Serial Relaying Over Gamma-Gamma MIMO FSO Links: Diversity Order and Aperture Allocation

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***Abstract*—Serial relaying is analyzed in the context where the Free-Space Optical (FSO) communicating nodes are equipped with multiple apertures. We derive asymptotic expressions for the outage probability over the gamma-gamma fading channel and we evaluate the diversity orders that can be achieved by combining the multi-hop and multi-aperture techniques. A recursive algorithm that optimally allocates the apertures to the hops is also proposed. Results highlight the importance of aperture allocation for multi-hop-multi-aperture systems where significant performance improvements can be gained.**

***Index Terms*—FSO, MIMO, serial relaying, multi-hop, gamma-gamma, diversity order, optimization.**

I. Introduction

In order to mitigate the degrading effects of the turbulence-induced fading over Free-Space-Optical (FSO) links, different diversity techniques have been proposed including serial relaying [1]–[6]. By relaying the information over a number of shorter hops, enhanced performance levels were reported. In [1], an outage analysis and optimal power control strategies were presented in the context of Decode-and-Forward (DF) serial relaying. Amplify-and-Forward (AF) serial relaying over gamma-gamma fading channels was studied in [2] while [3] compared the AF and DF techniques. Through a Bit-Error-Rate (BER) analysis, it was proven in [4] that multi-hop FSO DF systems profit from significant reductions in the mean BER as well as in the variance of the BER.

Despite the rich literature on multi-hop FSO systems [1]–[6], these systems were studied only in the context of Single-Input-Single-Output (SISO) hops. In this work, we highlight the utility of combining multi-hop communications with Multiple-Input-Multiple-Output (MIMO) techniques through an outage probability analysis over gamma-gamma fading channels. By appropriately approximating the gamma-gamma sum-distribution near the origin, we derive tractable and closed-form asymptotic expressions for the outage probability which readily provide the diversity orders that can be achieved by multi-hop MIMO systems. Unlike related works on the gamma-gamma channels that often involve the complicated Meijer G-function [2], [3] that fails in offering clear insights on the achievable performance levels, the derived expressions are simple and involve conventional mathematical functions.

The analysis of the multi-hop MIMO systems shows that these systems are very vulnerable to the specific allocation of the apertures among the hops. Under the constraint of a fixed number of total subchannels, we propose an algorithm that optimally assigns the available apertures to the hops in a way that maximizes the achievable diversity order. Relatively similar optimizations were carried out in the context of multi-hop SISO systems where power allocations were proposed in [1] and [6] while optimal relay placements were derived in [5]. The optimization that we perform in this paper differs substantially from the previously considered problems in the sense that integer solutions are sought which further complicates the problem. Unlike [1], [6] that require the knowledge of the channel and [5] that requires placing the relays at positions that might be infeasible following from the topology of the network, the proposed solution is capable of achieving enhanced diversity orders without the knowledge of the channel and for any relay placements.

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II. System Model

Consider a multi-hop DF-FSO system with Intensity-Modulation and Direct-Detection (IM/DD) where N_r relays are placed serially between a source node (S) and a destination node (D). MIMO links are assumed and we denote by P_n and Q_n the numbers of transmit and receive apertures, respectively, along the n-th hop for $n = 1, \dots, N_r + 1$.

We adopt the gamma-gamma fading model where the probability density function (pdf) of the irradiance is given by:

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

where $K_c(.)$ is the modified Bessel function of the second kind of order c and $\Gamma(.)$ is the Gamma function. α and β are given in [3] and they depend on the Rytov variance $\sigma_R^2 = 1.23 C_n^2 k^{7/6} d^{11/6}$ where d is the link distance, k is the wave number and C_n^2 is the refractive index structure parameter. The parameters of the n-th hop will be denoted by α_n and β_n.

Repetition Coding (RC) is implemented at each MIMO hop where the transmit power is evenly allocated between the transmit apertures in the absence of channel state information at the transmitter and receiver sides [7]. The non-coherent receiver performs Equal-Gain-Combining (EGC) and the equivalent irradiance along the n-th hop can be written as:

$$\mathcal{I}_n = \sum_{p=1}^{P_n} \sum_{q=1}^{Q_n} I_{n,p,q} \quad (2)$$

where $I_{n,p,q}$ stands for the irradiance between the p-th transmit aperture and the q-th receive aperture along the n-th hop. In what follows, we assume that the irradiances of the subchannels of a MIMO link are independent.

