Optimization of Transmit Powers for Cooperative Communication Systems over Rayleigh Fading Channels

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Abstract: **The paper studies the transmit power optimization for cooperative multiple-input multiple-output (MIMO) systems using amplify-and-forward (AF) technique. The study examines and evaluates the system in which the communication between the source and the multi-antenna equipped destination is helped by multi relay nodes. To further improve the performance of the system, the optimal power allocation between the source and the relay(s) is also considered. In terms of outage probability, numerical results show that cooperative communication systems using optimal power allocation profile outperform those with uniform power allocation profile.**

Keywords: MIMO systems, Cooperative MIMO, Amplify-and-Forward, Rayleigh fading channels.

I. INTRODUCTION

MIMO (Multiple-Input Multiple-Output) systems have been studied widely so far and considered a promising technology for providing high-speed data rate and wide network coverage. The MIMO concept is employed in current standards such as IEEE 802.11n, Wimax and 3.5G mobile networks [1-8]. Many studies on MIMO systems show that for the same setting condition of transmit power and allocated spectrum, capacity of MIMO systems increases significantly as compared to single input single output (SISO) systems [1-8]. However, in some certain situations, e.g. sensor or ad-hoc networks, due to constraints on space and power, employing MIMO technology for achieving spatial diversity is infeasible [9-11].

To overcome such the problem while still benefiting the advantage offered by MIMO technology, a new concept, named cooperative communications, was born [9-11]. The basic idea of cooperative communication is that the communication between the source and the destination is possibly helped by a single or multiple relay(s) while the destination employs a combining technique to efficiently combine the signals sent by the source and forwarded by relays. This technique allows single-antenna relays in cooperative systems achieve spatial diversity as in MIMO users [10, 12].

Up to now, there are many designed protocols for cooperative communications. In particular, based on the signal processing techniques at relays, cooperative communication protocols are classified as amplify-and-forward (AF), decode-and-forward (DF) and coded cooperation (CC) [9]. Regarding to forwarding technique, cooperative communication is categorized by repetition-based cooperative networks [10, 13, 14] and opportunistic cooperative networks [15, 16]. Compared with repetition-based cooperative networks, opportunistic cooperative networks have advantage in improving the spectral efficiency since only two timeslots are used regardless of the number of relays involved in the cooperative transmission. However, to choose the best relay, opportunistic cooperative networks require full channel state information (CSI) of instantaneous signal-to-noise ratios (SNRs) of the first hop and the second hop, resulting in more hardware complexity and power consuming, which is inappropriate for some networks, such as ad-hoc or sensor networks. To address this concern, Krikidis et. al. suggested a simpler relay selection scheme, which only needs the first hop CSI [17]. Some of extend works based on the relay selection scheme is proposed, (e.g. see [18-24]). Most of them focus limitedly on evaluating system performance with the assumption that the power allocation between source and relay(s) is equal [18-24, 25]. However, due to the mobility as well as the randomized distribution of relay nodes, the distances between nodes, i.e. source to relay, source to destination, and relay to destination, usually are not the same leading to the fact that the use of uniform power allocation is not reasonable and partially reduces the system performance.

In this paper, we aim at designing and solving the optimization problem of power allocation for MIMO cooperative networks with partial relay selection. Specifically, we consider the two hop cooperative network in which the destination is installed multiple antennae [25]. However, the authors in [25] only focused on finding the diversity order of the system according to the number of relays and the number of antennae installed at the destination. To the best knowledge of the author, there is no published work concerning the optimal power allocation for such system. And this paper aims to offer a first look at this problem. By using the Lagrange technique, the optimal power for the source and the relay can be found. The effect of relay positions is further studied indicating the best positions in which the system achieves the best performance.

