

Outage Performance of Multi-Antenna Cooperative Incremental Relaying Systems in the absence of Direct Link

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Abstract—Motivated by recent works involving multi-antenna fixed relay cooperation, this paper investigates the performance of fixed multi-antenna relay networks, where the source node communicates with the destination node via two fixed multi-antenna relays (infrastructure based relays). To improve the system spectral efficiency, incremental relaying technique is applied. The exact closed-form expression for the end-to-end system outage probability has been derived. It is numerically demonstrated that the system performance will achieve the best performance when one relay locates near the central point of the link from source to destination while the other locates near the destination. A performance comparison between the proposed system and the conventional system using fixed three transmission time slots is also represented and it is concluded that the proposed system outperforms the other in terms of spectral efficiency.

Index Terms—adaptive decode-and-forward, Rayleigh fading, outage probability, multi-hop communication, incremental relaying, fixed relay, multi-antenna relay.

I. INTRODUCTION

Cooperative communications [1]–[5] is an important technique for achieving spatial diversity in distributed wireless networks. The basic idea of cooperative networks is to utilize the coordination among participants to transmit the source signal to the destination; thereby, the destination can receive multiple independent copies of the same signal to achieve diversity gain. Thus, it is more reliable for the destination to receive the transmitted information of the source over wireless fading channels, since from statistical point of view, the probability that all independent channel links to the destination being in deep fade at the same time is low.

So far, several cooperative protocols have been presented in [5]–[7], where a user helps other users to forward information, i.e. it may decode the received information and then forward the decoded symbol (referred to as DF) or just simply amplify and forward it (referred to as AF). Correspondingly, various relay antenna configurations that compatible with the above protocols have been considered. Early work mainly focuses on the single-antenna relay system, where each relay only carries a single antenna, so multiple relays could construct

a virtual antenna array that offers diversity gain similar to that offered by the traditional MIMO system [8]–[10]. Recently, there has been many research works involving the using multiple antennas at relay nodes. However, employing multiple antennas on mobile user terminals is not really attractive and feasible due to space, complexity and cost constraints [3]. For this reason, the moving of multiple antennas to the fixed relay node (infrastructure based relay) is an interesting solution and very recently, gained high attention [11]–[16]. Benefits of multi-antenna fixed relay networks have been demonstrated in [11], [17].

Motivated by all the above, in this paper, we propose and analyze a two hop DF relaying system over Rayleigh fading channels with two multi-receive-antenna fixed relay nodes where the link between two relay nodes will act as an incremental link, and this system is referred to as incremental adaptive DF (IADF) system. In this work, we aim at deriving the exact closed-form expression of the end-to-end system outage probability and evaluating the impact of system and channel parameters including the number of antennas, the positions of relays on the system performance. Besides, the performance comparison in terms of spectral efficiency between the proposed system (IADF system) and the conventional system using fixed three transmission time slots referred as adaptive DF (ADF) system in this work also was shown.

The remainder of this paper is organized as follows. In Section II, we propose the system model under consideration, including IADF and ADF systems. In Section III, we derive the exact closed-form expressions of the end-to-end outage probability for the IADF and ADF system. Simulation results and some discussions are presented in Section IV and finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

As shown in Fig. 1, the proposed system includes a single-antenna source node s , a single-antenna destination node d , and two multi-receive-antenna relay nodes, r_1 and r_2 , that help

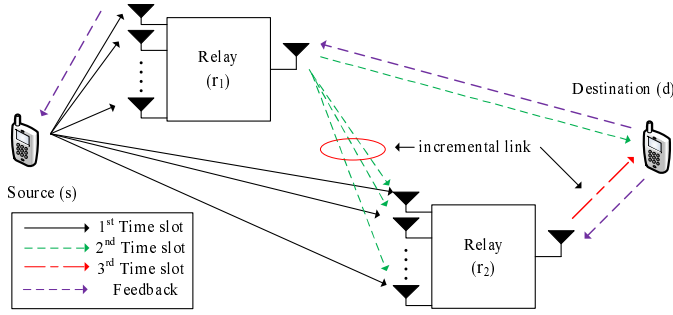


Fig. 1. The system under consideration.

the communication between s and d . Specially, the direct link (between s and d) is omitted while the link between two relay nodes together with the link from one of the two relay nodes to destination will act as an incremental transmission link. The relay nodes r_1 and r_2 are assumed to be equipped with M and N half-duplex receive antennas, respectively. In this system, r_1 and r_2 forward signals towards the destination following the adaptive decode-and-forward (DF) protocol. With this protocol, by setting a common signal-to-noise ratio (SNR) threshold at relays (r_1 and r_2) and destination (d), it has been assumed that the end-to-end system target rate is achieved and therefore, the relay and destination nodes likely decode signals correctly if their received SNR are above the pre-determined threshold [14], [18].

