All-Active and Selective FSO Relaying: Do We Need Inter-Relay Cooperation?

Chadi Abou-Rjeily, *Senior Member IEEE*

***Abstract*—In this paper, we study the impact of inter-relay cooperation on the outage performance of relay-assisted Free-Space Optical (FSO) systems with two relays. Despite the fact that in realistic networks a FSO link might be available between the deployed relays, the additional advantages of exploiting such link were never investigated before. We explore this new dimension under the two strategies where either all relays are active or a single relay is selected. We evaluate the achievable diversity orders over gamma-gamma channels and we derive conditions under which inter-relay cooperation is advantageous. We study two variants of inter-relay cooperation; namely, one-way and two-way cooperation. We prove that based on the network structure, one of these variants, both or neither may be beneficial.**

***Index Terms*—Free-space optics, FSO, cooperation, relaying, relay selection, outage, diversity order, gamma-gamma.**

I. Introduction

Several recent contributions have shed more light on the different features of cooperative Free-Space Optical (FSO) communications thus imposing this technology as a widely accepted solution for combatting turbulence-induced fading in FSO systems. This surge of interest in relay-assisted FSO communications has led to substantial progress in several directions. The seminal work in [1] revealed the utility of cooperation in FSO networks through an outage probability analysis in the context of serial and parallel relaying. All relays participated in the cooperation effort by simultaneously forwarding decoded or amplified versions of the received information symbols to the destination node. This approach is referred to as all-active relaying and is characterized by its remarked simplicity since it can be implemented without the need of acquiring any form of channel state information (CSI).

All-active relaying has then been adopted in the majority of subsequent research where [2] evaluated the Bit-Error-Rate (BER) performance of Amplify-and-Forward (AF) cooperation with one relay. [3] proposed a novel Decode-and-Forward (DF) strategy with one relay based on a proper exchange of information and redundant bits. This scheme was further investigated in [4] where the achievable diversity orders over gamma-gamma channels were evaluated. All-active relaying with one relay was further considered in [5]–[8]. In [5] the BER performance with noncoherent detection was studied, in [6] differential modulation was investigated, in [7] the outage probability and diversity-multiplexing tradeoff were evaluated and in [8] the BER performance in the presence of shot noise was derived. Furthermore, power allocation for serial-relaying was established in [9], [10], a scheme based on combining serial and parallel relaying was explored in [11] while [12] derived the optimal relay positions for minimizing the outage probability in both serial and parallel relaying.

An alternative to all-active relaying is selective-relaying where only one relay is selected from all available relays based on the state of the FSO network [13], [14]. Only the selected relay is involved in retransmitting to the destination while the remaining relays remain idle. Selective-relaying is superior to all-active relaying at the expense of an increased complexity since the CSI needs to be acquired.

Despite the rich and diverse literature on relay-assisted FSO communications, none of the existing contributions examined the gain that might arise from the presence of a FSO link connecting the relays in the context of parallel relaying. In other words, the parallel-relaying solutions in [1]–[8], [11]–[14] assumed the presence of source-relay and relay-destination links, and eventually a source-destination link, but the effect of the potential existence of a relay-relay link was never studied before. In the presence of such links, a signal is first transmitted from the source to the relays. However, unlike the existing parallel-relaying solutions, the relays cooperate with each other prior to forwarding the decoded signals to the destination. In this work, we explore the additional degree of freedom that arises from inter-relay cooperation and try to reveal whether the presence of an additional inter-relay link is useful or not. Our investigation is based on an outage probability analysis in the context of DF cooperation with two relays. We consider both all-active and selective relaying and we try to answer the question under consideration by evaluating the diversity orders that can be achieved under gamma-gamma turbulence-induced fading. We study one-way and two-way inter-relay cooperation schemes and we draw conclusions on whether or not to deploy such solutions depending on the positions of the relays.

II. System Model

Fig. 1 illustrates a cooperative FSO network where the communication between a source node S and a destination node D is assisted by two relays R_1 and R_2. Nodes S, D, R_1 and R_2 correspond to buildings on which several transceivers are installed each of which ensures a directive FSO link with a neighboring building. This work revolves around the implications of the availability of a FSO link between R_1 and R_2 on the outage performance. Note that the link R_1-R_2 (as well as the links S-R_1, S-R_2, R_1-D and R_2-D) is not

The author is with the Department of Electrical and Computer Engineering of the Lebanese American University (LAU), Byblos, Lebanon. (e-mail: chadi.abourjeily@lau.edu.lb).

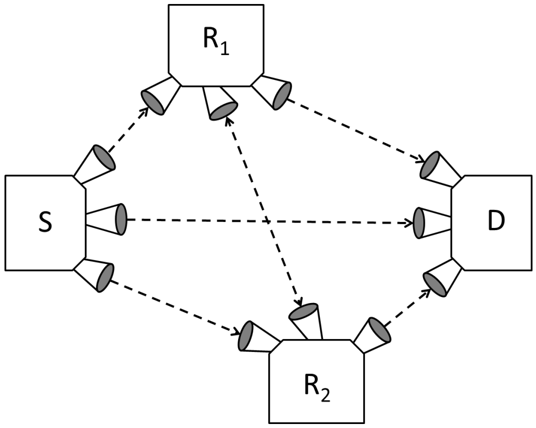

Fig. 1. FSO relay-assisted transmission with two inter-connected relays.

deployed for the sake of assisting S in its communication with D but for the exchange of information between buildings R_1 and R_2. In this context, cooperative communications take advantage of the presence of these links for boosting the system performance. In other words, the analyzed inter-relay cooperation schemes make use of the link R_1-R_2 when present and, hence, without requiring an additional infrastructure. In what follows, we denote by R_1 the relay that is closer to the source. By abuse of notation, S and D will be referred to as R_0 (node 0) and R_3 (node 3), respectively.

The FSO system under consideration employs Binary Pulse Position Modulation (BPPM) with Intensity-Modulation and Direct-Detection (IM/DD). Consider the FSO link between nodes i and j, the received electrical signal at the j-th node resulting from the optical signal transmitted by the i-th node can be written as [1]:

$$\mathbf{r}_{i,j} = \begin{bmatrix} \mathbf{r}_{i,j}^s \\ \mathbf{r}_{i,j}^n \end{bmatrix} = \begin{bmatrix} RT_b(G_{i,j}I_{i,j}P_t/N + P_b) + n_j^s \\ RT_bP_b + n_j^n \end{bmatrix} \quad (1)$$

where $\mathbf{r}_{i,j}^s$ and $\mathbf{r}_{i,j}^n$ are the received electrical signals that correspond to the signal and non-signal slots of the BPPM symbol, respectively. R is the photodetector's responsivity and T_b stands for the bit duration. P_b stands for the power of background radiation while P_t stands for the total transmitted optical signal power that is evenly split among N active links. In (1), n_j^s and n_j^n stand for the additive noise terms at the j-th receiver in the signal and non-signal slots, respectively. As in [1]–[7], [11]–[13], we assume background noise limited receivers implying that each of the above noise terms can be modeled as a signal-independent white Gaussian noise with zero mean and variance $N_0/2$.