Related works: There are many research works concerning the optimal problem of power allocation for relay (cooperative) networks, (e.g. see [26-32]. In particular, Hasna et. al. [26], for the first time, outlined and then solved the problem of power allocation for multihop transmission covering both relaying techniques, amplify-and-forward and decode-and-forward. Numerical results in the paper show that the relay networks with highly unbalanced links or with a large number of hops should be used along with optimal power allocation. Furthermore, it was confirmed that an AF system with optimum power allocation can outperform a DF system with no power allocation. In [27], the power allocation for multihop cooperative networks was considered. Based on the end-to-end symbol error rate (SER) of the system, the authors determined the optimum power allocation and show that equal power strategy is in general not optimum in multihop cooperative networks. Besides, an interesting result observed is that the optimum power allocation does not depend on the direct link between the source and the destination. It depends only on the channel links related to relays. In [28], Goudarzi et. al. presented a novel algorithm for partner selection (using only average channel powers) and power allocation in AF cooperative networks given outage probability constraints. Based on the KKT methods, the problem of power allocation was solved for a fixed set of relays. In [30], the power allocation for the space time coded DF cooperative networks with uniformly distributed nodes was studied. Assuming that the total power is fixed, a near-optimum power allocation requiring only mean channels gain at transmitter was derived. Different from the other papers, which focused on optimal power allocation only, the paper [31] took into account the relay positions, relay selection strategies and relaying protocols, which may also have great impact on the system performance. Finally, Yang et al. [32] successfully derived two power allocation schemes for two-way opportunistic relay networks showing that the proposed schemes significantly outperform the equal power allocation scheme.

The remaining of the paper is as follows. Section II describes in details the system model of cooperative networks under consideration. In Section III, we study the system performance by deriving its outage probability while the optimization of power allocation is considered in Section IV. Numerical results and discussion are presented in Section V. Finally, the paper is closed by Section VI.

II. SYSTEM MODEL

We consider a cooperative MIMO network as illustrated in Fig. 1 in which the source (s) communicates with the destination (d) via the help of K relays $(r_1,\dots,r_K)$ over Rayleigh fading channels. We assume that the source and relays have a single antenna while the destination is equipped with N antennae ($N \geq 1$). The communication between the source and the destination takes place at two timeslots, namely broadcasting timeslot and forwarding timeslot. For simplicity, we further assume that all nodes operate in half-duplex mode.

