MISO Relay-Assisted FSO Systems Over Gamma–Gamma Fading Channels With Pointing Errors

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***Abstract*— The impact of multiple-input/single-output (MISO) relay-assisted free-space optical systems by using transmit laser selection scheme in source-relay (S-R) and relay-destination (R-D) link on the diversity order as well as derive novel approximate closed-form bit-error rate expressions over gamma–gamma fading channels with pointing errors is investigated. Knowing that M and N are the number of transmit lasers corresponding to the MISO S-R and R-D links, respectively, and b_{SR}, b_{RD}, and b_{SD} are the parameters, which depend on the atmospheric turbulence as well as pointing errors, i.e., $b_m = \min(\beta_m, \varphi_m^2)$. It is concluded that the diversity order gain achieved is strongly dependent on the relay location, being significantly increased by $N(b_{RD}/b_{SD})$ when the relation $N < (b_{SD} + Mb_{SR})/b_{RD}$ is satisfied. This is dramatically decreased when diversity order is affected by pointing errors, being determined by $\min(N, M+1)$ regardless of the relay location.**

***Index Terms*— FSO, BER, MISO and diversity order gain.**

I. Introduction

FREE-SPACE optical (FSO) systems using intensity modulation and direct detection (IM/DD) can provide high-speed signaling for a variety of applications. FSO communications are mainly affected by various factors such as atmospheric turbulence induced fading, and misalignment [1].

In this letter, we investigate a decode-and-forward (DF) relaying scheme by using transmit laser selection (TLS) in source-relay (S-R) link as well as relay-destination (R-D) link with IM/DD in the context of cooperative FSO systems. Multiple-Input/Multiple-Output (MIMO) relay-assisted is a well-known technique studied in radio-frequency (RF) systems [2], [3], which can be perfectly applied to FSO systems, wherein the relay nodes can be equipped with multiple lasers and/or apertures, achieving more spatial degrees of freedom since the lasers are not completely distributed. Recently, the study of MIMO relay-assisted FSO communications by using TLS has been analyzed in [4] over gamma-gamma turbulence channels without considering pointing error effects. Transmit diversity by employing TLS scheme is a MIMO technique based on the selection of the optical path with a greater value of irradiance, which is able to achieve a better performance compared to general FSO space-time codes (STCs) designs and repetition codes (RCs) [5], [6], as well as can be perfectly applyed to cooperative FSO systems. That is the reason that TLS has been chosen from other MIMO techniques. In [7], a very simple case was recently considered when only one bit feedback about the instantaneous channel state information (CSI) is available in the transmitter, proposing a beamforming scheme that outperforms repetition coding despite of error in the feedback bit. The main contribution of this letter is to study the impact of MISO relay-assisted FSO systems by using TLS scheme in S-R link as well as R-D link on the diversity order and derive novel approximate closed-form bit-error rate (BER) expressions over gamma-gamma fading channels with pointing errors. Cooperative communication based on DF protocols can significantly improve the performance in FSO systems [8]–[10]. The obtained diversity order depends not only on the relay location but also on the pointing errors. A remarkable reduction of number of transmit lasers as well as receivers is achieved by employing MISO relay-assisted FSO systems if compared to a cooperative FSO scenario with N_r relays.

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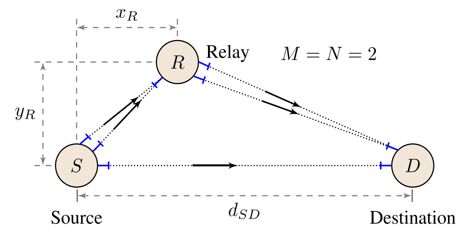

Fig. 1. Example diagram showing the MISO relay-assisted FSO system under study when $M = N = 2$.