In (1), $I_{i,j}$ represents the irradiance fluctuations along the link R_i-R_j caused by atmospheric turbulence. In this work, we adopt the widely accepted gamma-gamma turbulence-induced fading channel model [4]–[7], [13] where the probability density function (pdf) of the irradiance ($I > 0$) is given by:

$$f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \quad (2)$$

where $\Gamma(.)$ is the Gamma function and $K_c(.)$ is the modified Bessel function of the second kind of order c. The parameters α and β are given by:

$$\alpha(d) = \left[\exp\left(0.49\sigma_R^2(d)/(1+1.11\sigma_R^{12/5}(d))^{7/6}\right) - 1\right]^{-1} \quad (3)$$

$$\beta(d) = \left[\exp\left(0.51\sigma_R^2(d)/(1+0.69\sigma_R^{12/5}(d))^{5/6}\right) - 1\right]^{-1} \quad (4)$$

where $\sigma_R^2(d)$ is the Rytov variance related to the link distance d by:

$$\sigma_R^2(d) = 1.23 C_n^2 k^{7/6} d^{11/6} \quad (5)$$

where k is the wave number and C_n^2 denotes the refractive index structure parameter. From(3)-(4), the parameters of the link between nodes i and j can be written as:

$$\alpha_{i,j} \triangleq \alpha(d_{i,j}) \quad ; \quad \beta_{i,j} \triangleq \beta(d_{i,j}) \quad (6)$$

where $d_{i,j}$ stands for the length of the link R_i-R_j.

Finally, $G_{i,j}$ in (1) is a gain factor associated with the link R_i-R_j that might be shorter than the direct link S-D. In this context, $G_{0,3} = 1$ and from [1]:

$$G_{i,j} = \left(\frac{d_{0,3}}{d_{i,j}}\right)^2 e^{-\sigma(d_{i,j}-d_{0,3})} \quad (7)$$

where σ is the attenuation coefficient. Note that $G_{i,j} = G_{j,i}$ from (7) and $I_{i,j} = I_{j,i}$ following from the reciprocity of the optical channel.

III. Cooperation Strategies

A. Absence of CSI

In the absence of CSI, we compare the existing all-active parallel-relaying scheme, referred to as No Inter-Relay-Connection (NIRC) for convenience, with two schemes that arise in the case where the inter-relay connection is exploited (IRC schemes). NIRC is a two-phase scheme where in the first phase the information symbol is transmitted from S to D and to the relays. In the second phase, all relays decode the received BPPM symbol and retransmit this symbol simultaneously to D. In this case, retransmissions from a particular relay occur only if the received signal-to-noise ratio (SNR) at this relay exceeds a given decoding threshold [1].

In the case of interconnected relays, one-way (IRC1) and two-way (IRC2) cooperation are possible. In IRC1, since R_1 is closer to S, this relay contributes in enhancing the fidelity of signal reconstruction at R_2 that is farther from S. In this sense, IRC1 is a three-phase cooperation protocol. (i): An information symbol is transmitted from S to D and to the relays. (ii): R_1 forwards the decoded symbol to R_2 in the case where the SNR at R_1 exceeds the threshold. (iii): R_1 and R_2 forward the decoded symbols to D if the corresponding SNRs at these relays exceed threshold. In this case, the decision at R_1 is based on the signal it received along the link S-R_1 while the decision at R_2 is based on the two signals that this relay has acquired independently along the S-R_2 and R_1-R_2 links.

In IRC2, inter-relay cooperation is triggered in both directions resulting in the following three-phase protocol. (i): An information symbol is transmitted from S to D and to the relays. (ii): R_1 decodes the signal it received from S and forwards the decoded symbol to R_2 and, in a simultaneous manner, R_2 decodes the signal it received from S and forwards the decoded symbol to R_1. (iii): R_1 and R_2 forward the decoded symbols to D where R_1 (resp. R_2) has acquired two estimates of the information symbol; one from R_2 (resp. R_1) and the other from S. Note that, as before, transmissions along R_1-R_2 and R_1-D are initiated only if the SNR at R_1 (via S-R_1) exceeds threshold. The same holds for the transmissions along R_2-R_1 and R_2-D.

Note that for the parallel-relaying scheme in [1], the relays are deployed with the sole objective of assisting S in its communication with D. In this case, D is equipped with a single receiver (with a wide field of view) at which the signals transmitted from S, R_1 and R_2 add up. In the system model depicted in Fig. 1, the relays are independent entities that can communication their own data with S or D (or with each other). Three separate non-interfering signals are now available at D that merely needs to switch to the transceiver that was able to decode. This constitutes a simple reception approach that is adapted to the infrastructure of the existing FSO networks without inducing a substantial complexity on the installed transceivers. Similar switching approaches are deployed at the relays as well.

For NIRC, $N = 5$ in (1) since the links S-D, S-R_1, S-R_2, R_1-D and R_2-D are activated. For IRC1, $N = 6$ accounting for the additional R_1-R_2 link while $N = 7$ for IRC2 because of the additional R_2-R_1 link.

B. Presence of CSI

In the presence of CSI, selective-relaying protocols correspond to transmitting all information symbols along the unique strongest path between S and D [13], [14]. In the absence of an inter-relay connection, one of the three paths S-D, S-R_1-D and S-R_2-D is selected based on the specific channel realization. In the presence of an inter-relay connection, the additional paths S-R_1-R_2-D and S-R_2-R_1-D can be further exploited. As in the absence of CSI, the above variants of the selective-relaying protocol will be referred to as NIRC, IRC1 and IRC2, respectively. Moreover, each node along the selected path decodes the signal received from the previous node and forwards the decoded symbol to the subsequent node only when the SNR at this cooperating node exceeds the decoding threshold.

For simplicity, and since an optimized power allocation strategy falls beyond the scope of this work, the transmit power P_t will be evenly split among the active links. In this case, N in (1) stands for the number of hops along the selected path. In other words, $N = 1$ if direct transmissions along S-D are preferred, $N = 2$ for the two-hop paths S-R_1-D and S-R_2-D while $N = 3$ if one of the paths S-R_1-R_2-D and S-R_2-R_1-D is selected in the case of interconnected relays.