The outage probability along the n-th hop is given by [8]:

$$P_{\text{out},n} = \Pr\left(\frac{1}{P_n}\mathcal{I}_n < \left[\frac{\mathcal{P}_M}{\sqrt{Q_n}}\right]^{-1}\right) = \Pr\left(\mathcal{I}_n < \frac{P_n\sqrt{Q_n}}{\mathcal{P}_M}\right) \quad (3)$$

where $\mathcal{P}_M$ stands for the electrical power margin defined in [8]. In the first equation of (3), the normalization by P_n ensures the same transmit power as in single-aperture systems while the division by $\sqrt{Q_n}$ results from the Q_n-fold increase in the noise variance resulting from EGC [8].

III. Outage Probability and Diversity Order

The random variable $\mathcal{I}_n$ in (2) corresponds to the summation of $K_n \triangleq P_nQ_n$ independent gamma-gamma random variables. The characteristic function (CHF) of this sum-distribution has been previously derived in the context of performance analysis of diversity reception [9], [10]. In this section, we derive an asymptotic expression of the CHF that yields an approximate expression of the pdf near the origin. This pdf is then integrated to yield an asymptotic expression of the outage probability in (3).

From eq. (20) in [9], the CHF of $\mathcal{I}_n$ can be written as:

$$\Phi_{\mathcal{I}_n}(\omega) = \sum_{k=0}^{K_n}\binom{K_n}{k}\left[G_{\alpha_n,\beta_n}(\omega)\right]^{K_n-k}\left[G_{\beta_n,\alpha_n}(\omega)\right]^{k} \quad (4)$$

where $G_{x,y}(\omega) \triangleq \sum_{m=0}^{+\infty}\alpha_m(x,y)\Gamma(m+y)(-i\omega)^{-m-y}$ and $\alpha_m(x,y) \triangleq \frac{(xy)^{m+y}\Gamma(x-y)\Gamma(y-x+1)}{\Gamma(x)\Gamma(y)\Gamma(m-x+y+1)m!}$.

If $\alpha_n > \beta_n$, (4) can be further approximated by the term obtained for $k=0$. If $\alpha_n < \beta_n$, (4) can be approximated by the term obtained for $k=K_n$. Defining $\delta_n = \min\{\alpha_n,\beta_n\}$ and $\rho_n = \max\{\alpha_n,\beta_n\}$ while approximating $G_{x,y}(\omega)$ by the term at $m=0$, (4) can be written as:

$$\Phi_{\mathcal{I}_n}(\omega) \approx \left[(\delta_n\rho_n)^{\delta_n}\frac{\Gamma(\rho_n-\delta_n)}{\Gamma(\rho_n)}(-i\omega)^{-\delta_n}\right]^{K_n} \quad (5)$$

Applying the inverse Fourier transform of (5) results in [1]:

$$f_{\mathcal{I}_n}(I) \approx \frac{1}{\Gamma(K_n\delta_n)}\left[\frac{(\delta_n\rho_n)^{\delta_n}\Gamma(\rho_n-\delta_n)}{\Gamma(\rho_n)}\right]^{K_n} I^{K_n\delta_n-1} \quad (6)$$

Replacing (6) in (3) results in:

$$P_{\text{out},n} \approx \frac{1}{\Gamma(K_n\delta_n+1)}\left[\frac{(\delta_n\rho_n)^{\delta_n}\Gamma(\rho_n-\delta_n)}{\Gamma(\rho_n)}\right]^{K_n}\left[\frac{\mathcal{P}_M}{P_n\sqrt{Q_n}}\right]^{-K_n\delta_n} \quad (7)$$

Writing (7) under the form $P_{\text{out},n} = (\Lambda_n\mathcal{P}_M)^{-d_n}$ shows that the diversity order is equal to $d_n \triangleq K_n\delta_n = P_nQ_n\delta_n$. In the same way, the coding advantage takes the value:

$$\Lambda_n = \frac{1}{\delta_n\rho_nP_n\sqrt{Q_n}}\left[\frac{\Gamma(\rho_n)}{\Gamma(\rho_n-\delta_n)}\right]^{\frac{1}{\delta_n}}\Gamma(K_n\delta_n+1)^{\frac{1}{K_n\delta_n}} \quad (8)$$

Writing (8) as $\Lambda_n(P_n,Q_n)$ shows that the coding gain of a $P\times Q$ system with respect to a $P'\times Q'$ system is given by (where $K_n = PQ = P'Q'$ so that d_n is the same):

$$g_c = 10\log_{10}\left(\frac{\Lambda_n(P,Q)}{\Lambda_n(P',Q')}\right) = 10\log_{10}\left(\frac{P'\sqrt{Q'}}{P\sqrt{Q}}\right) \text{ (dB)} \quad (9)$$

[1]The same expression was derived independently in [8] using a completely different calculation methodology.

