Optimal Relay Location and Opportunistic User-Scheduling for Stratospheric Communications

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***Abstract*—This paper investigates the outage performance of a Decode-and-Forward (DF) Multi-User (MU) stratospheric relay communication system operating over Generalized-Gamma (GG) fading channels. This system consists of multiple users-sources, multiple users-destinations and a High-Altitude Platform (HAP) acting as a relay station in the stratosphere. Geometry-based optimal relay location with fixed power allocation is proposed, in order to minimize the outage probability. Exact and approximated expressions for the End-to-End (E2E) outage probability are derived and opportunistic scheduling is applied, where the Source-Destination (SD) pair with the highest instantaneous E2E Signal-to-Noise Ratio (SNR) is scheduled for communication. The results highlight the gains offered by the opportunistic SD scheduling and the optimization of the relay location on the overall performance.**

Keywords-Generalized Gamma (GG) fading; High-Altitude Platforms (HAPs); Multi-User (MU); oppurtunistic scheduling; outage probability; relay location.

I. INTRODUCTION

A key objective in the development of future generation communication systems and the Internet of Things (IoT) applications is the seamless integration of wireless terrestrial and aerospace infrastructures over heterogeneous networks [1] [2]. In recent years, a great interest has been drawn towards the development of High-Altitude Platforms (HAPs), intending to provide ubiquitous wireless access over large coverage areas at low cost, while attaining network flexibility and adaptability due to their rapid deployment and movement on demand [3]. The term HAPs defines aerial platforms flying in the stratosphere.

The radio links of terrestrial nodes are usually vulnerable to fading effects arising from scattering, reflection, diffraction, or blockage of the radiated energy by objects in the propagation environment. Hence, exploiting the features of cooperative diversity techniques by preserving the End-to-End (E2E) communication between a source (S) and a destination (D) via an intermediate relay (R) can fulfill the demands for enhanced link reliability with greater mobility support and extended network range [4].

With the rapid growth of the number of connected devices, Fifth-Generation (5G) communication systems will be deployed in dense-user environments. Hence, shifting from Single-User (SU) to Multi-User (MU) systems is indispensable [5]. In MU systems, the MU diversity gain can significantly improve the system performance by appropriately designing user scheduling schemes. These schemes are necessary, as a single relay may be incapable of simultaneously serving multiple users. The opportunistic scheduling is a well-known and efficient user selection schemes that are usually used to select among the users [6]. In this scheme, the user with the best channel conditions is always allowed to conduct its transmission in both downlink and uplink scenarios. Also, this scheme is usually used to achieve the maximum sum-rate capacity in wireless networks. However, in scenarios where asymmetric link conditions exist, a trade-off between capacity and fairness among users arises.

More recently, the investigation of relaying in Multi-Source (MS) Multi-Destination (MD) networks has been investigated [7], since based on these schemes substantial achievable rate improvement in shared-spectrum multiple access wireless systems are offered. In these networks, multiple Source-Destination (SD) pairs simultaneously communicate with the help of relay nodes. Typical paradigm of this configuration is the Interference Relay Channel (IRC) [8], where a relay assists two independent source-destination pairs by using different relaying methods, as well as the cellular operation, in which multiple users within a cell communicate with each other through a base station acting as a relay unit.

Motivated by the aforementioned observations, this paper investigates the use of a radio relay installed on a HAP that acts as a stratospheric relay station, between multiple user pairs. This configuration is envisioned to be applied in 5G systems, where the relay nodes are expected to be located at the cell edge establishing the communication links between cell-edge users. An opportunistic scheduling scheme is adopted, in order to select the pair with the best E2E channel among the available ones. In the proposed system, each user pair is able to communicate through the relay. Depending on the propagation environment, each link may experience different channel fading conditions. In particular, Rician, Rayleigh, and log-normal distributions are suggested to model the channel fading in urban, sub-urban, and rural environments, respectively [9]. By generalizing the previous approaches, this paper considers that the channel fading follows the Generalized-Gamma (GG) distribution [10], which includes many well-known distributions as special cases, whereas it has the important advantage of approximately describing other distributions [11]. Also, this paper proposes geometry-based optimization schemes regarding the position of the stratospheric relay for determining the SD pair with the best E2E Signal-to-Noise Ratio (SNR). The performance of the underlying system is analyzed in terms of the outage probability. The results demonstrate the effect of the number of SD pairs, fading characteristics, and optimized relay location on the system's performance.