II. System and Channel Model

We consider a three-node cooperative FSO system, as shown in Fig. 1. Here, two MISO arrays based on M and N transmit lasers are considered in S-R and R-D links, respectively. These MISO FSO systems can be considered as an equivalent single-input/single-output (SISO) system model where the channel irradiance corresponding to the TLS scheme, i.e., $I_{SR_{\max}}$ and $I_{RD_{\max}}$ can be written as $I_{SR_{\max}} = \max(I_{SR_1}, \ldots, I_{SR_M})$ and $I_{RD_{\max}} = \max(I_{RD_1}, \ldots, I_{RD_N})$, respectively. This relaying scheme is based on the basis of the value of the fading gain or irradiance between source-destination (S-D) and S-R link. In this way, the source node sends data to the destination node or to the relay node depending on which path, S-D (I_{SD}) or S-R-D ($I_{SR_{\max}}$), has been selected according to greater value of fading gain. It is taking into account that CSI is known not only at the receiver but also at the transmitter. The knowledge of CSIT is feasible for FSO channels given that scintillation is a slow time varying process relative to the large symbol rate. In this way, the CSI can be acquired by using the training sequence at the receiver side and feedback the CSI back to transmitter [11]. Here, it is considered that all the bits detected at the relay node are always forwarded with the new power to the destination node D regardless of these bits are detected correctly or incorrectly. The received electrical signal for each link is given by $Y_m = XI_m + Z_m$, where X is the binary transmitted signal, I_m is the equivalent real-value fading gain (irradiance) through the optical channel, and Z_m is additive white Gaussian noise (AWGN) with zero mean and variance $\sigma^2 = N_0/2$, i.e., $Z_m \sim N(0, N_0/2)$. Here, on-off keying (OOK) modulation scheme is used, X is either 0 or $2P_{opt}\sqrt{T_b\xi}$, where P_{opt} is the average transmitted optical power from each node, T_b is the bit period, and ξ is related to the used pulse shape. The irradiance is considered to be a product of three factors i.e., $I_m = L_m I_m^{(a)} I_m^{(p)}$ where L_m is the deterministic propagation loss, $I_m^{(a)}$ is the attenuation due to atmospheric turbulence and $I_m^{(p)}$ the attenuation due to geometric spread and pointing errors. L_m is determined by the exponential Beers-Lambert law as $L_m = e^{-\Phi d_m}$, where d_m is the link distance and Φ is the atmospheric attenuation coefficient. It is given by $\Phi = (3.91/V(\text{km}))(\lambda(\text{nm})/550)^{-q}$ where V is the visibility in kilometers, λ is the wavelength in nanometers and q is a parameter related to the visibility, being $q = 1.3$ for average visibility (6 km $< V <$ 50 km) and $q = 0.16V + 0.34$ for haze visibility (1 km $< V <$ 6 km). To consider a wide range of turbulence conditions, the gamma-gamma turbulence model proposed in [12] is assumed here. Regarding the impact of pointing errors, which can arise due to building sways, mechanical misalignment, errors in tracking systems, or due to mechanical vibrations, we use the general model of misalignment fading given in [13], wherein the effect of beam width, detector size and jitter variance is considered. Assuming a Gaussian spatial intensity profile of beam waist radius, ω_z, on the receiver plane at distance z from the transmitter and a circular receive aperture of radius r, $\varphi = \omega_{z_{eq}}/2\sigma_s$ is the ratio between the equivalent beam radius at the receiver and the pointing error displacement standard deviation (jitter) at the receiver, $\omega_{z_{eq}}^2 = \omega_z^2\sqrt{\pi}\,\text{erf}(v)/2v\exp(-v^2)$, $v = \sqrt{\pi}r/\sqrt{2}\omega_z$, $A_0 = [\text{erf}(v)]^2$ and erf(·) is the error function [14, eq. (8.250)]. A closed-form expression of the combined probability density function (PDF) of I_m was derived in [15, eq. (12)] in terms of the Meijer's G-function [14, eq. (9.301)]. This PDF can be approximated by using the first two terms of the Taylor expansion at $i = 0$ as $f_{I_m}(i) = a_m i^{b_m-1} + c_m i^{b_m} + O(i^{b_m+1})$. As proposed in [16], the PDF is approximated as $f_{I_m}(i) \approx a_m i^{b_m-1} e^{i\frac{c_m}{a_m}}$. Different expressions for a_m, b_m and c_m, depending on the relation between the values of φ^2 and β, can be written as

$$f_{I_m}(i) \approx a_m i^{b_m-1} e^{i\frac{c_m}{a_m}} = \begin{cases} \dfrac{\varphi^2(\alpha\beta)^{\beta}\Gamma(\alpha-\beta)i^{\beta-1}}{(A_0L_m)^{\beta}\Gamma(\alpha)\Gamma(\beta)(\varphi^2-\beta)} e^{i\frac{\alpha\beta(\varphi^2-\beta)(A_0L_m)^{-1}}{(\alpha-\beta-1)(\beta-\varphi^2+1)}}, & \varphi^2 > \beta \\ \dfrac{\varphi^2\Gamma(\alpha-\varphi^2)\Gamma(\beta-\varphi^2)i^{\varphi^2-1}}{(\alpha\beta)^{-\varphi^2}(A_0L_m)^{\varphi^2}\Gamma(\alpha)\Gamma(\beta)}, & \varphi^2 < \beta \end{cases} \tag{1}$$