The coding gain in (9) quantifies the power margin improvement at a given small value of the outage probability. In other words, for the same value of d_n that fixes the slopes of the $P_{\text{out},n}$ versus $\mathcal{P}_M$ curves, g_c quantifies the shift between the corresponding curves. In this case, the maximum coding gain can be obtained by placing all apertures at the receiver (i.e. SIMO system with $P_n = 1$ and $Q_n = K_n$) while the minimum coding gain is obtained by placing all apertures at the transmitter (i.e. MISO system with $Q_n = 1$ and $P_n = K_n$). From (9), the coding gain (resp. loss) of the $P_n \times Q_n$ MIMO n-th hop with respect to the corresponding $P_nQ_n \times 1$ MISO (resp. $1 \times P_nQ_n$ SIMO) hop is $10\log_{10}(\sqrt{Q_n})$ dB (resp. $10\log_{10}(\sqrt{P_n})$ dB). Note that SIMO systems outperform MISO systems because of the enhanced energy capture achieved by the additional receive apertures.

Despite the superiority of SIMO systems with respect to the corresponding MIMO systems (for the same value of the product P_nQ_n), MIMO systems might be desirable for the following reasons. (i): For practical purposes, there are limitations on the number of apertures that can be placed at each communicating node. This follows mainly from the size of the transceivers and from the need of sufficiently spacing the apertures in order to reduce the correlation between the sub-channels. (ii): For the same value of the product $K_n = P_nQ_n$, the $1\times K_n$ SIMO (as well as the $K_n\times 1$ MISO) systems require the largest number of apertures that is equal to K_n+1. In this case, the minimum number of apertures needed by the MIMO system to achieve the same diversity order is $\frac{K_n}{D}+D$ where D stands for the largest integer in $\{1,\dots,K_n-1\}$ that divides K_n. Evidently, this number is less than K_n+1 and MIMO systems require at most the same total number of apertures as SIMO systems to achieve the same diversity order.

The outage probability of a serial relaying system with N_r relays is given by [5]: $P_{\text{out}} = 1 - \prod_{n=1}^{N_r+1}(1-P_{\text{out},n})$ which scales asymptotically as $P_{\text{out}} \approx \sum_{n=1}^{N_r+1}P_{\text{out},n}$. This outage probability can be further approximated by $P_{\text{out}} \approx \max_{n=1,\dots,N_r+1}P_{\text{out},n}$ where, for large values of $\mathcal{P}_M$, the hop that manifests the highest outage probability is the one for which the exponent $K_n\delta_n$ is the smallest following from (7). Therefore, the diversity order is equal to:

$$d = \min_{n=1,\dots,N_r+1}\{K_n\delta_n\} = \min_{n=1,\dots,N_r+1}\{P_nQ_n\delta_n\} \quad (10)$$

IV. Optimal Aperture Allocation

Maximizing the diversity order can be expressed as a maximin optimization problem as follows:

$$\max_{K_1,\dots,K_{N_r+1}}\left\{\min_{n=1,\dots,N_r+1}[K_n\delta_n]\right\} \text{ s.t.: } \sum_{n=1}^{N_r+1}K_n = K_{\text{tot}} \quad (11)$$

where K_{tot} stands for the total number of sub-channels along the multi-hop link and it is a fixed quantity. Note that the considered problem is not an integer linear programming (ILP) problem since the objective function in (11) is nonlinear. Consequently, the algorithms developed for solving ILP problems can not be applied in this case.

It is worth noting that the diversity order depends on the number of transmit apertures P_n and the number of receive apertures Q_n only through the parameter $K_n = P_nQ_n$. In other words, different values of (P_n, Q_n) that yield the same value of K_n will result in the same diversity order. Once the optimal value of K_n is derived, P_n and Q_n can be derived by solving the equation $P_nQ_n = K_n$ that might admit more than one integer solution all achieving the same diversity order.