The rest of the paper is organized as follows. Section II presents the system model and the geometrical characteristics, whereas Section III analyzes the channel statistics. In Section IV, mathematical expressions for the outage probability are derived. Section V proposes geometrical design recommendation for optimal outage performance. Results are provided in Section VI. Finally, conclusions are drawn in Section VII.

II. SYSTEM MODEL

This paper considers a MS-MD relay-assisted airborne communication system with slowly-varying, frequency-flat block-fading channels, where the channel coefficients stay constant over an entire block of communication. As shown in Figure 1, the proposed system consists of one cluster of K users, the sources, trying to communicate with one cluster of K users, the destinations, with the aid of a Decode-and-Forward (DF) stratospheric relay. This relay is situated approximately 20 km above the ground, equipped with two antennas, one for transmitting and the other for receiving. In this system, two users communicate with each other with the help of the relay since the direct links between them are obstructed due to high attenuation in the propagation medium. To aid our analysis, the subscripts S_k, R, and D_k, where $1 \le k \le K$, are affiliated with the k-th source, the relay, and the k-th destination, respectively. All of the user pairs are in the set U, where the k-th user pair is denoted by (S_k, D_k). Due to hardware limitations, the communication operates in a Half-Duplex (HD) mode and is conducted over two phases; the first phase (hop) includes the link between S_k and R, while the second phase (hop) involves the link between R and D_k. Time is divided in time-slots and multiple access is based on Time-Division Multiple Access (TDMA), where at each time-slot one SD pair is activated for transmission. The channel coefficients $h_{S_k,R}\left(h_{R,D_k}\right)$ between the k-th source (destination) and the relay are generalized gamma fading coefficients and identically distributed. In addition, in all cases the received signal is also affected by Additive White Gaussian Noise (AWGN) with variance N_O.

A. Geometrical Characteristics

For analytical simplification purposes, we assume that the users and the relay are placed on a x-y plane. Specifically, as shown in Figure 2, the users are placed on the horizontal axis, whereas the relay is placed on the vertical axis. This assumption is reasonable since it minimizes the effect of path loss. The fundamental parameters, which describe the geometry of the proposed system, are the elevation angle $\beta_{S_k}\left(\beta_{D_k}\right)$ of the relay relative to the k-th source (k-th destination), the height of the relay H_R, the distance $d_{S_k}\left(d_{D_k}\right)$ between the k-th source (k-th destination) and the relay, and the distance $D_{S_k}\left(D_{D_k}\right)$ from the k-th source (k-th destination) to the Sub-Platform Point (SPP). According to this geometry, the distance between the k-th source and the k-th destination is $D_{S_kD_k}$.

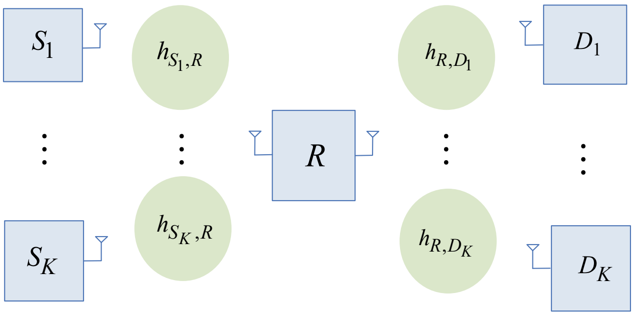

Figure 1. The MS-MD stratospheric relay fading channel.