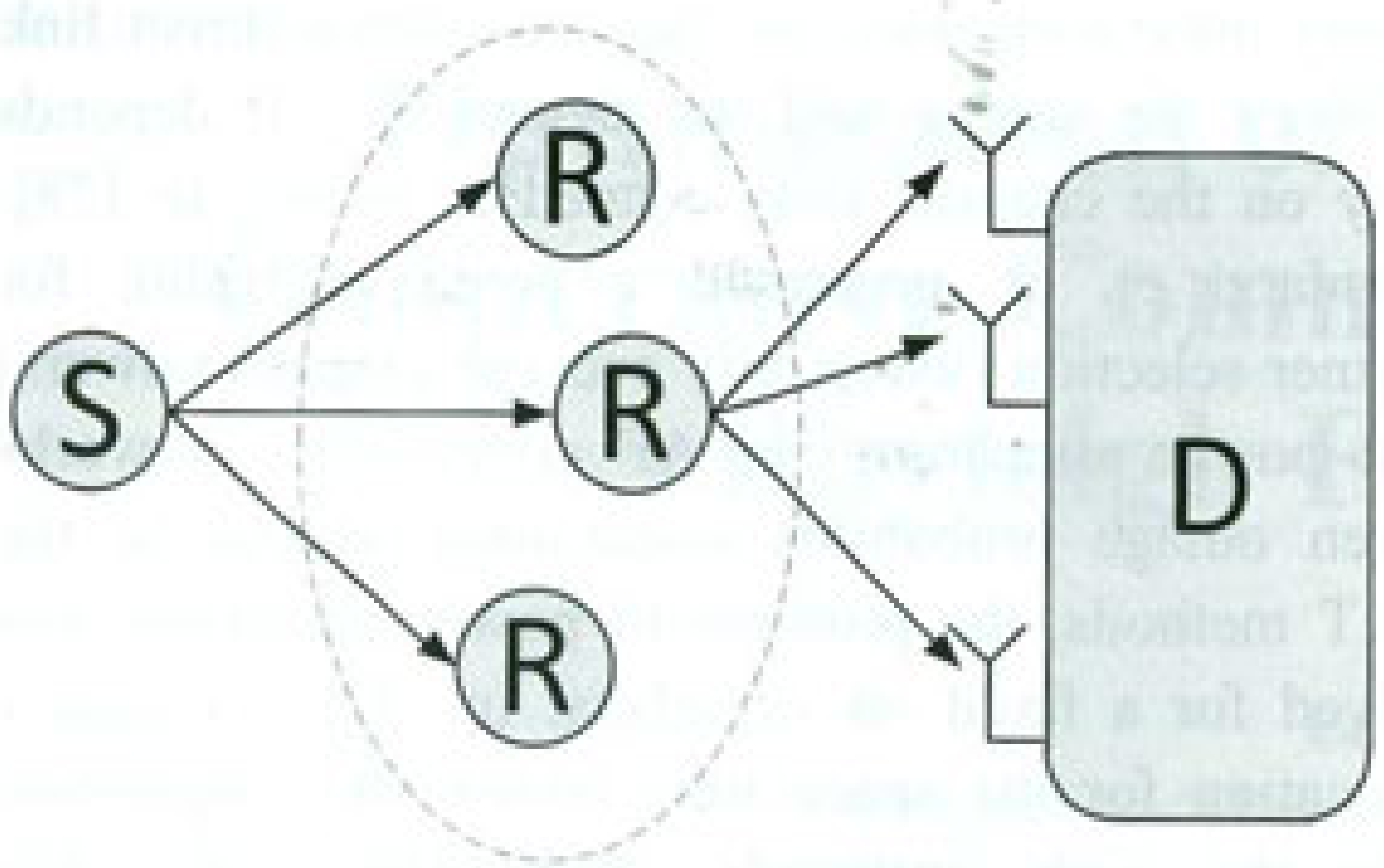

Figure 1. The cooperative MIMO network with partial relay selection.

Taking into account the effect of relay positions on the system performance, in this paper, we consider a linear network, where all nodes are placed on a straight line as shown in Fig. 2. This model is widely accepted in the literature in investigating cooperative networks [27, 33-35]. Denoting d_k as the distance between the source and relay k, then the distance between the k th relay and the destination will be $1-d_k$ if the distance between the source and the destination is normalized by one. In this study, we deal with a network in which relays are grouped into clusters where the chosen criterion is based on their geographical proximity (or equivalently average SNRs). Therefore, it is reasonable to assume that $\{d_k\}_{k=1}^{K} = d, \forall k$. Under Rayleigh fading channels, the instantaneous channel powers of the link $s \to r_k$ and $r_k \to d$, $|h_{sr_k}|^2$ and $|h_{r_k d}|^2$, are exponentially distributed random variables. Under the assumption of independent and identical distributed Rayleigh fading channels, correspondingly, their average values are denoted by $E\{|h_{sr_k}|^2\} = d^{-\eta}$ and $E\{|h_{r_k d}|^2\} = (1-d)^{-\eta}$, where η is the path-loss exponent of wireless channels and $E\{.\}$ is the expectation operator. The value of η varies from 2 (in free space environments) to 5 or 6 (in shadowed areas or constructed in-building scenarios) [36, 37].

In the first timeslot, the source transmits its signal, x_s, with transmit power P_s which is received by relays due to the broadcast nature of wireless channels. The received signal at relay k is mathematically written as follows:

$$y_{sk} = \sqrt{P_s} h_{sk} x_s + z_k, \quad k = 1, \dots, K, \tag{1}$$

where h_{sk} denotes the channel coefficient between the source and relay k. And z_k is the additive white Gaussian noise having the variance of N_0.