Assume that the functions $K_1\delta_1, \dots, K_{N_r+1}\delta_{N_r+1}$ intersect at a certain point. In this case, d will be maximized at this point of intersection. In fact, for any other point, one of the functions $K_1\delta_1, \dots, K_{N_r+1}\delta_{N_r+1}$ will be smaller than the others and d will decrease. Consequently, (10) is maximized for $K_1\delta_1 = \cdots = K_{N_r+1}\delta_{N_r+1}$. Solving these N_r equations as well as the constraint equation $\sum_{n=1}^{N_r+1} K_n = K_{\text{tot}}$ results in the following solution that will be denoted by $\{K'_n\}_{n=1}^{N_r+1}$:

$$K'_n = \frac{K_{\text{tot}}}{\delta_n \sum_{i=1}^{N_r+1} \frac{1}{\delta_i}} \quad ; \quad n = 1, \dots, N_r + 1 \tag{12}$$

The values of K'_n in (12) are not necessarily integers and we need to derive the corresponding integer solution that maximizes d. The optimization problem in (11) can be written as $\min\{\max[-K_n\delta_n]\}$ which is known to be a convex problem following from the convexity of the functions $-K_n\delta_n$. Consequently, it can be conjectured that the optimal integer solution will not be very "far" from the non-integer solution. Therefore, as an initial condition, we first floor the values of K'_n in (12) in order not to exceed K_{tot}. At this level, the corresponding set is $\mathcal{C}^{(0)} = \{\lfloor K'_1 \rfloor \delta_1, \dots, \lfloor K'_{N_r+1} \rfloor \delta_{N_r+1}\}$ and $K_{\text{rem}} = K_{\text{tot}} - \sum_{n=1}^{N_r+1} \lfloor K'_n \rfloor$ remaining subchannels need to be added to the hops in order to maximize the minimum of $\mathcal{C}^{(0)}$ (where $\lfloor x \rfloor$ rounds x to the largest integer smaller than x). Without any loss of generality, we assume that the elements of $\mathcal{C}^{(0)}$ are arranged in an ascending order in what follows.

Observation 1: The best way to add the remaining K_{rem} subchannels is to select the K_{rem} smallest elements of $\mathcal{C}^{(0)}$ and to assign one additional path to each one of the corresponding hops. In other words, $\lfloor K'_n \rfloor$ will be transformed to $\lceil K'_n \rceil$ for $n = 1, \dots, K_{\text{rem}}$ while $\lfloor K'_{K_{\text{rem}}+1} \rfloor, \dots, \lfloor K'_{N_r+1} \rfloor$ will remain unchanged. Now, for any integers i and j in $\{1, \dots, N_r + 1\}$, the following relation holds:

$$\lceil K'_i \rceil \delta_i \geq K'_i\delta_i = K'_j\delta_j \geq \lfloor K'_j \rfloor \delta_j \tag{13}$$

where the equality follows from (12). Consequently, at the second iteration, the corresponding set whose elements are arranged in an ascending order is:

$$\mathcal{C}^{(1)} = \{\lfloor K'_{K_{\text{rem}}+1} \rfloor \delta_{K_{\text{rem}}+1}, \dots, \lfloor K'_{N_r+1} \rfloor \delta_{N_r+1}, \lceil K'_1 \rceil \delta_1, \dots, \lceil K'_{K_{\text{rem}}} \rceil \delta_{K_{\text{rem}}}\} \tag{14}$$

implying that the minimum is now $\lfloor K'_{K_{\text{rem}}+1} \rfloor \delta_{K_{\text{rem}}+1}$. Note that if the K_{rem} subchannels were assigned in any possible way among the smallest $K_{\text{rem}} - h$ values of $\mathcal{C}^{(0)}$ (where $h > 0$), then the corresponding minimum would be $\lfloor K'_{K_{\text{rem}}-h+1} \rfloor \delta_{K_{\text{rem}}-h+1}$ which is smaller than the minimum of (14).

Observation 2: $\lceil K'_1 \rceil, \dots, \lceil K'_{K_{\text{rem}}} \rceil$ are the optimal integer values assigned to the corresponding links. In other words, these values do not need to be reconsidered in the next iteration. In fact, increasing any one of these values will not change the minimum value of (14) where the minimum value will always be equal to $\lfloor K'_{K_{\text{rem}}+1} \rfloor \delta_{K_{\text{rem}}+1}$. On the other hand, if any one of these values, say $\lceil K'_h \rceil$ ($h \in \{1, \dots, K_{\text{rem}}\}$) is decreased, then the minimum of (14) will be at most $\lfloor K'_h \rfloor \delta_h$ which is smaller than $\lfloor K'_{K_{\text{rem}}+1} \rfloor \delta_{K_{\text{rem}}+1}$ since $h < K_{\text{rem}} + 1$.

