of FSO uplink's CSI estimations. Also, for both proposed schemes, coherent FSO system shows improved performance than the SIM/DD FSO system at the cost of its increased hardware complexity. By the end, the choice of which FSO transmission scheme and which FSO detection type to be used is a compromise between the required QoS and system's complexity.

References

[1] Leyva-Mayorga I, Soret B, Röper M, Wübben D, Matthiesen B, Dekorsy A and Popovski P 2020 *IEEE Access* **8** 184955–184964
[2] Chan V W 2006 *Journal of Lightwave technology* **24** 4750–4762
[3] Sodnik Z, Lutz H, Furch B and Meyer R 2010 Optical satellite communications in europe *Free-Space Laser Communication Technologies XXII* vol 7587 (SPIE) pp 49–57
[4] Andrews L C and Phillips R L 2008 Recent results on optical scintillation in the presence of beam wander *Atmospheric Propagation of Electromagnetic Waves II* vol 6878 (SPIE) pp 23–36
[5] Farid A A and Hranilovic S 2007 *Journal of Lightwave technology* **25** 1702–1710
[6] Viswanath A, Jain V K and Kar S 2015 *IET Communications* **9** 2253–2258
[7] Kaushal H, Jain V K and Kar S 2010 Improvement of ground to satellite fso link performance using transmit diversity in weak atmospheric turbulence *2010 International Conference on Intelligent and Advanced Systems* (IEEE) pp 1–6

[8] Viswanath A, Kumar Jain V and Kar S 2017 *Journal of Optical Communications* **39** 61–70
[9] Sun J, Huang P, Yao Z and Guo J 2019 *Optics Communications* **444** 32–38
[10] Alshaer N, Ismail T and Nasr M E 2020 *AEU-International Journal of Electronics and Communications* **125** 153366
[11] Adel S, Alshaer N and Ismail T 2022 Enhancing spectral efficiency of ground-to-hap fso system with adaptive mask in presence of beam-wander and aoa fluctuation *2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)* (IEEE) pp 65–70
[12] Elsaidy E and Rakia T 2022 A unified performance analysis of ogs-to-satellite fso uplink under turbulence and beam wander *2022 5th International Conference on Communications, Signal Processing, and their Applications (ICCSPA)* (IEEE) pp 1–6
[13] Gradshteyn I S and Ryzhik I M 2014 *Table of integrals, series, and products* (Academic press)
[14] Andrews L C and Phillips R L 2005 *Laser Beam Propagation Through Random Media: Second Edition*
[15] Vu B T, Dang N T, Thang T C and Pham A T 2013 *Journal of Optical Communications and Networking* **5** 437–446
[16] Goldsmith A 2005 *Wireless communications* (Cambridge university press)