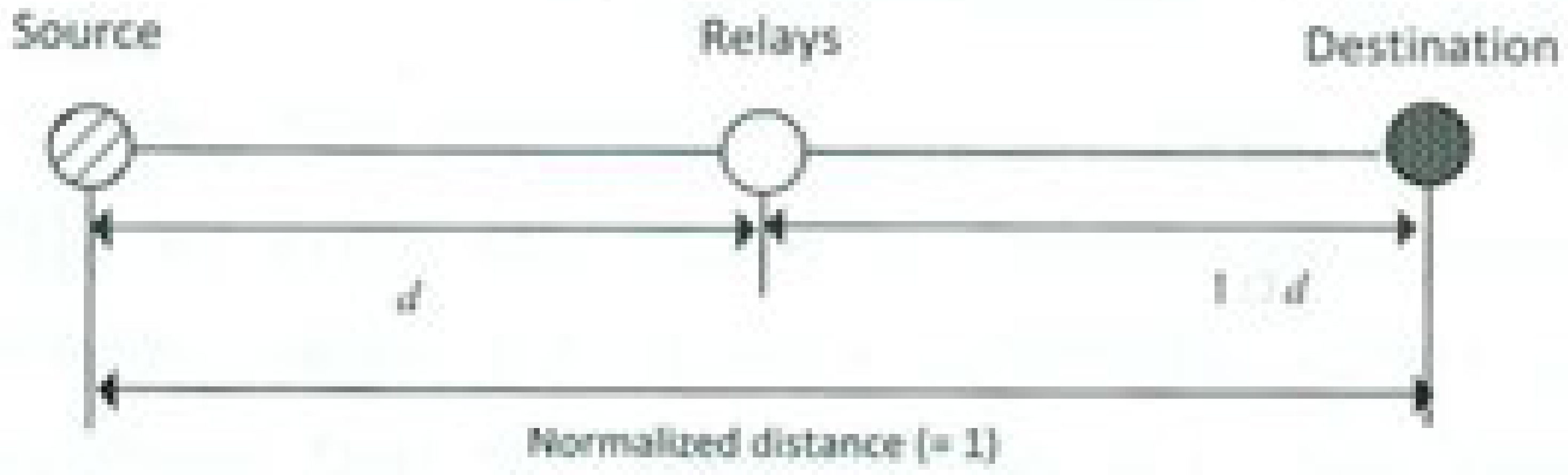

Figure 2. A linear network.

In the second timeslot, only the relay having the highest instantaneous SNR of the first hop, indexed by b, will forward the received signal to the destination [17]. According to [9], two processing techniques, i.e. AF and DF, could be employed at the relays. However, in this paper, we focus on the AF protocol due to its simplicity. Under amplify-and-forward relaying, the best relay amplifies the received signal with an amplifying factor, G, given by [10]

$$\mathrm{G} = \sqrt{\frac{P_r}{P_s |h_{sb}|^2 + \mathrm{N}_0}}. \tag{2}$$

The purpose of the amplifying factor, G, is to assure that the best relay will transmit the received signal toward the destination with the allowed transmit power, P_r, regardless of the power of the received signal. It also avoids the saturation effect at the amplifying stage at the transmitters of relays. With G in hand, the received signal at the destination can be written as

$$y_{bn} = \sqrt{P_r} h_{bn} \mathrm{G} y_{sb} + z_n. \tag{3}$$

At the destination, maximal-ratio combining technique is used [36], thus the instantaneous channel power of the second hop is given by

$$\beta_2 = \sum_{n=1}^{N} |h_{bn}|^2. \tag{4}$$

Then the equivalent end-to-end SNR of the dual-hop AF is [10, 38]

$$\gamma_{e2e} = \frac{P_s \beta_1 P_r \beta_2}{P_s \beta_1 + P_r \beta_2 + 1}, \tag{5}$$

where

$$\beta_1 = \max_{k=1,\dots,K} |h_{sk}|^2. \tag{6}$$

III. OUTAGE ANALYSIS

Before dealing with the problem of power allocation, we derive the system outage probability, considered as one of the most important performance measures for wireless communication systems. For the system under consideration, the outage event occurs since the mutual information between the source and the destination, i.e., $I = \frac{1}{2}\log_2(1+\gamma_{e2e})$, is less than the desired spectral efficiency R in bps/Hz, where the pre-log term of $1/2$ is included to reflect the fact that the source-to-destination data transmission via relays occupies two time slots. Mathematically speaking, the system outage probability is written as