The end-to-end communication in the system occurs in two phases: broadcasting phase and incremental phase, where the first phase includes two orthogonal time slots (the first and second time slot). In the first time slot, s transmits signals to r_1 and r_2 , then the relays r_1 and r_2 receive the signals by using the maximal-ratio-combining (MRC) technique. If the SNR at r_1 after coherently combining signals is above Θ^1 , (i.e. *active*), r_1 will decode and retransmit the re-encoded signals to d and r_2 in the second time slot, otherwise, it will keep silent (i.e. *inactive*). At the end of the second time slot, if d can decode signals successfully, i.e. its received SNR is above Θ , a new transmission phase will be started after d sends an acknowledgment message to r_1 and r_2 . Otherwise, d is outage (i.e. the system is outage) and r_1 , r_2 , and s will be notified this as well. In this situation, the incremental phase will be used. In particular, the destination will request the help of r_2 and the third time slot should be used. We assume that there are available feedback channels from d to r_1 and r_2 and from r_1 to s . After receiving the feedback signal from d , r_2 will check the combined SNR, if it is above Ω , r_2 will forward the re-encoded signals to d (*active*), otherwise, it keeps idle

¹In adaptive DF protocol, setting correctly SNR threshold for achieving system target rate is important. Here, we assume that the target rate of the overall system is R . In the first phase, the end-to-end transmission experience in two time slots, so the transmission rate between nodes should be $2R$ and the adaptive DF SNR threshold is set to be $\Theta = 2^{2R} - 1$ applied at r_1 and d . If the incremental phase is used, the corresponding SNR threshold is $\Omega = 2^{3R} - 1$ that will be applied at r_2 and d [14].

(*inactive*)². At d , the received signal from r_2 will be decoded if the SNR is above Ω , otherwise, an outage event occurred.

In this work, it is assumed that every channel between nodes experiences slow, flat, Rayleigh fading. Let us denote $\bar{\gamma}_{ij}$ as the average SNR between node i and j , where $(i, j) \in \{(s, r_1), (s, r_2), (r_1, r_2), (r_1, d), (r_2, d)\}$. The average SNR of channels between different pairs of nodes can be written as $\bar{\gamma}_{ij} = \frac{\rho}{(2l_{ij}/l_{sd})^\varphi}$ [14], [15], where φ is the path loss exponent, l_{ij} is the distance between node i and j , which is normalized by the reference distance $l_{sd}/2$, ρ represents the average SNR at the reference point. For convenience, we also use the notation $\lambda_{ij} = 1/\bar{\gamma}_{ij}$. The modulated signals from s , r_1 , r_2 are transmitted with unit power. Furthermore, r_1 , r_2 and d are assumed to have perfect knowledge of full channel state information (CSI).

It is worth noting here that at a glance, our proposed system is similar to that of [14]; however, the proposed operation strategy in our system is completely different from and better than that in [14] in terms of spectral efficiency. Therefore, it should be shown a comparison between our proposed system (IADF system) and that in [14] with using selection combining (SC) technique at destination which referred to as the ADF system in this work. For convenience, we briefly introduce the ADF system here. In ADF system, the end-to-end communication always occurs in three time slots. The transmission in the first time slot is identical to that in IADF system. In the second time slot, r_1 transmits the re-encode signals to r_2 and d if its MRC combined SNR is above Ω , otherwise it remains idle. Relay r_2 coherently combines the buffered copies of signals received in the first time slot and any signals that are received in the second time slot. The relay r_2 adaptively decodes and forwards the signal with the SNR threshold Ω to d in the third time slot. After that, the destination d select the best signal from r_1 and r_2 for decoding, and this is the different point compared to the system investigated in [14]. This assumption is due to the fact that in IADF system, the destination node d receives signals in the way, which is similar to the applying SC technique. Hence, for a fair comparison, the ADF system should use the SC technique at destination as well.