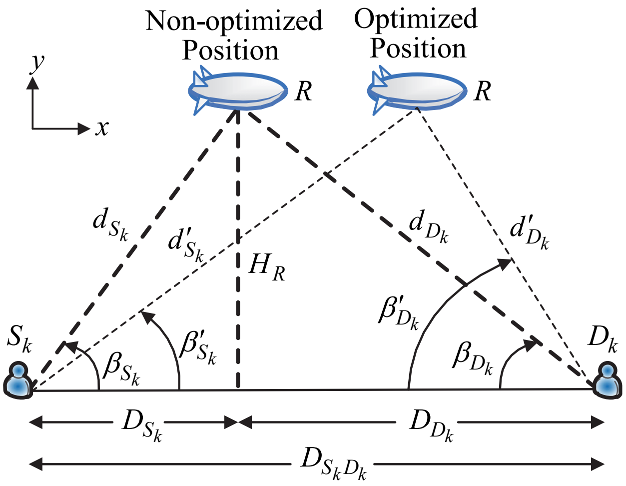

Figure 2. The geometrical characteristics of the proposed stratospheric relay communication system.

From Figure 2, one observes that d_{S_k} can be written as a function of $\beta_{S_k} \in \left(0, \pi/2\right)$ as follows

$$d_{S_k} = H_R / \sin \beta_{S_k}. \tag{1}$$

Using (1) and applying the cosine law to the triangle $S_k R D_k$ in Figure 2, d_{D_k} can be also written as a function of β_{S_k} as

$$d_{D_k} = \sqrt{\frac{H_R^2}{\sin^2 \beta_{S_k}} + D_{S_k D_k}^2 - 2\frac{H_R D_{S_k D_k}}{\tan \beta_{S_k}}}. \tag{2}$$

B. *First Hop*

The received signal at the stratospheric relay *R* from the *k*th source can be expressed as

$$y_{S_k,R} = \sqrt{P_{S_k}} h_{S_k,R} x_{S_k} + n_R, \tag{3}$$

where P_{S_k} is the transmit power at S_k, x_{S_k} is the transmitted symbol from the *k*th source with $\mathrm{E}\left\{\left|x_{S_k}\right|^2\right\} = 1$, $\mathrm{E}\{\cdot\}$ is the statistical expectation operator, and n_R represents the AWGN. The channel gain $\left|h_{S_k,R}\right|^2$ has mean power [12]:

$$\mathrm{E}\left\{\left|h_{S_k,R}\right|^2\right\} = d_{S_k}^{-a}, \tag{4}$$

where a is the path loss exponent. The instantaneous received SNR in the first hop is denoted as $\gamma_{S_k,R}$ and can be expressed as

$$\gamma_{S_k,R} = \frac{P_{S_k}}{N_O}\left|h_{S_k,R}\right|^2. \tag{5}$$

Using (4), the average SNR can be expressed as

$$\overline{\gamma}_{S_k,R} = \frac{P_{S_k}}{N_O}\mathrm{E}\left\{\left|h_{S_k,R}\right|^2\right\} = \frac{P_{S_k}}{N_O} d_{S_k}^{-a}. \tag{6}$$

C. *Second Hop*

The signal received at the destination can be written as

$$y_{R,D_k} = \sqrt{P_R} h_{R,D_k} y_{S_k,R} + n_{D_k}, \tag{7}$$

where P_R is the transmit power at *R* and n_{D_k} is the AWGN. The channel gain $\left|h_{R,D_k}\right|^2$ has mean power [12]:

$$\mathrm{E}\left\{\left|h_{R,D_k}\right|^2\right\} = d_{D_k}^{-a}. \tag{8}$$

The instantaneous received SNR in the second hop is denoted as γ_{R,D_k} and can be expressed as

$$\gamma_{R,D_k} = \frac{P_R}{N_O}\left|h_{R,D_k}\right|^2. \tag{9}$$

Using (8), the average SNR can be expressed as

$$\overline{\gamma}_{R,D_k} = \frac{P_R}{N_O}\mathrm{E}\left\{\left|h_{R,D_k}\right|^2\right\} = \frac{P_R}{N_O} d_{D_k}^{-a}. \tag{10}$$

Finally, the E2E SNR at the *k*-th destination can be approximated as follows

$$\gamma_{D_k} \simeq \min\left\{\gamma_{S_k,R}, \gamma_{R,D_k}\right\}. \tag{11}$$

To analyze the performance of the proposed system, obtaining the statistics of the E2E SNR provided in (11) is required.