$$\begin{aligned} P_o &= \Pr\left\{\frac{1}{2}\log_2(1+\gamma_{e2e}) \le R\right\} \\ &= \Pr\{\gamma_{e2e} \le \gamma_{th}\} \end{aligned} \tag{7}$$

where $\gamma_{th} = 2^{2R} - 1$. It seems dificult to further analyze the system with the exact form of (6) [39]. To circumvent the difficulty in the exact analysis, we use the following approximation at high SNRs for the end-to-end SNR of the relaying link, namely

$$\gamma_{e2e} \approx \min(P_s \beta_1, P_r \beta_2), \tag{8}$$

which is based upon the fact that the relaying link is dominated by the weakest of the first and second hops. This approximation has been employed in several research works dealing with performance analysis of amplify-and-forward relaying systems, such as [40-43]. Consequently, using (8), (7) can be re-written as

$$\begin{aligned} P_o &= 1 - \Pr(P_s \beta_1 > \gamma_{th}) \Pr(P_r \beta_2 > \gamma_{th}) \\ &= 1 - \Pr\left(\beta_1 > \frac{\gamma_{th}}{P_s}\right) \Pr\left(\beta_2 > \frac{\gamma_{th}}{P_r}\right) \end{aligned} \tag{9}$$

Since $|h_{bn}|^2$ is independent and identically distributed (i.i.d.) exponential random variable with parameter $(1-d)^{-\eta}$ for all n, it is obvious that β_2 is a central chi-squared random variable with $2N$ degrees of freedom and the probability density function (PDF) of β_2 can be defined [44] as follows:

$$f_{\beta_2}(\gamma) = \frac{\gamma^{N-1}}{(N-1)!\,\overline{\gamma}_2^{N}} e^{-\frac{\gamma}{\overline{\gamma}_2}}. \tag{10}$$

where $\overline{\gamma}_2 = (1-d)^{-\eta}$. And its relative cumulative probability function, $F_{\beta_2}(\gamma) = \Pr(\beta_2 \le \gamma)$, is obtained by integrating (10) between 0 and g as follows:

$$\begin{aligned} F_{\beta_2}(\gamma) &= \int_0^{\gamma} f_{\beta_2}(\gamma) d\gamma \\ &= 1 - e^{-\frac{\gamma}{\overline{\gamma}_2}} \sum_{u=0}^{N-1} \frac{1}{u!}\left(\frac{\gamma}{\overline{\gamma}_2}\right)^{u} \end{aligned}. \tag{11}$$

If all the links from the source are statistically independent, using theory of order statistic [44], the PDF and CDF of β_1 are given, respectively

$$f_{\beta_1}(\gamma) = \sum_{k=1}^{K} (-1)^{(k-1)} \binom{K}{k} \frac{k}{\overline{\gamma}_1} e^{-\frac{\gamma k}{\overline{\gamma}_1}}, \tag{12}$$

$$\begin{aligned} F_{\beta_1}(\gamma) &= \Pr(\beta_1 \le \gamma) \\ &= \int_0^{\gamma} f_{\beta_1}(\gamma) d\gamma \\ &= \sum_{k=1}^{K} (-1)^{(k-1)} \binom{K}{k} \left(1 - e^{-\frac{k\gamma}{\overline{\gamma}_1}}\right) \end{aligned} \tag{13}$$

where $\overline{\gamma}_1 = d^{-\eta}$. Finally, replacing (11) and (13) into (10), we obtain the end-to-end outage probability of the system with $\Pr(\beta_m > \gamma) = 1 - \Pr(\beta_m \le \gamma)$ as

$$\begin{aligned} P_o = 1 - &\left[1 - \sum_{k=1}^{K} (-1)^{(k-1)} \binom{K}{k} \left(1 - e^{-\frac{k}{\overline{\gamma}_1}\frac{\gamma_{th}}{P_s}}\right)\right] \\ &\times \left(e^{-\frac{\gamma_{th}/P_r}{\overline{\gamma}_2}} \sum_{u=0}^{N-1} \frac{1}{u!}\left(\frac{\gamma_{th}/P_r}{\overline{\gamma}_2}\right)^{u}\right) \end{aligned} \tag{14}$$