Note that the parameter c_m is equal to 0 when the relation $\varphi^2 < \beta$ is satisfied. Hereinafter, the fading coefficient I_m for all links are assumed statistically independent. It is also assumed that the spacing between transmitters in S-R as well as R-D MISO channel are sufficiently larger than the correlation length, l_c, then uncorrelated fading can be considered [17], [18]. Due to the fact that pointing displacements will not be exactly on the same transverse plane for all lasers, the correlation among pointing errors can be considered negligible when d_{SR} and d_{RD} are larger than the correlation length.

III. Error-Rate Performance Analysis

In this section, we obtain approximate expressions in order to quantify the bit error probability for this FSO relaying scheme in the range from low to high signal-to-noise ratio (SNR), taking advantage of the simpler expression in Eq. (1). Firstly, in order to establish the baseline performance, we can obtain the approximate closed-form solution corresponding to the direct path link (DL). In this way, the conditional BER for the direct path link assuming CSI at the receiver (CSIR) is given by $P_b^{DL}(I_{SD}) = Q\left(\sqrt{4P_{opt}^2T_b\xi/2N_0}\,i\right)$, where $Q(\cdot)$ is the Gaussian-Q function. Hence, the average BER, P_b^{DL}, can be obtained by averaging $P_b^{DL}(I_{SD})$ over the PDF as follows

$$P_b^{DL} = \int_0^{\infty} Q\left(\sqrt{2\gamma\xi}\,i\right) f_{I_{SD}}(i)di, \tag{2}$$

where $\gamma = P_{\text{opt}}^2T_b/N_0$ represents the received electrical SNR in absence of turbulence. To evaluate the integral in Eq. (2), we can use that the Q-function is related to the complementary error function erfc(·) by $\text{erfc}(x) = 2Q(\sqrt{2}x)$ [14, eq. (6.287)] and the fact that $\int_0^\infty \text{erfc}(cx)x^{\alpha-1}e^{-px}dx$ can be found in [19, eq. (2.8.5.2)], obtaining an approximate closed-form solution for a generic BER as follows

$$\begin{aligned} P_b \simeq\ & \frac{a_T\Gamma((b_T+1)/2)(\gamma\xi)^{-b_T/2}}{2b_T\sqrt{\pi}} \\ & \times {}_2F_2\left(\frac{b_T}{2}, \frac{b_T+1}{2}; \frac{b_T+2}{2}, \frac{1}{2}; \frac{c_T^2}{4a_T^2\gamma\xi}\right) \\ & + \frac{c_T\Gamma((b_T+2)/2)(\gamma\xi)^{-(b_T+1)/2}}{2(b_T+1)\sqrt{\pi}} \\ & \times {}_2F_2\left(\frac{b_T+1}{2}, \frac{b_T+2}{2}; \frac{b_T+3}{2}, \frac{3}{2}; \frac{c_T^2}{4a_T^2\gamma\xi}\right). \end{aligned} \tag{3}$$

For the sake of clarity, coefficients a_T, b_T and c_T have been adopted in Eq. (3) in order to obtain a simpler generic expression of BER, wherein ${}_2F_2(a_1, a_2; b_1, b_2; z)$ is the generalized hypergeometric function [14, eq. (9.14.1)]. By using Eq. (3), we obtain the corresponding approximate closed-form solution for the direct path link, P_b^{DL}, but substituting the corresponding coefficients a_T, b_T and c_T by the coefficients corresponding to the direct path link, i.e., a_{SD}, b_{SD} and c_{SD} derived via Eq. (1). Next, we obtain the BER at the destination node D corresponding to the FSO relaying scheme proposed as follows $P_T = P_b^{SRD} + P_b^{SD}$, where $P_b^{SRD} = P_b^{SR}(1-P_b^{RD}) + P_b^{RD}(1-P_b^{SR})$ is the BER corresponding to the S-R-D path when $I_{SR_{\max}} > I_{SD}$, as well as, P_b^{SR} and P_b^{RD} denote the BER corresponding to the S-R and R-D links, respectively. P_b^{SD} is the BER corresponding to the S-D link when $I_{SR_{\max}} < I_{SD}$. Assuming CSI at the receiver and transmitter (CSIRT), the average BER at the relay node R corresponding to S-R link is given by