In other words, the first iteration yields the optimal values $\hat{K}_n = \lceil K'_n \rceil$ for $n = 1, \dots, K_{\text{rem}}$. The same procedures as the ones described above need to be repeated recursively for determining the remaining values of $\hat{K}_n$ where after each iteration K_{tot} needs to be replaced by $K_{\text{tot}} - \sum_{n=1}^{K_{\text{rem}}} \hat{K}_n$.

In what follows, $\hat{\mathbf{K}} = [\hat{K}_1, \dots, \hat{K}_{N_r+1}]$ is defined as the optimal integer solution outputted by the algorithm. We also define Δ as a subset of $\{1, \dots, N_r + 1\}$ containing the indices of the hops whose numbers of subchannels need to be optimized. Finally, the variable M stands for the remaining number of subchannels that need to be allocated.

The proposed algorithm is described by the following steps:

- *Step 0*: Set $\hat{\mathbf{K}} = [0 \cdots 0]$, $\Delta = \{1, \dots, N_r + 1\}$ and $M = K_{\text{tot}}$.
- *Step 1*: Evaluate $K'_i = \frac{M}{\delta_i \sum_{j\in\Delta} \frac{1}{\delta_j}}$ for $i \in \Delta$.
- *Step 2*: Construct the $(N_r + 1)$-dimensional set $\mathcal{C}$ whose i-th element is equal to $\lfloor K'_i \rfloor \delta_i$ if $i \in \Delta$ and to ∞ otherwise.
- *Step 3*: Construct the set $\mathcal{S}$ that contains the indices of the $M - \sum_{i\in\Delta} \lfloor K'_i \rfloor$ smallest elements of $\mathcal{C}$.
- *Step 4*: Find the optimal values $\hat{K}_n = \lceil K'_n \rceil$ for $n \in \mathcal{S}$.
- *Step 5*: Set $\Delta = \Delta \backslash \mathcal{S}$ and $M = M - \sum_{n\in\mathcal{S}} \hat{K}_n$. If $|\Delta| = 0$, exit. If $|\Delta| = 1$, set $\hat{K}_\Delta = M$ and exit. Go to *Step 1*.

It is worth noting that the above algorithm will be invoked at most N_r times. However, even in this extreme case, the computational complexity of the proposed algorithm remains much smaller than that of the brute-force exhaustive method whose complexity increases very rapidly with N_r and K_{tot}.

Given that the power allocation does not affect the diversity order, then the proposed aperture allocation will maximize the diversity gain with any power allocation strategy. In this context, the joint aperture-power optimal allocation can be realized by first invoking the proposed algorithm to yield the optimal aperture allocation and then optimize the power allocation conditioned on the fact that the optimal aperture allocation is as derived in the first step.

V. Numerical Results

We set $C_n^2 = 1.7 \times 10^{-14}$ m$^{-2/3}$ and $\lambda = 1550$ nm. An extensive numerical analysis showed that the proposed algorithm always yields the optimal solution. We assume that the transmit power is evenly split among the hops.

Fig. 1 shows the performance with two relays for $K_{\text{tot}} = 10$ where MISO links are considered. The source and destination are separated by 5 km and the lengths of the hops are 1 km, 1.5 km and 2.5 km. Results show the accuracy of the derived outage probability expressions that are very close to the exact results for large values of $\mathcal{P}_M$ and, hence, can accurately predict the achievable diversity orders. In Fig. 1, all possible aperture allocations are considered while respecting the condition that longer hops must be assigned a larger number of apertures in order to enhance the diversity order in (10) (note that δ decreases with the length of the hop).