Using the relationship $\sum_{k=1}^{K}(-1)^{(k-1)}\binom{K}{k}=1$ [45] (14) simplifies as

$$P_o=1-\left[\sum_{k=1}^{K}(-1)^{(k-1)}\binom{K}{k}e^{-\frac{k}{\bar{\gamma}_1}\frac{\gamma_{th}}{P_s}}\right]\times\left[e^{-\frac{\gamma_{th}/P_r}{\bar{\gamma}_2}}\sum_{u=0}^{N-1}\frac{1}{u!}\left(\frac{\gamma_{th}/P_r}{\bar{\gamma}_2}\right)^{u}\right]. \quad (15)$$

IV. POWER OPTIMIZATION PROBLEM

In this section, we are interested in finding optimal power allocation among the source and the relays to maximize the end-to-end mutual information subject to the total transmitted power constraints. Stated another way, this is equivalent to obtaining the optimal power allocation strategy that minimizes the system outage probability (OP). The problem of power optimization is outlined as follows: for a given total transmit power, (P), we find the optimal ratio, $\frac{P_s}{P_r}$, which makes the end-to-end OP minimize. Mathematically speaking, we have

$$\min_{P_r,P_s} P_o(P_s,P_r) \text{ subject to } \begin{cases} P_s+P_r=P \\ P_s\geq 0 \\ P_r\geq 0 \end{cases}. \quad (16)$$

In particular, equation (16) is of the form

$$\min_{P_s,P_r} 1-\left[\sum_{k=1}^{K}(-1)^{k-1}\binom{K}{k}e^{-\frac{k}{\bar{\gamma}_1}\frac{\gamma_{th}}{P_s}}\right]\times\left[e^{-\frac{\gamma_{th}/P_r}{\bar{\gamma}_2}}\sum_{u=0}^{N-1}\frac{1}{u!}\left(\frac{\gamma_{th}/P_r}{\bar{\gamma}_2}\right)^{u}\right]$$
$$\text{subject to } \begin{cases} P_s+P_r=P \\ P_s\geq 0 \\ P_r\geq 0 \end{cases}. \quad (17)$$

With the current form of (17), it is difficult to process further whithout using numerical methods. Therefore, to get around this problem, instead of direct solving (17), we use its equivalent approximation for tractable analysis. In particular, based on the equivalent average SNR of each hop, an equivalent approximation of (17) is then given by

$$\min_{\rho} P_{out}=1-e^{-\gamma_{th}\left(\frac{1}{P_s\lambda_1}+\frac{1}{P_r\lambda_2}\right)} \text{ subject to } \begin{cases} P_s+P_r=P \\ P_s\geq 0 \\ P_r\geq 0 \end{cases}, \quad (18)$$

where l_m with m Î $\{1,2\}$ is defined as

$$\lambda_m=\int_0^{+\infty}\beta_m f_{\beta_m}(\beta)d\beta \quad (19)$$

Substituting (12) into (19), we have [44]

$$\begin{aligned}\lambda_1&=\int_0^{+\infty}\beta f_{\beta_1}(\beta)d\beta\\&=\int_0^{+\infty}\beta\sum_{k=1}^{K}(-1)^{(k-1)}\binom{K}{k}\frac{k}{\bar{\gamma}_1}e^{-\frac{\beta k}{\bar{\gamma}_1}}d\beta \quad (20)\\&=d^{-\eta}\sum_{k=1}^{K}\frac{1}{k}\end{aligned}$$