IV. Outage Analysis in the Absence of CSI

A. Outage Probability

From (1), after removing the constant bias RT_bP_b from both BPPM slots, the SNR of the link R_i-R_j (in the case where transmissions occur from R_i) can be written as [1]:

$$\gamma_{i,j} = \frac{R^2 T_b^2 G_{i,j}^2 I_{i,j}^2 P_t^2}{N^2 N_0} \tag{8}$$

The link R_i-R_j is in outage when the signal transmitted from R_i can not ensure a SNR at R_j exceeding a certain threshold value. The outage probability of this link can be written as:

$$p_{i,j}^{(N)} \triangleq \Pr\left(\gamma_{i,j} < \gamma_{th}\right) = \Pr\left(I_{i,j} < \frac{N}{G_{i,j} P_M}\right) \tag{9}$$

where $P_M \triangleq \frac{RT_bP_t}{\sqrt{N_0 \gamma_{th}}}$ denotes the power margin and γ_{th} is the SNR threshold above which no outage occurs and the signal can be decoded with an arbitrarily low error probability. Using the cumulative distribution function (cdf) of the gamma-gamma distribution, (9) can be written as [13]:

$$p_{i,j}^{(N)} = \frac{1}{\Gamma(\alpha_{i,j})\Gamma(\beta_{i,j})} \times G_{1,3}^{2,1}\left[\frac{\alpha_{i,j}\beta_{i,j}N}{G_{i,j}P_M}\middle|\, {}^{1}_{\alpha_{i,j},\beta_{i,j},0}\right] \tag{10}$$

where $G_{p,q}^{m,n}[.]$ is the Meijer G-function.

A serial two-hop path R_i-R_j-R_k is not in outage only when the two links R_i-R_j and R_j-R_k are not in outage resulting in:

$$p_{i,j,k}^{(N)} = 1 - (1 - p_{i,j}^{(N)})(1 - p_{j,k}^{(N)}) = p_{i,j}^{(N)} + p_{j,k}^{(N)} - p_{i,j}^{(N)} p_{j,k}^{(N)} \tag{11}$$

1) NIRC: The performance of all-active relaying with non-interconnected relays is provided as a benchmark. A NIRC system is in outage only when the parallel and independent paths S-D, S-R_1-D and S-R_2-D all suffer from outage. Consequently [1]:

$$P_{out,no-CSI}^{(NIRC)} = p_{0,3}^{(5)} p_{0,1,3}^{(5)} p_{0,2,3}^{(5)} \tag{12}$$

which at large SNR scales asymptotically as:

$$P_{out,no-CSI}^{(NIRC)} \approx p_{0,3}^{(5)}(p_{0,1}^{(5)} + p_{1,3}^{(5)})(p_{0,2}^{(5)} + p_{2,3}^{(5)}) \tag{13}$$

2) IRC1: When the link R_1-R_2 is activated in one direction for enhancing the quality of signal reception at R_2, the outage probability can be written as:

$$\begin{aligned} P_{out,no-CSI}^{(IRC1)} = p_{0,3}^{(6)} \Big[& p_{0,1}^{(6)} p_{0,2}^{(6)} q_1 + p_{0,1}^{(6)}(1 - p_{0,2}^{(6)}) q_2 \\ & + (1 - p_{0,1}^{(6)}) p_{0,2}^{(6)} q_3 + (1 - p_{0,1}^{(6)})(1 - p_{0,2}^{(6)}) q_4 \Big] \end{aligned} \tag{14}$$

where $q_1 = 1$ since when R_0-R_3, R_0-R_1 and R_0-R_2 are in outage, no signal will reach D since, on one hand, the direct link from S is in outage and, on the other hand, R_1 and R_2 are not transmitting any signal since these relays were not able to decode the message transmitted from S in this case. For evaluating q_2, link R_0-R_1 is in outage and R_1 is not forwarding any signal to D while R_0-R_2 is not in outage implying that the decoding at R_2 was successful and that this relay will be forwarding the decoded message to D. The message retransmitted from R_2 will not reach D only when the link R_2-D is in outage implying that $q_2 = p_{2,3}^{(6)}$. For evaluating q_3, only R_1 decoded the message transmitted from S correctly in the first phase. R_1 will forward the message to R_2 in the second phase and R_2 can still acquire the message despite the failure of link S-R_2. In other words, the message retransmitted from R_1 can reach D via the two paths R_1-D and R_1-R_2-D implying that D will be in outage only when these paths fail simultaneously resulting in $q_3 = p_{1,3}^{(6)} p_{1,2,3}^{(6)}$. Finally, for evaluating q_4, both relays are retransmitting the information message and, consequently, no signal will be received at D

TABLE I
DIVERSITY ORDERS IN THE ABSENCE OF CSI

Network Setup	$d_1^{(NIRC)}$	$d_1^{(IRC1)}$	$d_1^{(IRC2)}$	Summary
$d_{0,1} < d_{1,3}$ and $d_{0,2} < d_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$	$d_1^{(IRC2)}=d_1^{(IRC1)}=d_1^{(NIRC)}$
$d_{0,1} > d_{1,3}$ and $d_{0,2} > d_{2,3}$	$\beta_{0,3}+\beta_{0,1}+\beta_{0,2}$	$\beta_{0,3}+\beta_{0,1}+\beta_{0,2}$	$\beta_{0,3}+\beta_{0,1}+\beta_{0,2}$	$d_1^{(IRC2)}=d_1^{(IRC1)}=d_1^{(NIRC)}$
$d_{0,1} < d_{1,3}$ and $d_{0,2} > d_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{0,2}$	$\beta_{0,3}+\min\{\beta_{0,1}+\beta_{0,2},$ $\beta_{1,3}+\beta_{2,3},\beta_{0,2}+\beta_{1,2}+\beta_{1,3}\}$	$\beta_{0,3}+\min\{\beta_{0,1}+\beta_{0,2},$ $\beta_{1,3}+\beta_{2,3},\beta_{0,2}+\beta_{1,2}+\beta_{1,3}\}$	$d_1^{(IRC2)}=d_1^{(IRC1)}>d_1^{(NIRC)}$
$d_{0,1} > d_{1,3}$ and $d_{0,2} < d_{2,3}$	$\beta_{0,3}+\beta_{0,1}+\beta_{2,3}$	$\beta_{0,3}+\beta_{0,1}+\beta_{2,3}$	$\beta_{0,3}+\min\{\beta_{0,1}+\beta_{0,2},$ $\beta_{1,3}+\beta_{2,3},\beta_{0,1}+\beta_{1,2}+\beta_{2,3}\}$	$d_1^{(IRC2)}>d_1^{(IRC1)}=d_1^{(NIRC)}$

only when both links R_1-D and R_2-D are in outage implying that $q_4=p_{1,3}^{(6)}p_{2,3}^{(6)}$.