III. PERFORMANCE ANALYSIS

A. IADF System

We first consider the IADF system. Following the system operation strategy and the law of total probability [19], the end-to-end system outage probability expression P_{out}^{IADF} can be written as

$$P_{out}^{IADF} = \Pr[r_1^{int}] \{ \Pr[r_2^{int}|r_1^{int}] + \Pr[r_2^{act}|r_1^{int}] P_o[r_2^{act}] \} + \Pr[r_1^{act}] P_o[r_1^{act}] \times \{ \Pr[r_2^{int}|r_1^{act}] + \Pr[r_2^{act}|r_1^{act}] P_o[r_2^{act}] \} \quad (1)$$

where $r_i^{int/act}$, $i = \{1, 2\}$ denotes the event that r_i is either inactive or active, $\Pr[r_2^{int/act}|r_1^{int/act}]$ is the probability of

²Note that in the second time slot, r_2 will also coherently combine the signals from r_1 with the ones from s in the first time slot.

the events that r_2 is inactive/active, when r_1 is inactive/active, $P_o[r_1^{act}]$ is the system outage probability conditioned on the active state of r_1 or r_2 . Next, we derive all the discrete terms in (1).

To do so, we first introduce a general expression that can be used to derive many individual terms in (1) relying on the observing that all the links $s \rightarrow r_1$, $s \rightarrow r_2$ and $r_1 \rightarrow r_2$ are equivalent to a single-input multi-output (SIMO) system. Now, considering a SIMO system with L independent and identical (i.i.d) diversity branches, using MRC technique. Denote $\bar{\gamma}$ as the average SNR on each receive antenna, the probability distribution function (PDF) of MRC combined SNR is given by [20]

$$f_\gamma(\gamma) = \frac{\gamma^{L-1}}{(L-1)!\bar{\gamma}^L} e^{-\frac{\gamma}{\bar{\gamma}}}. \quad (2)$$

So the outage probability can be easily obtained as [21]

$$\begin{aligned} I(\bar{\gamma}, L, \chi) &= \int_0^\chi f_\gamma(\gamma) d\gamma \\ &= \frac{\gamma(L, \lambda\chi)}{(L-1)!}, \end{aligned} \quad (3)$$

where $\lambda = 1/\bar{\gamma}$, χ is the SNR threshold determining the outage event and $\gamma(\cdot, \cdot)$ is the lower incomplete gamma function defined in [22, eq. 8.2.1]. Having the general result in (3), we readily derive many terms in (1).

Considering the term $\Pr[r_1^{int}]$, this is the outage probability of a SIMO system with M receive antenna, average channel SNR $\bar{\gamma}_{sr_1}$ and outage threshold Θ . Hence, from (3), we have

$$\Pr[r_1^{int}] = I(\bar{\gamma}_{sr_1}, M, \Theta) \quad (4)$$

and

$$\begin{aligned} \Pr[r_1^{act}] &= 1 - \Pr[r_1^{int}] \\ &= \tilde{I}(\bar{\gamma}_{sr_1}, M, \Theta). \end{aligned} \quad (5)$$

The probability $\Pr[r_2^{int}|r_1^{int}]$ only depends on the link $s \rightarrow r_2$ and is equivalent to the outage probability of a SIMO system with N receive antennas, average channel SNR $\bar{\gamma}_{sr_2}$ and outage threshold Ω , so we have

$$\Pr[r_2^{int}|r_1^{int}] = I(\bar{\gamma}_{sr_2}, N, \Omega) \quad (6)$$

and

$$\begin{aligned} \Pr[r_2^{act}|r_1^{int}] &= 1 - \Pr[r_2^{int}|r_1^{int}] \\ &= \tilde{I}(\bar{\gamma}_{sr_2}, N, \Omega). \end{aligned} \quad (7)$$

To calculate the term $\Pr[r_2^{int}|r_1^{act}]$, note that this is the probability of the event that the SNR at r_2 after coherently combining signals from r_1 and s is lower than Ω . Mathematically, this term can be expressed as

$$\Pr[r_2^{int}|r_1^{act}] = \Pr[\gamma_{sr_2} + \gamma_{r_1 r_2} < \Omega]. \quad (8)$$