The scheduling is based on an opportunistic SD pair selection, where at each time-slot, the pair with the best E2E SNR is activated for communication. More specifically, the opportunistic SD pair selection will activate the k^*-th pair according to:

$$k^* = \arg\max_{1 \le k \le K} \min\left\{\gamma_{S_k,R}, \gamma_{R,D_k}\right\}. \tag{12}$$

In this way, the SD pair will be the one having the E2E channel offering the maximum capacity at each time-slot.

III. CHANNEL STATISTICS

In this paper, the GG distribution is utilized to model the channels for the S_k–R and R–D_k links. Hence, the Probability Density Function (PDF) of the instantaneous SNR received at *R*, denoted as $\gamma_{S_k,R}$, is given by [13]

$$f_{\gamma_{S_k,R}}\left(\gamma_{S_k,R}\right) = \frac{b_{S_k,R}\gamma_{S_k,R}^{m_{S_k,R}b_{S_k,R}/2-1}}{2\Gamma\left(m_{S_k,R}\right)\left(\tau_{S_k,R}\overline{\gamma}_{S_k,R}\right)^{mb_{S_k,R}/2}} \times \exp\left[-\left(\frac{\gamma_{S_k,R}}{\tau_{S_k,R}\overline{\gamma}_{S_k,R}}\right)^{b_{S_k,R}/2}\right], \tag{13}$$

where $b_{S_k,R} > 0$ and $m_{S_k,R} \ge 1/2$ are the distribution's shaping parameters related to the fading severity, $\tau_{S_k,R} = \Gamma\left(m_{S_k,R}\right)/\Gamma\left(m_{S_k,R} + 2/b_{S_k,R}\right)$, and $\Gamma(\cdot)$ is the Gamma function [14, eq. (8.310/1)]. For different values of $b_{S_k,R}$ and $m_{S_k,R}$, several distributions used in fading channel modeling can be obtained, e.g., Rayleigh (for $b_{S_k,R} = 2$ and $m_{S_k,R} = 1$), Nakagami-*m* (for $b_{S_k,R} = 2$), Weibull (for $m_{S_k,R} = 1$), and log-normal (for the limiting case of $b_{S_k,R} \to 0$ and $m_{S_k,R} \to \infty$). In addition, the PDF in (13) can approximately describe the Rician fading for $b_{S_k,R} = 2$ and $m_{S_k,R} = \left(K_{S_k,R} + 1\right)^2 / \left(2K_{S_k,R} + 1\right)$, where $K_{S_k,R}$ is the Rician factor of the first hop, i.e., the average power ratio of the Line-of-Sight (LoS) component to the Non-Line-of-Sight (NLoS) component.

The Cumulative Distribution Function (CDF) of the instantaneous SNR received at R can be expressed as

$$F_{\gamma_{S_k,R}}\left(\gamma_{S_k,R}\right) = 1 - \frac{\Gamma\left[m_{S_k,R}, \left(\gamma_{S_k,R} / \left(\tau_{S_k,R}\bar{\gamma}_{S_k,R}\right)\right)^{b_{S_k,R}/2}\right]}{\Gamma\left(m_{S_k,R}\right)}, \tag{14}$$

where $\Gamma(\cdot,\cdot)$ stands for the upper incomplete Gamma function [14, eq. (8.350/2)]. Note that the PDF $f_{\gamma_{R,D_k}}\left(\gamma_{R,D_k}\right)$ and the CDF $F_{\gamma_{R,D_k}}\left(\gamma_{R,D_k}\right)$ of the GG distribution for the second RF link can be defined as in the first RF link by replacing the indices.

IV. DERIVATION OF THE OUTAGE PROBABILITY

The outage probability is defined as the probability that the SNR at the destination goes below a predetermined outage threshold γ_{out}, i.e., $P_{out} = \Pr\left[\gamma_{D_k} \leq \gamma_{out}\right]$, where $\Pr[\cdot]$ is the probability operation. In this case, the communication system cannot achieve adequate reception. Using (11), the outage probability can be obtained from the CDF of the E2E SNR as $P_{out} = F_{\gamma_{D_k}}\left(\gamma_{out}\right)$ and can be written in terms of CDFs of the two hops' SNRs as follows [15]

$$P_{out} = 1 - \left[\left(1 - F_{\gamma_{S_k,R}}\left(\gamma_{out}\right)\right)\left(1 - F_{\gamma_{R,D_k}}\left(\gamma_{out}\right)\right)\right]. \tag{15}$$