Ignoring the terms in (14) that correspond to the product of four or more outage probabilities, the outage probability of IRC1 takes the following asymptotic form:

$$P_{out,no-CSI}^{(IRC1)} \approx p_{0,3}^{(6)}\Big[p_{1,3}^{(6)}p_{2,3}^{(6)}+p_{0,1}^{(6)}p_{2,3}^{(6)}(1-p_{1,3}^{(6)}) +p_{0,1}^{(6)}p_{0,2}^{(6)}(1-p_{2,3}^{(6)})+p_{0,2}^{(6)}p_{1,2}^{(6)}p_{1,3}^{(6)}\Big] \quad (15)$$

3) IRC2: For IRC2, the expression of the outage probability takes the general form in (14) where $q_1=1$, $q_3=p_{1,3}^{(7)}p_{1,2,3}^{(7)}$ and $q_4=p_{1,3}^{(7)}p_{2,3}^{(7)}$ as for IRC1. For evaluating q_2, the message transmitted from R_2 (that is not in outage in this case) can reach D along either R_2-D or R_2-R_1-D in the case of IRC2 (rather than along R_2-D uniquely as in the case of IRC1). Consequently, q_2 needs to be adjusted from $q_2=p_{2,3}^{(6)}$ to $q_2=p_{2,3}^{(7)}p_{2,1,3}^{(7)}$. After straightforward calculations, the asymptotic outage probability is given by:

$$P_{out,no-CSI}^{(IRC2)} \approx p_{0,3}^{(7)}\Big[p_{1,3}^{(7)}p_{2,3}^{(7)}+p_{0,1}^{(7)}p_{0,2}^{(7)} +p_{0,1}^{(7)}p_{1,2}^{(7)}p_{2,3}^{(7)}+p_{0,2}^{(7)}p_{1,2}^{(7)}p_{1,3}^{(7)}\Big] \quad (16)$$

where $p_{2,1}^{(7)}$ was replaced by $p_{1,2}^{(7)}$ since both outage probabilities are the same following from (10) and from the reciprocity of the FSO link between the two relays.

B. Diversity Order

The expression in (10) does not lend itself to an analytical evaluation implying that the outage probabilities in (13), (15) and (16) do not offer clear and intuitive insights that allow us to compare the considered cooperation schemes under different network setups. Consequently, we further proceed with an asymptotic analysis that will be culminated by closed-form expressions for the diversity orders of the different schemes.

For large values of the SNR, the outage performance is dominated by the behavior of the pdf near the origin where (2) can be approximated by [4]:

$$f(I_{i,j}) \approx a_{i,j} I_{i,j}^{\beta_{i,j}-1} \quad (17)$$

where $\alpha_{i,j}$ and $\beta_{i,j}$ are defined in (6) and:

$$a_{i,j}=\frac{(\alpha_{i,j}\beta_{i,j})^{\beta_{i,j}}\Gamma(\alpha_{i,j}-\beta_{i,j})}{\Gamma(\alpha_{i,j})\Gamma(\beta_{i,j})} \quad (18)$$

Based on (17), equations (9)-(10) can be approximated by:

$$p_{i,j}^{(N)} \approx \frac{a_{i,j}}{\beta_{i,j}}\left(\frac{G_{i,j}P_M}{N}\right)^{-\beta_{i,j}} \quad (19)$$

Based on the approximation in (19) that scales asymptotically as $P_M^{-\beta_{i,j}}$, (13), (15) and (16) show that the diversity orders of the considered schemes are given by:

$$d_1^{(NIRC)}=\beta_{0,3}+\min\{\beta_{0,1},\beta_{1,3}\}+\min\{\beta_{0,2},\beta_{2,3}\} \quad (20)$$

$$d_1^{(IRC1)}=\beta_{0,3}+\min\{\beta_{0,1}+\beta_{0,2},\beta_{1,3}+\beta_{2,3}, \beta_{0,1}+\beta_{2,3},\beta_{0,2}+\beta_{1,2}+\beta_{1,3}\} \quad (21)$$

$$d_1^{(IRC2)}=\beta_{0,3}+\min\{\beta_{0,1}+\beta_{0,2},\beta_{1,3}+\beta_{2,3}, \beta_{0,1}+\beta_{1,2}+\beta_{2,3},\beta_{0,2}+\beta_{1,2}+\beta_{1,3}\} \quad (22)$$

Note that since the parameters $\beta_{i,j}$ can take arbitrary values depending on the relay positions, further simplifications of the expressions in (20)-(22) are not possible in the general case. In order to shed more light on the impact of inter-relay cooperation, we next analyze the four typical scenarios that might arise depending on the relay positions. Note that from (4), the parameter $\beta_{i,j}$ is positive and decreases with the link distance resulting in $\beta_{0,1}>\beta_{0,2}$ in all considered scenarios since R_1 is defined as the relay closer to S.

(i): Both relays are in the vicinity of S. In this case, the relays are closer to S than they are to D resulting in $\beta_{0,1}>\beta_{1,3}$ ($d_{0,1}<d_{1,3}$) and $\beta_{0,2}>\beta_{2,3}$ ($d_{0,2}<d_{2,3}$). In this case, (20) simplifies to $d_1^{(NIRC)}=\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$. The above two inequalities imply that $\beta_{0,1}+\beta_{0,2}>\beta_{1,3}+\beta_{2,3}$ and $\beta_{0,1}+\beta_{2,3}>\beta_{1,3}+\beta_{2,3}$. Consequently, (21) simplifies to $d_1^{(IRC1)}=\beta_{0,3}+\min\{\beta_{1,3}+\beta_{2,3},\beta_{0,2}+\beta_{1,2}+\beta_{1,3}\}=\beta_{0,3}+\beta_{1,3}+\min\{\beta_{2,3},\beta_{0,2}+\beta_{1,2}\}$ which simplifies to $d_1^{(IRC1)}=\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$ since $\beta_{0,2}>\beta_{2,3}$ resulting in $\beta_{0,2}+\beta_{1,2}>\beta_{2,3}$. From (22), the inequalities $\beta_{0,1}>\beta_{1,3}$ and $\beta_{0,2}>\beta_{2,3}$ imply that $\beta_{0,1}+\beta_{0,2}>\beta_{1,3}+\beta_{2,3}$ and $\beta_{0,2}+\beta_{1,2}+\beta_{1,3}>\beta_{1,3}+\beta_{2,3}$ resulting in $d_1^{(IRC2)}=\beta_{0,3}+\min\{\beta_{1,3}+\beta_{2,3},\beta_{0,1}+\beta_{1,2}+\beta_{2,3}\}=\beta_{0,3}+\beta_{2,3}+\min\{\beta_{1,3},\beta_{0,1}+\beta_{1,2}\}$ which finally results in $d_1^{(IRC2)}=\beta_{0,3}+\beta_{2,3}+\beta_{1,3}$ since $\beta_{0,1}>\beta_{1,3}$ implies that $\beta_{0,1}+\beta_{1,2}>\beta_{1,3}$.