$$P_b^{SR} = \int_0^\infty Q\left(\sqrt{2\gamma\xi} i\right) F_{I_{SD}}(i) f_{I_{SR_{\text{Max}}}}(i) di, \tag{4}$$

under the assumption that $I_{SR_{\max}} > I_{SD}$ as determined by $F_{I_{SD}}(i_{SR_{\max}})$. $F_{I_m}(i)$ is the cumulative density function (CDF) of the random variable I_m, which is given by $F_{I_m}(i) = Prob(I_m \leq i)$. For the sake of simplicity, in spite of the fact that this CDF can be expressed in terms of the Meijer's G-function as in [15, eq. (15)], an approximate expression can easily be deduced from Eq. (1) as follows $F_{I_m}(i) \approx (a_m/b_m)\, i^{b_m} e^{i\frac{c_m b_m}{a_m(b_m+1)}}$. According to order statistics [20], the PDF corresponding to $I_{m_{\text{Max}}}$ is given by $f_{I_{m_{\text{Max}}}}(i) = M f_{I_m}(i)[F_{I_m}(i)]^{M-1}$, being M the number of transmit lasers. Hence, the corresponding approximate expression for $f_{I_{m_{\text{Max}}}}(i)$ can be written as $f_{I_{m_{\text{Max}}}}(i) \approx \left(M a_m^M / b_m^{M-1}\right) i^{M b_m - 1} e^{i\left(\frac{c_m(M b_m+1)}{a_m(b_m+1)}\right)}$. In this way, the approximate closed-form solution for the BER, P_b^{SR}, is evaluated by using Eq. (3), substituting the corresponding coefficients a_T, b_T and c_T by the corresponding coefficients a_{SR_T}, b_{SR_T} and c_{SR_T}, respectively. These coefficients are obtained via Eq. (1) as $a_{SR_T} = \frac{M a_{SD} a_{SR}^M}{b_{SD} b_{SR}^{M-1}}$, $b_{SR_T} = b_{SD} + M b_{SR}$ and $c_{SR_T} = a_{SR_T}\left(\frac{c_{SD} b_{SD}}{a_{SD}(b_{SD}+1)} + \frac{c_{SR}(M b_{SR}+1)}{a_{SR}(b_{SR}+1)}\right)$. Alternatively, the probability when the bit is detected correctly at the relay node R, i.e., $P_b^{SR_1}$ is computed as $P_b^{SR_1} = \int_0^\infty \left(1 - Q\left(\sqrt{2\gamma\xi} i\right)\right) F_{I_{SD}}(i) f_{I_{SR_{\text{Max}}}}(i) di$. Here, we can use that the Gaussian Q-function tends to 0 as $\gamma \to \infty$, simplifying the integral as follows

$$P_b^{SR_1} \doteq \int_0^\infty M F_{I_{SD}}(i) f_{I_{SR}}(i)[F_{I_{SR}}(i)]^{M-1} di. \tag{5}$$

It can be noted that the asymptotic behavior corresponding to $P_b^{SR_1}$ is independent of the SNR γ, resulting in a positive value that is upper bounded by 1. It should be also noted that this expression has been numerically calculated by using the Monte Carlo integration being analytically intractable for values of $M \geq 2$. Next, assuming CSIR, the average BER, P_b^{RD}, is given by

$$P_b^{RD} = \int_0^\infty Q(\sqrt{2\gamma\xi} i) f_{I_{RD_{\max}}}(i) di, \tag{6}$$