From (15), one observes that the system gets in outage providing that at least one of the two hops gets in outage or, equivalently, the SNR of that hop becomes less than γ_{out}. Using (14), (15) becomes

$$\begin{aligned} P_{out} &= 1 - \frac{1}{\Gamma\left(m_{S_k,R}\right)\Gamma\left(m_{R,D_k}\right)} \\ &\quad \times \Gamma\left[m_{S_k,R}, \left(\gamma_{out} / \left(\tau_{S_k,R}\bar{\gamma}_{S_k,R}\right)\right)^{b_{S_k,R}/2}\right] \\ &\quad \times \Gamma\left[m_{R,D_k}, \left(\gamma_{out} / \left(\tau_{R,D_k}\bar{\gamma}_{R,D_k}\right)\right)^{b_{R,D_k}/2}\right] \\ &= 1 - \left[\exp\left(-\left(\gamma_{out} / \left(\tau_{S_k,R}\bar{\gamma}_{S_k,R}\right)\right)^{b_{S_k,R}/2}\right)\right. \\ &\quad \left. \times \sum_{k=0}^{m_{S_k,R}-1} \frac{1}{k!}\left(-\left(\gamma_{out} / \left(\tau_{S_k,R}\bar{\gamma}_{S_k,R}\right)\right)^{b_{S_k,R}/2}\right)^{k}\right] \\ &\quad \times \left[\exp\left(-\left(\gamma_{out} / \left(\tau_{R,D_k}\bar{\gamma}_{R,D_k}\right)\right)^{b_{R,D_k}/2}\right)\right. \\ &\quad \left. \times \sum_{k=0}^{m_{R,D_k}-1} \frac{1}{k!}\left(-\left(\gamma_{out} / \left(\tau_{R,D_k}\bar{\gamma}_{R,D_k}\right)\right)^{b_{R,D_k}/2}\right)^{k}\right], \end{aligned} \tag{16}$$

where $\Gamma(n,x) = \Gamma(n)\exp(-x)\sum_{k=0}^{n-1}\left(x^k / k!\right)$ for arbitrary integer n. At high SNRs and for the special case of Nakagami-m fading, using the approximation $\exp(-x) \approx 1 - x$ for small x, (16) can be approximated as follows [12]

$$P_{out} \approx \frac{A}{\bar{\gamma}_{S_k,R}^{m_{S_k,R}}} + \frac{B}{\bar{\gamma}_{R,D_k}^{m_{R,D_k}}}, \tag{17}$$

where

$$A = m_{S_k,R}^{m_{S_k,R}} \gamma_{out}^{m_{S_k,R}} / \Gamma\left(m_{S_k,R} + 1\right), \tag{18}$$

$$B = m_{R,D_k}^{m_{R,D_k}} \gamma_{out}^{m_{R,D_k}} / \Gamma\left(m_{R,D_k} + 1\right). \tag{19}$$

Note that the aforementioned approximation is valid in a broad SNR regime [12].

Depending on the values of the parameters $b_{S_k,R}\left(b_{R,D_k}\right)$ and $m_{S_k,R}\left(m_{R,D_k}\right)$, the S_k–R and R–D_k links may experience either symmetric, e.g., Rayleigh/Rayleigh or Rician/Rician, or asymmetric, e.g., Rayleigh/Rician or Rician/Rayleigh, fading phenomena.

V. OPTIMAL LOCATION OF THE STRATOSPHERIC RELAY

An important design parameter is to determine the optimal relay position that will minimize the outage probability for a given set of users. For this optimal position, the proposed scheduling approach determines the pairs of users that will communicate, according to the opportunistic scheduling principle.