Similar calculations can be carried out in the remaining three scenarios, (ii): $d_{0,1}>d_{1,3}$ and $d_{0,2}>d_{2,3}$, (iii): $d_{0,1}<d_{1,3}$ and $d_{0,2}>d_{2,3}$ and (iv): $d_{0,1}>d_{1,3}$ and $d_{0,2}<d_{2,3}$. The diversity orders achieved by the different schemes are summarized in Table-I. This table shows that inter-relay cooperation in the absence of CSI is not beneficial under the first and second scenarios. For the third scenario, from Table-I, $\beta_{0,1}>\beta_{1,3}$ and $\beta_{0,2}<\beta_{2,3}$ resulting in $\beta_{0,1}+\beta_{0,2}>\beta_{1,3}+\beta_{0,2}$ and $\beta_{1,3}+\beta_{2,3}>\beta_{1,3}+\beta_{0,2}$. Naturally, $\beta_{1,3}+\beta_{0,2}+\beta_{1,2}>\beta_{1,3}+\beta_{0,2}$. The last three inequalities show that $d_1^{(IRC2)}$ (which is equal to $d_1^{(IRC1)}$) exceeds $d_1^{(NIRC)}$. Under this operating scenario, inter-relay cooperation enhances the achievable diversity order while two-way cooperation does not present any additional advantage compared to one-way cooperation. In a similar way, it can be proven that $d_1^{(IRC2)} > d_1^{(IRC1)} = d_1^{(NIRC)}$ under the fourth scenario implying that two-way inter-relay cooperation is the superior solution in this case.

Assume that relay R_i is in the median plane of S-D implying that $\beta_{0,i} = \beta_{i,3} \triangleq \beta_i$. In this case, direct manipulations of (20)-(22) show that the three cooperation schemes achieve the same diversity order of $\beta_{0,3}+\beta_i+\min\{\beta_{0,\bar{i}},\beta_{\bar{i},3}\}$ where $\bar{i}=2$ for $i=1$ and $\bar{i}=1$ for $i=2$. Consequently, inter-relay cooperation is not useful if at least one relay is at the same distance from S and D.

As a conclusion of the diversity analysis, since the implementation of NIRC is simpler than that of IRC1 which in turn is simpler than that of IRC2, the existing all-active parallel-relaying solution is the most appropriate if both relays are in the vicinity of S or D while one-way (resp. two-way) inter-relay cooperation is the most appropriate when R_1 is in the vicinity of S (resp. D) and R_2 is in the vicinity of D (resp. S).

V. Outage Analysis in the Presence of CSI

Denote by $\mathcal{P}_1$ =S-D, $\mathcal{P}_2$ =S-R_1-D, $\mathcal{P}_3$ =S-R_2-D, $\mathcal{P}_4$ =S-R_1-R_2-D and $\mathcal{P}_5$ =S-R_2-R_1-D the five possible paths between S and D. The strength of a particular path is measured by the SNR of its weakest hop (the one having the smallest SNR) as in [13]. Removing the constant term $\frac{R^2T_b^2P_t^2}{N_0}$ that is common to the SNRs of the different links in (8), the metrics associated with the above five paths are as follows:

$$m_1=k_{0,3}\ ;\ m_2=\frac{1}{2}\min\{k_{0,1},k_{1,3}\}\ ;\ m_3=\frac{1}{2}\min\{k_{0,2},k_{2,3}\}$$
$$m_4=\frac{1}{3}\min\{k_{0,1},k_{1,2},k_{2,3}\};m_5=\frac{1}{3}\min\{k_{0,2},k_{1,2},k_{1,3}\} \quad (23)$$

where $k_{i,j} \triangleq G_{i,j}I_{i,j}$ and N in (8) was replaced by the number of hops along each path.

A. Outage Probability

1) NIRC: In this case, the path $\mathcal{P}_i$ is selected such that $i=\arg\max_{j=1,2,3}\{m_j\}$. Since the paths $\mathcal{P}_1$, $\mathcal{P}_2$ and $\mathcal{P}_3$ do not share any common links, the outage probability of NIRC can be written as:

$$P_{out,CSI}^{(NIRC)} = \prod_{j=1}^{3}\Pr(m_j \leq P_M^{-1}) = p_{0,3}^{(1)}p_{0,1,3}^{(2)}p_{0,2,3}^{(2)} \quad (24)$$

where for $\mathcal{P}_1$ (9) was applied with $N=1$ while for $\mathcal{P}_2$ and $\mathcal{P}_3$ (11) was applied with $N=2$. For large SNRs:

$$P_{out,CSI}^{(NIRC)} \approx p_{0,3}^{(1)}(p_{0,1}^{(2)}+p_{1,3}^{(2)})(p_{0,2}^{(2)}+p_{2,3}^{(2)}) \quad (25)$$

which has a form similar to (13) except for the power distribution factor N.

2) IRC1: For IRC1, the path $\mathcal{P}_i$ is selected (out of $\mathcal{P}_1,\dots,\mathcal{P}_4$) according to $i=\arg\max_{j=1\cdots 4}\{m_j\}$. Since $\mathcal{P}_4$ has the links S-R_1 and R_2-D common with $\mathcal{P}_2$ and $\mathcal{P}_3$, respectively, the outage probability of this scheme is given by:

$$P_{out,CSI}^{(IRC1)} = P_{out,CSI}^{(NIRC)}\Pr(m_4 \leq P_M^{-1} \mid m_2 \leq P_M^{-1}, m_3 \leq P_M^{-1}) \triangleq P_{out,CSI}^{(NIRC)}Q_1 \quad (26)$$

and the outage probability of IRC1 is equal to that of NIRC reduced by a factor Q_1. From (23), Q_1 can be written as:

$$Q_1 = 1-\Pr\left(\min\{k_{0,1},k_{1,2},k_{2,3}\} \geq 3P_M^{-1} \mid m_2 \leq P_M^{-1}\ ,\ m_3 \leq P_M^{-1}\right) \quad (27)$$
$$= 1-\Pr(k_{1,2} \geq 3P_M^{-1})\Pr(k_{0,1} \geq 3P_M^{-1} \mid m_2 \leq P_M^{-1}) \Pr(k_{2,3} \geq 3P_M^{-1} \mid m_3 \leq P_M^{-1}) \quad (28)$$
$$\triangleq 1-Q_{1,1}Q_{1,2}Q_{1,3} \quad (29)$$

where (28) follows since $k_{1,2}$ is independent of $k_{0,1}$, $k_{1,3}$, $k_{0,2}$ and $k_{2,3}$ and thus of m_2 and m_3. In the same way, $k_{0,1}$ is independent of m_3 and $k_{2,3}$ is independent of m_2.