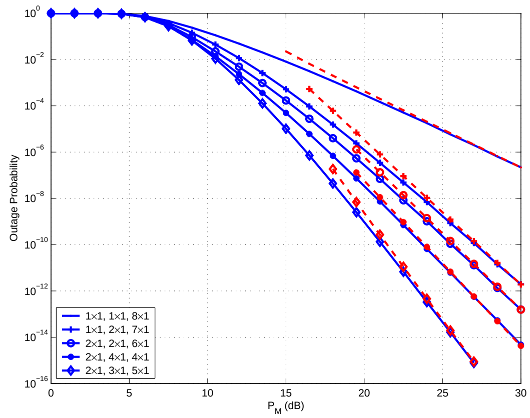

Fig. 1. Performance of a three-hop system for a link distance of 5 km. Solid and dashed lines correspond to the exact and approximate results, respectively.

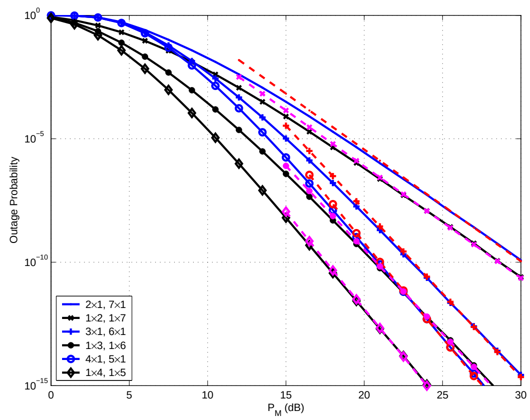

Fig. 2. Performance of a two-hop system for a link distance of 5 km. Solid and dashed lines correspond to the exact and approximate results, respectively.

For this simulation setup, the $(1\times1, 3\times1, 6\times1)$ and $(1\times1, 4\times1, 5\times1)$ systems exhibit outage curves that are very close to that of the $(1\times1, 2\times1, 7\times1)$ system and, hence, these curves are not presented for clarity. The same holds for the $(3\times1, 3\times1, 4\times1)$ system whose performance is very close to that of the $(2\times1, 4\times1, 4\times1)$ system. Results in Fig. 1 highlight the importance of aperture allocation where the optimal solution $(K_1, K_2, K_3) = (2, 3, 5)$ significantly outperforms the other possibilities by several orders of magnitude. Note that, in this case, the proposed algorithm reaches the optimal solution in only one iteration.

Fig. 2 shows the performance with one relay for $K_{\text{tot}} = 9$ where the hop lengths are 2 km and 3 km. The cases of MISO and SIMO links are compared. Results show that MISO and SIMO systems achieve the same diversity order where the corresponding outage curves are parallel to each other for large values of $\mathcal{P}_M$. As expected, SIMO links result in a better performance following from the enhanced coding gain.

Fig. 3 compares the proposed algorithm with the case where the apertures are allocated uniformly among the hops: $K_1 = \cdots = K_{N_r+1} = \frac{K_{\text{tot}}}{N_r+1}$. The source and destination nodes are separated by 10 km and 5 relays are placed randomly between these nodes. Fig. 3 shows the cumulative distribution functions (cdf's) of the diversity orders pertaining to the compared

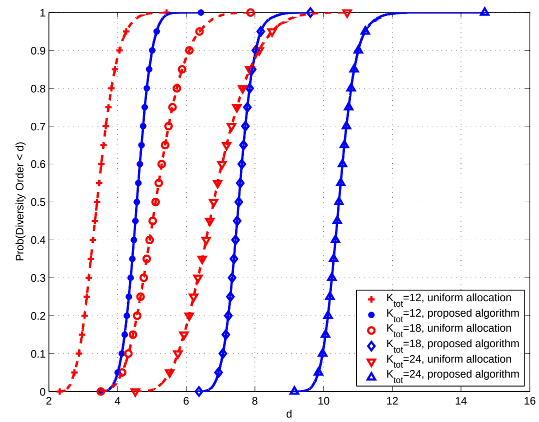

Fig. 3. cdf's of the diversity orders for a 10 km link with 5 relays.

techniques for $K_{\text{tot}} = 12$, 18 and 24. Once again, results highlight the importance of aperture allocation where high diversity orders can be achieved by the proposed algorithm. Moreover, the cdf's corresponding to this algorithm are steeper indicating a reduction in the variability of the diversity orders.

VI. Conclusion

Combining multi-hop relaying with MIMO techniques results in significant improvements in terms of the achievable outage probabilities and diversity orders. Adequately allocating the available subchannels or apertures among the hops is of critical importance for exploiting the full capabilities of such hybrid-diversity systems. We proposed a recursive algorithm that fulfills this task in an optimal way while having an acceptable level of complexity.

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