Likewise, the average equivalent of the second hop, $\bar{g}_2$, can be calculated as

$$\begin{aligned}\lambda_2&=\int_0^{+\infty}\beta f_{\beta_2}(\beta)d\beta\\&=\int_0^{+\infty}\beta\frac{\beta^{N-1}}{(N-1)!\bar{\gamma}_2^{N}}e^{-\frac{\beta}{\bar{\gamma}_2}}d\beta\end{aligned} \quad (21)$$

Using integral by parts, we have

$$\lambda_2=N(1-d)^{-\eta}.$$

To that end, taking into account the characteristics of the exponential function, i.e. the exponential function is a mono-increasing function, thus the optimal problem in (18) can be equivalently reduced to

$$\max-\gamma_{th}\left(\frac{1}{P_s\lambda_1}+\frac{1}{P_r\lambda_2}\right) \text{ subject to } \begin{cases} P_s+P_r=P \\ P_s\geq 0 \\ P_r\geq 0 \end{cases} \quad (22)$$

To solve the problem, we first form the Lagrangian function [46]

$$L=-\gamma_{th}\left(\frac{1}{P_s\lambda_1}+\frac{1}{P_r\lambda_2}\right)+\mu\left(P_s+P_r-P\right) \quad (23)$$

Applying the Lagrange condition yields three equations with three unknowns as

$$\frac{\gamma_{th}}{\lambda_1 P_s^2} + \mu = 0, \quad (24a)$$

$$\frac{\gamma_{th}}{\lambda_2 P_r^2} + \mu = 0, \quad (24b)$$

$$P_s + P_r = P, \quad (24c)$$

where $\mu \in \mathbf{R}_1$. We now solve for P_s and P_r in the Lagrange equations. First, by subtracting the first equation from the second equation, we arrive at

$$\frac{P_s}{P_r} = \sqrt{\frac{\lambda_2}{\lambda_1}}. \quad (25)$$

Next, from (25) and the constraint equation, i.e. (24c), the optimum power allocation solutions can be shown, after some manipulation, to be given by

$$P_s^* = P\left[1 + \sqrt{\frac{\lambda_1}{\lambda_2}}\right]^{-1}, \quad (26a)$$

$$P_r^* = P\left[1 + \sqrt{\frac{\lambda_2}{\lambda_1}}\right]^{-1}. \quad (26b)$$

Recalling that $\lambda_1 = d^{-\eta}$ and $\lambda_2 = (1-d)^{-\eta}$, we have

$$P_s^* = P\left[1 + \left(\frac{1-d}{d}\right)^{\eta/2}\right]^{-1} \quad (27a)$$

$$P_r^* = P\left[1 + \left(\frac{d}{1-d}\right)^{\eta/2}\right]^{-1}. \quad (27b)$$

Notice that we have ignored the constraints that P_s and P_r are positive so that we can solve the problem using Lagrange's theorem [47]. However, there is only one solution to the Lagrange equations, and the solution is positive. Therefore, if a solution exists for the problem with positivity constraints on the variables P_s and P_r, then this solution must necessarily be equal to above solution obtained by ignoring the positivity constraints.

From (27), it suffices to say that the solution of the above optimization problem is a function of distance between the source and the relays and the path-loss exponent. Besides, it can be seen that the solution is very simple. Therefore, the calculation of power allocation can be done before the real data transmission is started with the assumption that average channel state information (CSI) of all channels is available at the source and relays.

V. NUMERICAL RESULTS AND DISCUSSION

In this section, Monte Carlo simulations are carried out to verify the analytical results. For brevity, BPSK modulation is used in all numerical results. Table 1 provides network and channel setting parameters used in the numerical results.