Now, $Q_{1,1}=1-p_{1,2}^{(3)}$ and:

$$Q_{1,2} = \frac{\Pr(k_{0,1} \geq 3P_M^{-1}, \min\{k_{0,1},k_{1,3}\} \leq 2P_M^{-1})}{\Pr(m_2 \leq P_M^{-1})} \quad (30)$$

now, the inequalities $k_{0,1} \geq 3P_M^{-1}$ and $\min\{k_{0,1},k_{1,3}\} \leq 2P_M^{-1}$ implies that $k_{0,1} \geq k_{1,3}$ (since $P_M > 0$) resulting in:

$$Q_{1,2} = \frac{(1-p_{0,1}^{(3)})p_{1,3}^{(2)}}{p_{0,1,3}^{(2)}} \quad (31)$$

Similarly, $Q_{1,3} = \frac{(1-p_{2,3}^{(3)})p_{0,2}^{(2)}}{p_{0,2,3}^{(2)}}$. After straightforward calculations, (29) can be written under the following form that is more amenable to a diversity analysis:

$$Q_1 = 1-(1-q_1)(1-q_2)(1-q_3) \quad (32)$$
$$= 1-\left(1-p_{1,2}^{(3)}\right)\left(1-\frac{p_{0,1}^{(2)}+(p_{0,1}^{(3)}-p_{0,1}^{(2)})p_{1,3}^{(2)}}{p_{0,1,3}^{(2)}}\right)\left(1-\frac{p_{2,3}^{(2)}+(p_{2,3}^{(3)}-p_{2,3}^{(2)})p_{0,2}^{(2)}}{p_{0,2,3}^{(2)}}\right) \quad (33)$$

3) IRC2: In this case, the path $\mathcal{P}_i$ is selected according to $i=\arg\max_{j=1\cdots 5}\{m_j\}$ showing that the additional path $\mathcal{P}_5$ can be selected. The path $\mathcal{P}_5$ has the links R_1-D, S-R_2 and R_1-R_2 common with $\mathcal{P}_2$, $\mathcal{P}_3$ and $\mathcal{P}_4$, respectively. The outage probability of IRC2 is given by:

$$P_{out,CSI}^{(IRC2)} = P_{out,CSI}^{(IRC1)}\Pr(m_5 \leq P_M^{-1} \mid m_2 \leq P_M^{-1}, m_3 \leq P_M^{-1}, m_4 \leq P_M^{-1}) \triangleq P_{out,CSI}^{(IRC1)}Q_2 \quad (34)$$

where from (23), Q_2 is given by:

$$Q_2 = 1-\Pr\left(\min\{k_{0,2},k_{1,2},k_{1,3}\} \geq 3P_M^{-1} \mid m_2 \leq P_M^{-1}\ ,\ m_3 \leq P_M^{-1}\ ,\ m_4 \leq P_M^{-1}\right) \quad (35)$$
$$= 1-\Pr(k_{1,3} \geq 3P_M^{-1} \mid m_2 \leq P_M^{-1})\Pr(k_{0,2} \geq 3P_M^{-1} \mid m_3 \leq P_M^{-1})\Pr(k_{1,2} \geq 3P_M^{-1} \mid m_4 \leq P_M^{-1}) \quad (36)$$
$$\triangleq 1-Q_{2,1}Q_{2,2}Q_{2,3} \quad (37)$$

In a way similar to (31), $Q_{2,1} = \frac{(1-p_{1,3}^{(3)})p_{0,1}^{(2)}}{p_{0,1,3}^{(2)}}$ and $Q_{2,2} =$

TABLE II
DIVERSITY ORDERS IN THE PRESENCE OF CSI

Network Setup	$d_2^{(NIRC)}$	$d_2^{(IRC1)}$	$d_2^{(IRC2)}$	Summary
$d_{0,1} < d_{1,3}$ and $d_{0,2} < d_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{2,3}$	$d_2^{(IRC2)}=d_2^{(IRC1)}=d_2^{(NIRC)}$
$d_{0,1} > d_{1,3}$ and $d_{0,2} > d_{2,3}$	$\beta_{0,3}+\beta_{0,1}+\beta_{0,2}$	$\beta_{0,3}+\beta_{0,1}+\beta_{0,2}$	$\beta_{0,3}+\beta_{0,1}+\beta_{0,2}$	$d_2^{(IRC2)}=d_2^{(IRC1)}=d_2^{(NIRC)}$
$d_{0,1} < d_{1,3}$ and $d_{0,2} > d_{2,3}$	$\beta_{0,3}+\beta_{1,3}+\beta_{0,2}$	$\beta_{0,3}+\beta_{1,3}+\beta_{0,2}+$ $\min\{\beta_{0,1}-\beta_{1,3},\beta_{2,3}-\beta_{0,2},\beta_{1,2}\}$	$\beta_{0,3}+\beta_{1,3}+\beta_{0,2}+$ $\min\{\beta_{0,1}-\beta_{1,3},\beta_{2,3}-\beta_{0,2},\beta_{1,2}\}$	$d_2^{(IRC2)}=d_2^{(IRC1)}>d_2^{(NIRC)}$
$d_{0,1} > d_{1,3}$ and $d_{0,2} < d_{2,3}$	$\beta_{0,3}+\beta_{0,1}+\beta_{2,3}$	$\beta_{0,3}+\beta_{0,1}+\beta_{2,3}$	$\beta_{0,3}+\beta_{0,1}+\beta_{2,3}+$ $\min\{\beta_{1,3}-\beta_{0,1},\beta_{0,2}-\beta_{2,3},$ $(\beta_{1,2}-\min\{\beta_{0,1},\beta_{2,3}\})^+\}$	$d_2^{(IRC2)}>d_2^{(IRC1)}=d_2^{(NIRC)}$