where $I_{RD_{\max}}$ is the greatest value of irradiance corresponding to relay-destination link. Hence, the approximate closed-form solution for P_b^{RD} is evaluated by using Eq. (3), substituting the corresponding coefficients a_T, b_T and c_T by the corresponding coefficients a_{RD_T}, b_{RD_T} and c_{RD_T}, respectively. These coefficients are obtained via Eq. (1) as $a_{RD_T} = a_{RD}^N$, $b_{RD_T} = N b_{RD}$ and $c_{RD_T} = a_{RD_T}\left(\frac{c_{RD}(N b_{RD}+1)}{a_{RD}(b_{RD}+1)}\right)$. Finally, we obtain the BER at the destination node D corresponding to the S-D link. Therefore, assuming CSI at the receiver and transmitter, the average BER at the destination node D corresponding with S-D link, under the assumption that $I_{SD} > I_{SR_{\max}}$ as determined by $F_{I_{SR_{\max}}}(i_{SD})$, is given by

$$P_b^{SD} = \int_0^\infty Q\left(\sqrt{2\gamma\xi} i\right) F_{I_{SR_{\text{Max}}}}(i) f_{I_{SD}}(i) di, \tag{7}$$

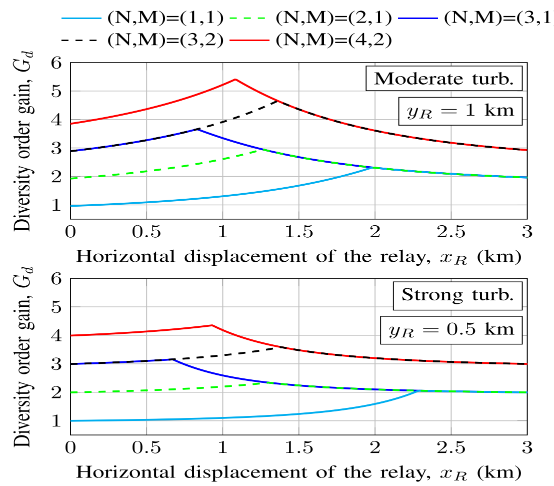

Fig. 2. Diversity order gain, G_d, for a S-D link distance of $d_{SD} = 3$ km. Once the condition $\varphi^2 > \beta$ is satisfied for each link.

where $F_{I_{m_{\text{Max}}}}(i) = [F_{I_m}(i)]^M$ [20]. Hence, the approximate closed-form solution for the BER, P_b^{SD}, is evaluated by using Eq. (3), substituting the corresponding coefficients a_T, b_T and c_T by the corresponding coefficients a_{SD_T}, b_{SD_T} and c_{SD_T}, respectively. These coefficients are obtained via Eq. (1) as $a_{SD_T} = \frac{a_{SD} a_{SR}^M}{b_{SD} b_{SR}^M}$, $b_{SD_T} = b_{SD} + M b_{SR}$ and $c_{SD_T} = a_{SD_T}\left(\frac{c_{SD}}{a_{SD}} + \frac{M b_{SR} c_{SR}}{a_{SR}(b_{SR}+1)}\right)$. Considering now that the parameter $c_m = 0$, the PDF in Eq. (1) can be approximated by only using the first term of the Taylor expansion given by $f_{I_m}(i) = a_m i^{b_m - 1}$ [21]. It is straightforward to show that the average BER behaves asymptotically as $(G_c \gamma \xi)^{-G_d}$ due to ${}_2F_2(a_1, a_2; b_1, b_2; 0) = 1$, where G_d and G_c denote diversity order and coding gain, respectively. Therefore, the BER expression of this FSO relaying scheme, P_T, can be simplified taking into account this asymptotic behavior obtained as follows

$$P_T \doteq \begin{cases} P_b^{SR} + P_b^{SD}, & b_{SD} + M b_{SR} < N b_{RD} \\ P_b^{SR_1} \cdot P_b^{RD}, & b_{SD} + M b_{SR} > N b_{RD} \end{cases} \tag{8}$$

being $b_{SD} + M b_{SR}$ and $N b_{RD}$ the diversity order gain corresponding to $P_b^{SR} + P_b^{SD}$ and P_b^{RD}, respectively. Taking into account the expression in Eq. (8), the diversity order gain G_d relative to the direct path link can be written as $G_d = \min(N b_{RD}, b_{SD} + M b_{SR}) / b_{SD}$, where $b_m = \min(\beta_m, \varphi_m^2)$.