Table 1. Simulation parameters

Number of relays, K	2
Number of antennas at the destination, N	2
Path loss exponent, η	3
The desired spectra efficiency, R	1

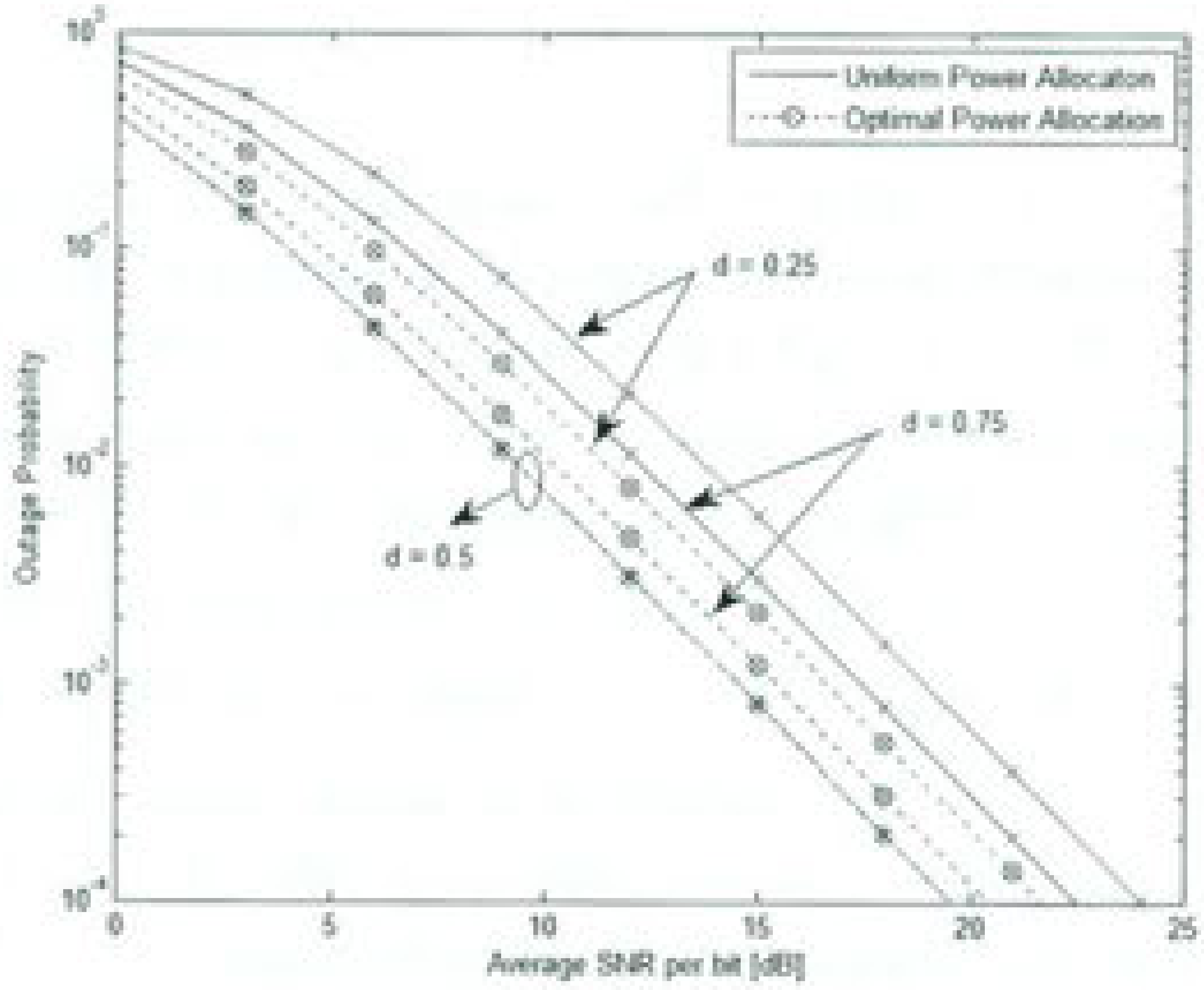

Figure 3. Effects of relay positions on the system performance, "x" denotes simulation results.

In Fig. 3, we first investigate the relay position on the system performance by varying the distance between the source to the relay, i.e. d = [0.25 0.50.75]. For ease of comparison, we also plot the outage probability of the system operating on non-optimal power (uniform power allocation) mode as a baseline. It is clearly observed that when the relay nodes are in between the source and the destination,

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