$\frac{(1-p_{0,2}^{(3)})p_{2,3}^{(2)}}{p_{0,2,3}^{(2)}}$. The probability $Q_{2,3}$ can be calculated from:

$$\begin{aligned} Q_{2,3} &= \frac{\Pr(k_{1,2}\geq 3P_M^{-1}, \min\{k_{0,1},k_{1,2},k_{2,3}\}\leq 3P_M^{-1})}{\Pr(m_4\leq P_M^{-1})} \\ &= \frac{\Pr(k_{1,2}\geq 3P_M^{-1}, \min\{k_{0,1},k_{2,3}\}\leq 3P_M^{-1})}{\Pr(m_4\leq P_M^{-1})} \\ &= \frac{(1-p_{1,2}^{(3)})\left(1-(1-p_{0,1}^{(3)})(1-p_{2,3}^{(3)})\right)}{1-(1-p_{0,1}^{(3)})(1-p_{1,2}^{(3)})(1-p_{2,3}^{(3)})} \end{aligned} \quad (38)$$

Finally, the outage probability of IRC2 is smaller than that of IRC1 by a factor Q_2 that takes the following form:

$$\begin{aligned} Q_2 = 1 - &\left(1-\frac{p_{1,3}^{(2)}+(p_{1,3}^{(3)}-p_{1,3}^{(2)})p_{0,1}^{(2)}}{p_{0,1,3}^{(2)}}\right) \\ &\left(1-\frac{p_{0,2}^{(2)}+(p_{0,2}^{(3)}-p_{0,2}^{(2)})p_{2,3}^{(2)}}{p_{0,2,3}^{(2)}}\right)\left(1-\frac{p_{1,2}^{(3)}}{p_{0,1,2,3}^{(3)}}\right) \end{aligned} \quad (39)$$

where $p_{0,1,2,3}^{(3)} \triangleq 1-(1-p_{0,1}^{(3)})(1-p_{1,2}^{(3)})(1-p_{2,3}^{(3)})$.

B. Diversity Order

1) NIRC: From (25), the diversity order of NIRC in the presence of CSI is:

$$d_2^{(NIRC)} = \beta_{0,3} + \min\{\beta_{0,1},\beta_{1,3}\} + \min\{\beta_{0,2},\beta_{2,3}\} \quad (40)$$

which is equal to $d_1^{(NIRC)}$ in (20) in the absence of CSI. In other words, the availability of CSI does not enhance the diversity order of the NIRC scheme and it results only in a reduction in the outage probability, from (13) and (25), since $p_{i,j}^{(N)}$ is an increasing function of N. In particular, this reduction is equal to $2^{\beta_{0,3}}(5/2)^{d_2^{(NIRC)}}$ at large SNRs.

2) IRC1: From (32) and (33), q_1 scales asymptotically as $P_M^{-\beta_{1,2}}$. On the other hand, the diversity orders of the numerator and denominator of q_2 are $\beta_{0,1}$ and $\min\{\beta_{0,1},\beta_{1,3}\}$, respectively. Consequently, q_2 has a diversity order of $\beta_{0,1}-\min\{\beta_{0,1},\beta_{1,3}\}$ which can be written as $(\beta_{0,1}-\beta_{1,3})^+$ where $(x)^+ = \max\{0,x\}$. Similarly, q_3 scales asymptotically as $P_M^{-(\beta_{2,3}-\beta_{0,2})^+}$. As a conclusion, in the presence of CSI, IRC1 achieves a diversity order of:

$$d_2^{(IRC1)} = d_2^{(NIRC)} + \min\left\{(\beta_{0,1}-\beta_{1,3})^+, (\beta_{2,3}-\beta_{0,2})^+, \beta_{1,2}\right\} \quad (41)$$

showing a potential improvement over NIRC.

3) IRC2: Similarly to the above analysis, from (34) and (39), the diversity order of IRC2 in the presence of CSI can be written as:

$$\begin{aligned} d_2^{(IRC2)} = d_2^{(IRC1)} + \min\big\{&(\beta_{1,3}-\beta_{0,1})^+, (\beta_{0,2}-\beta_{2,3})^+, \\ &(\beta_{1,2}-\min\{\beta_{0,1},\beta_{2,3}\})^+\big\} \end{aligned} \quad (42)$$

Consider the two number $\beta_{0,1}-\beta_{1,3}$ and $\beta_{2,3}-\beta_{0,2}$. If these numbers have opposite signs, then the additional diversity gains in (41) and (42) will be zero implying that IRC1 and IRC2 will achieve the same diversity order as NIRC and inter-relay cooperation is not useful in this case. On the other hand, if the above numbers are both positive, then the gain in (41) will be positive while that in (42) will be zero implying that IRC1 and IRC2 will achieve the same diversity order that exceeds that of NIRC. Finally, if both numbers are negative, then IRC1 and NIRC achieve the same diversity order and IRC2 can potentially improve over these schemes if $\beta_{1,2} > \min\{\beta_{0,1},\beta_{2,3}\}$. Note that this inequality translates to $d_{1,2} < \max\{d_{0,1},d_{2,3}\}$ which can be easily satisfied if the two relays are not very far from each other. Finally, note that if either relay is in the median plane of S-D then either $\beta_{0,1}-\beta_{1,3}=0$ or $\beta_{2,3}-\beta_{0,2}=0$ resulting in $d_2^{(IRC2)} = d_2^{(IRC1)} = d_2^{(NIRC)}$. In this scenario, inter-relay cooperation is not advantageous similar to the case of no CSI.

Table-II summarizes the diversity orders that can be achieved for different network setups. Table-I and Table-II show that the superiority of one cooperation scheme over another is the same for a given network setup whether in the absence or presence of CSI.

VI. NUMERICAL RESULTS

We next present some numerical results that support the theoretical claims made in the previous sections. The refractive index structure constant and the attenuation constant are set to $C_n^2 = 1\times 10^{-14}$ m$^{-2/3}$ and $\sigma = 0.43$ dB/km. In all scenarios, the distance between S and D is $d_{0,3}=3$ km. The responsivity of the photodetector is $R = 0.625$ A/W (detector's quantum efficiency of 0.5 at an operating wavelength of 1550 nm). The data rate of FSO systems is in the order of several Gbits/s while typical values of P_t range from 10 dBm to 20 dBm. The presented results show the variation of the outage probability as a function of the power margin P_M. Power margins ranging from 0 dB to 50 dB (above threshold) are often included for compensating the losses arising from scintillation, changing weather conditions, building sway, or temperature fluctuations.