IV. Numerical Results and Conclusions

The diversity order gain is depicted in Fig. 2 as a function of the horizontal displacement of the relay node, x_R, for a source-destination link distance of $d_{SD} = 3$ km when different relay locations of $y_R = \{0.5, 1\}$ km are assumed, together with a value of $\lambda = 1550$ nm. Different weather conditions are adopted: haze visibility of 4 km with $C_n^2 = 1.7 \times 10^{-14}$ $m^{-2/3}$ and clear visibility of 16 km with $C_n^2 = 8 \times 10^{-14}$ $m^{-2/3}$, corresponding to moderate and strong turbulence, respectively. The results corresponding to this error-rate performance analysis with rectangular pulse shapes and $\xi = 1$ are illustrated in Fig. 3 when values of normalized beam width and jitter

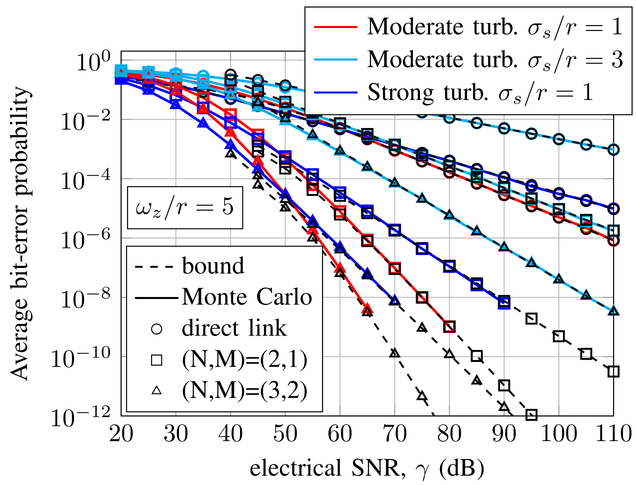

Fig. 3. BER performance for a S-D link distance of $d_{SD} = 3$ km when different relay locations of $(x_R, y_R) = (1, 1)$ km and $(x_R, y_R) = (1, 0.5)$ km are assumed for strong and moderate turbulence, respectively.

of $(\omega_z/r, \sigma_s/r) = \{(5,1),(5,3)\}$ are considered. It can be corroborated that these BER results are in excellent agreement with previous results shown in Fig. 2 in relation to the diversity order gain achieved when different values of M and N are assumed, once the condition $\varphi^2 > \beta$ is satisfied for each link and, hence, the diversity order is only dependent on the atmospheric turbulence. To confirm the accuracy and usefulness of the derived bounds, Monte Carlo simulation results, where each of considered FSO links is modeled by using the statistical model given by $Y_m = XI_m + Z_m$ are furthermore included by using solid line generating the corresponding variates from the exact combined PDF. The obtained results have shown a relevant improvement in relation to the diversity order gain under different weather conditions. Diversity order gain is mainly determined by Nb_{RD}/b_{SD} when the relation $N < (b_{SD} + Mb_{SR})/b_{RD}$ holds, due to the parameter N is bounded by this relation. Moreover, when values of normalized beam width and jitter of $(\omega_z/r, \sigma_s/r) = (5, 3)$ are considered in all FSO links, the condition $\varphi^2 > \beta$ is not satisfied for any link. In this case, when diversity order is affected by pointing errors and due to the fact that $\varphi^2 < 1$ and, hence, $b_m = \varphi_m^2$, the diversity order gain is determined by $G_d = \min(N\varphi_m^2, (M+1)\varphi_m^2)/\varphi_m^2 = \min(N, M+1)$ regardless of the relay location. It can be concluded that a robust and higher diversity order gain can be achieved when a MISO FSO link by using TLS in S-R link is considered, and thus the diversity order is increased. The maximum diversity order is obtained when the relation $Nb_{RD} = b_{SD} + Mb_{SR}$ holds. It is noteworthy that the diversity order gain depicted in Fig. 2 is independent of the used MIMO scheme due to the fact TLS, RC as well as STBC are able to achieve the diversity order. It should be highlighted that MISO relay-assisted FSO systems can significantly reduce the required number of relays in a cooperative FSO system. Furthermore, it can be also observed that the number of transmit lasers and receivers is surprisingly reduced when a MISO relay-assisted FSO system is implemented. Comparing with the FSO scenario in [10, Fig. 1], wherein N_r relays and, hence, $2N_r + 1$ on both transmit lasers and apertures were considered, a remarkable reduction of $2N_r - 2$ receivers is achieved regardless of M and N. A similar reduction of $N_r - M$ transmit lasers is also obtained when the parameter N is set to N_r.

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