In order to determine the optimal relay position, we set $x = \sin\beta_{S_k}$ and consider a predetermined power allocation $\left(P_{S_k} / N_O, P_R / N_O\right)$ and fixed values of H_R and D_{SD_k}. Thus, the problem of finding the optimal relay location with respect to S_k and D_k can be stated as follows

$$\begin{aligned} x^* &= \arg\min_{x} P_{out} \\ &\text{subject to: } 0 < x < 1 \end{aligned} \tag{20}$$

Using (6), (10), and (17)-(19) and computing the second derivative of P_{out} with respect to x, one can easily show that the objective function is a strictly convex function of $x \in (0,1)$. Moreover, computing the first derivative of P_{out} with respect to x, the optimal relay location is the root of the equation in (21).

Standard iterative root-finding algorithms can be used to efficiently find numerical solutions to x^* and then compute $\beta_{S_k} = \arcsin x$. Then, using (2), we can compute d_{D_k} and $\beta_{D_k} = \arcsin\left(H_R / d_{D_k}\right)$.

$$0.5aBm_{R,D_k}\left(-\frac{2H_R^2}{x^3}+\frac{2D_{S_kD_k}H_R}{\sqrt{1-x^2}}+\frac{2D_{S_kD_k}H_R\sqrt{1-x^2}}{x^2}\right)$$

$$\times\left(D_{S_kD_k}^2+\frac{H_R^2}{x^2}-\frac{2D_{S_kD_k}H_R\sqrt{1-x^2}}{x}\right)^{-1+\frac{a}{2}}\left(\frac{P_R}{N_O}\right)^{-1}$$

$$\times\left(\frac{\left(D_{S_kD_k}^2+\frac{H_R^2}{x^2}-\frac{2D_{S_kD_k}H_R\sqrt{1-x^2}}{x}\right)^{a/2}}{\left(\frac{P_R}{N_O}\right)}\right)^{-1+m_{R,D_k}}$$

$$-aAH_Rm_{S_k,R}x^{-2}\left[\frac{\left(\frac{H_R}{x}\right)^a}{\left(\frac{P_{S_k}}{N_O}\right)}\right]^{-1+m_{S_k,R}}\left(\frac{H_R}{x}\right)^{-1+a}\left(\frac{P_{S_k}}{N_O}\right)^{-1}=0 \tag{21}$$

VI. NUMERICAL RESULTS

This section investigates the performance of the proposed system in terms of the outage probability for a wide range of transmit SNR values. For this purpose, a simulation setup was developed in MATLAB and the transmission of 10^6 packets for each SNR value was performed. Unless indicated otherwise, the values of model parameters used are $\left(P_{S_k}/N_O\right)=\left(P_R/N_O\right)=10$ dB, $a=3$, $H_R=20$ km, and $D_{S_kD_k}=40$ km. By adopting the recommendations for the optimal stratospheric relay location in (20) and (21), we obtain $\beta_{S_k}=\beta_{D_k}=45^\circ$. For the Rician fading conditions, it is considered that $K_{S_k,R}=K_{R,D_k}=3$ dB. Then, we obtain $m_{S_k,R}=m_{R,D_k}=1.8$.

Figure 3 and Figure 4 depict the outage probability as a function of the transmit SNR for different number of SD pairs and symmetric Rician/Rician and Rayleigh/Rayleigh fading, respectively. Both the optimal and the non-optimal location of the stratospheric relay is considered. One observes that the optimized system outperforms the non-optimized one. Moreover, a significant performance improvement can be achieved, as the number of users increases. By comparing the results in Figure 3 and Figure 4, it is also obvious that the Rician/Rician fading leads to significantly better results.

Figure 5 shows the outage probability as a function of the transmit SNR for four SD pairs and asymmetric Rayleigh/Rician and Rician/Rayleigh fading. One observes that the type of fading slightly affects the outage probability when the stratospheric relay is located at an optimal position.

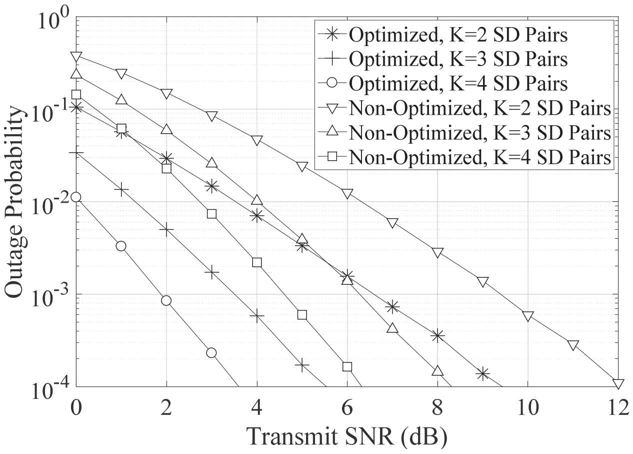

Figure 3. Outage probability of the proposed system in terms of the transmit SNR for Rician/Rician fading and different SD pairs.