Fig. 2 shows the performance under the two scenarios S.1: $(d_{0,1},d_{1,3}) = (0.8, 2.7)$ km and $(d_{0,2},d_{2,3}) = (1.2, 2.5)$ km

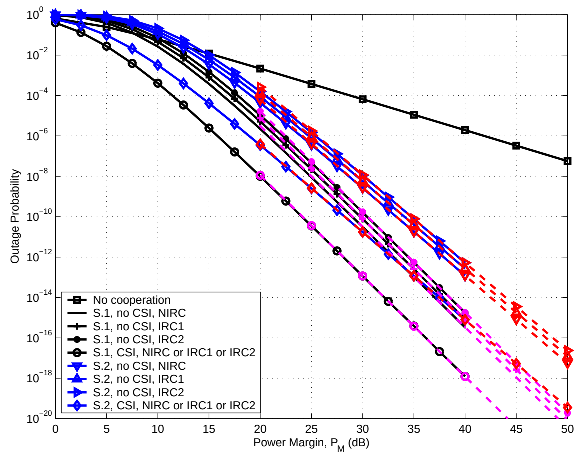

Fig. 2. Performance for setup S.1: $(d_{0,1}, d_{1,3}) = (0.8, 2.7)$ km and $(d_{0,2}, d_{2,3}) = (1.2, 2.5)$ km and for setup S.2: $(d_{0,1}, d_{1,3}) = (3, 2)$ km and $(d_{0,2}, d_{2,3}) = (4, 1)$ km. Solid and dashed lines correspond to the exact outage probabilities and asymptotic bounds, respectively.

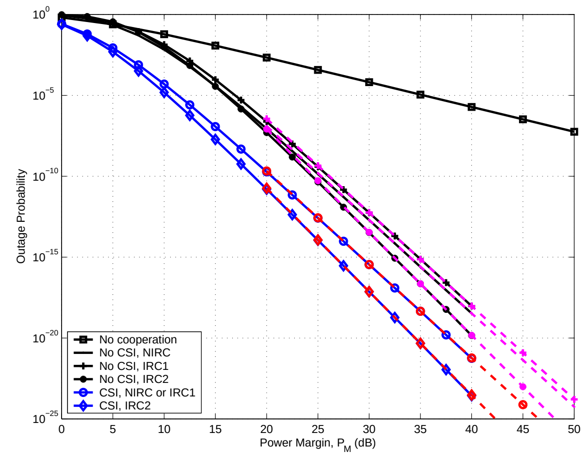

Fig. 4. Performance for $(d_{0,1}, d_{1,3}) = (1.8, 1.2)$ km and $(d_{0,2}, d_{2,3}) = (2, 2.7)$ km. Solid and dashed lines correspond to the exact outage probabilities and asymptotic bounds, respectively.

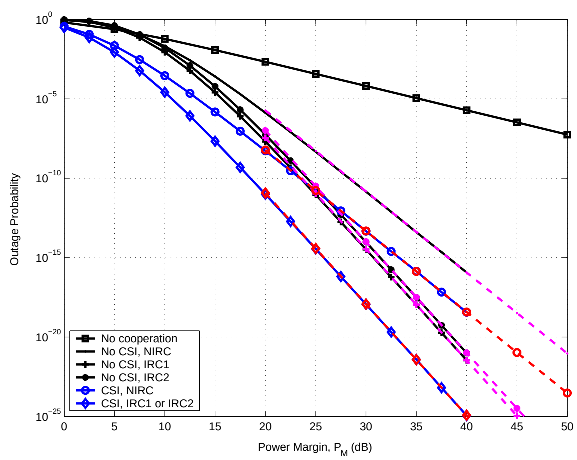

Fig. 3. Performance for $(d_{0,1}, d_{1,3}) = (1, 2.5)$ km and $(d_{0,2}, d_{2,3}) = (2.5, 1)$ km. Solid and dashed lines correspond to the exact outage probabilities and asymptotic bounds, respectively.

and S.2: $(d_{0,1}, d_{1,3}) = (3, 2)$ km and $(d_{0,2}, d_{2,3}) = (4, 1)$ km. In coherence with the first two rows in Table-I and Table-II, the three investigated cooperation schemes achieve the same diversity order of 4.98 and 4.35 for S.1 and S.2, respectively, whether in the absence or presence of CSI. In the absence of CSI, NIRC outperforms IRC1 that in turn outperforms IRC2. This follows since the power normalization factor N increases from 5 to 6 and 7 in (13), (15) and (16), respectively. In other words, for IRC1 and IRC2, the transmit power is split among an increased number of links without affecting the diversity order which ultimately degrades the performance. On the other hand, in the presence of CSI, the three schemes manifest exactly the same outage performance. As a conclusion, inter-relay cooperation is not useful under the above two scenarios. Results in Fig. 2 show the extremely close match (for large values of P_M) between the exact outage probabilities and the upper-bounds in (13), (15) and (16) where the outage probabilities of the different links were approximated by (19). Results also show that (20)-(22) and (40)-(42) accurately predict the achievable diversity orders in the absence and presence of CSI, respectively.

Fig. 3 shows the performance for $d_{0,1} = d_{2,3} = 1$ km and $d_{1,3} = d_{0,2} = 2.5$ km. As predicted from the third row in Table-I and Table-II, IRC1 and IRC2 achieve the same diversity order that is superior to NIRC. In particular, inter-relay cooperation increases the diversity order from 5.1 to 7 whether in the absence or presence of CSI. Under this operating scenario, IRC1 is the best solution realizing performance gains of about 4.8 dB (in the absence of CSI) and 5 dB (in the presence of CSI) at $P_{out} = 10^{-10}$ with respect to the existing literature where the relays do not cooperate with each other. This follows since IRC1 is simpler than IRC2 yet it achieves a better performance in the absence of CSI and the same performance in the presence of CSI.

Fig. 4 shows the performance for $(d_{0,1}, d_{1,3}) = (1.8, 1.2)$ km and $(d_{0,2}, d_{2,3}) = (2, 2.7)$ km. In this case, NIRC slightly outperforms IRC1 in the absence of CSI while achieving exactly the same performance in the presence of CSI. As shown in the last row in Table-I and Table-II, IRC2 enhances the diversity order compared to NIRC and IRC1; in particular, the diversity order is increased from 5.77 to 6.37. Under this operating scenario, IRC2 is the best solution although the performance gains are not very large.

VII. Conclusion

A comprehensive study on the utility of inter-relay cooperation in FSO networks was presented. Contrary to the intuition, abandoning transmissions over a probably existing link between the relays is not only desirable from a system's complexity point of view but may also not incur any performance losses since exploiting this link is not always beneficial. In some scenarios, one-way inter-relay cooperation is sufficient while in other scenarios the more sophisticated two-way cooperation needs to be implemented. Similarly to the existing literature that highlights the superiority of selective relaying compared to all-active relaying with non-interconnected relays, our work reported similar findings in the presence of inter-relay connections under all network setups as well. Selective relaying avoids spreading the power over an increased number of links and can profit from the large coherence times of FSO systems for acquiring accurate CSI with limited overhead. Future work targets power allocation strategies to the proposed schemes.

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