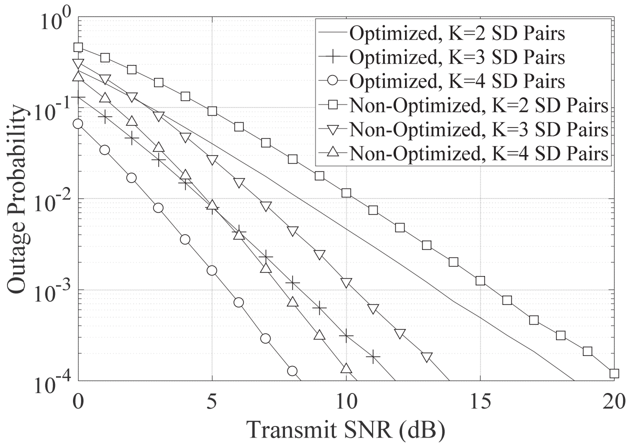

Figure 4. Outage probability of the proposed system in terms of the transmit SNR for Rayleigh/Rayleigh fading and different SD pairs.

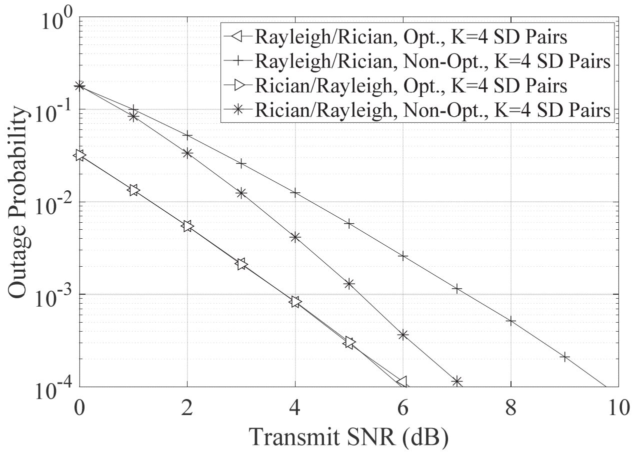

Figure 5. Outage probability of the proposed system in terms of the transmit SNR for Rayleigh/Rician and Rician/Rayleigh fading conditions.

Overall, the design recommendations ensure the successful operation and feasibility of the proposed system regardless of the variation of the propagation phenomena of both links. On the contrary, the improper position of the relay substantially influences the system performance depending on the fading conditions.

VII. CONCLUSION

In this paper, an opportunistic MS-MD pair selection scheme for stratospheric relay systems over GG fading channels has been presented. An optimum geometry-based design criterion for the placement of the stratospheric relay has been also developed, under a high SNR assumption and the impact of the number of SD pairs, the type of fading, and the proper/improper relay location on the system performance has been studied. The results have demonstrated that the performance decreases, as the fading conditions worsen, the number of SD pairs decreases, and the stratospheric relay shifts from its optimized location. These results provide guidelines for the solution of the fundamental problem of relay placement, in order to guarantee the MS-MD advantage in practice.

This work could be further improved or extended into different areas. Apart from the outage performance, the bit-error-rate (BER) and the throughput performance should be also evaluated. It would be also interesting to apply the proposed schemes to systems, where the users and the relay are equipped with multiple antennas, in order to exploit full diversity, i.e., both multi-antenna diversity and MS-MD diversity. Since power control is important in MS-MD relay networks, jointly optimizing the power allocation and the relay location is desirable. Also, in topologies where asymmetric link conditions exist, scheduling should be modified in order to ensure fairness among the SD pairs. Finally, this work can be extended to additionally support multiple stratospheric relays with free-space optical (FSO) inter-platform links.

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