Following the same procedure as in [15], we have

$$\begin{aligned} \Pr[r_2^{int}|r_1^{act}] &= \frac{\gamma(N, \lambda_{r_1 r_2} \Omega)}{(N-1)!} - \frac{(\lambda_{r_1 r_2})^N e^{-\lambda_{sr_2} \Omega}}{(N-1)!} \times A \\ &= J(\bar{\gamma}_{sr_2}, \bar{\gamma}_{r_1 r_2}, N, \Omega) \end{aligned} \quad (9)$$

where $\lambda_{sr_2} = 1/\bar{\gamma}_{sr_2}$, $\lambda_{r_1 r_2} = 1/\bar{\gamma}_{r_1 r_2}$ as defined early and

$$A = \sum_{k=0}^{N-1} \frac{(\lambda_{sr_2})^k}{k!} \sum_{l=0}^k \binom{k}{l} \Omega^l (-1)^{k-l} \times B, \quad (10)$$

$$B = \begin{cases} (\lambda_{r_1 r_2} - \lambda_{sr_2})^{-N-k+l} \\ \quad \times \gamma(N+k-l, (\lambda_{r_1 r_2} - \lambda_{sr_2}) \Omega), & \text{if } \lambda_{r_1 r_2} \neq \lambda_{sr_2} \\ \frac{\Omega^{N+k-l}}{N+k-l}, & \text{if } \lambda_{r_1 r_2} = \lambda_{sr_2} \end{cases}. \quad (11)$$

So, from (9), we obtain

$$\begin{aligned} \Pr[r_2^{act}|r_1^{act}] &= 1 - \Pr[r_2^{int}|r_1^{act}] \\ &= \tilde{J}(\bar{\gamma}_{sr_2}, \bar{\gamma}_{r_1 r_2}, N, \Omega). \end{aligned} \quad (12)$$

To complete the calculation of (1), we must solve the term $P_o[r_1^{act}]$. Now, we consider the term $P_o[r_1^{act}]$, this is the outage event of the link $r_1 \rightarrow d$ with the outage threshold Θ . Because this is a single-channel Rayleigh fading with average received SNR $\bar{\gamma}_{r_1 d}$ (this is because $\bar{\gamma}_{r_1 d}$ is the average channel SNR and r_1 transmits signals with unit power), we easily obtain

$$\begin{aligned} P_o[r_1^{act}] &= 1 - \exp(-\lambda_{r_1 d} \Theta) \\ &= Y(\bar{\gamma}_{r_1 d}, \Theta), \end{aligned} \quad (13)$$

where $\lambda_{r_1 d} = 1/\bar{\gamma}_{r_1 d}$ as introduced early. Similarly, we also have

$$\begin{aligned} P_o[r_2^{act}] &= 1 - \exp(-\lambda_{r_2 d} \Omega) \\ &= Y(\bar{\gamma}_{r_2 d}, \Omega). \end{aligned} \quad (14)$$

Up to here, all the terms in (1) are solved. By putting all of the above results into (1), we obtain the closed-form expression of P_{out}^{IADF} , which can be expressed as

$$\begin{aligned} P_{out}^{IADF} &= I(\bar{\gamma}_{sr_1}, M, \Theta) \\ &\times [I(\bar{\gamma}_{sr_2}, N, \Omega) + \tilde{I}(\bar{\gamma}_{sr_2}, N, \Omega) \times Y(\bar{\gamma}_{r_2 d}, \Omega)] \\ &+ \tilde{I}(\bar{\gamma}_{sr_1}, M, \Theta) \times Y(\bar{\gamma}_{r_1 d}, \Theta) \\ &\times \left[J(\bar{\gamma}_{sr_2}, \bar{\gamma}_{r_1 r_2}, N, \Omega) \right. \\ &\quad \left. + \tilde{J}(\bar{\gamma}_{sr_2}, \bar{\gamma}_{r_1 r_2}, N, \Omega) \times Y(\bar{\gamma}_{r_2 d}, \Omega) \right]. \end{aligned} \quad (15)$$

B. ADF System

For comparing to the performance of IADF systems, we provide here the outage expression of ADF systems, given by [15]

$$\begin{aligned} P_{out}^{ADF} &= \Pr[r_1^{int}, r_2^{int}] \\ &+ \Pr[r_1^{int}, r_2^{act}] \times P_o[r_1^{int}, r_2^{act}] \\ &+ \Pr[r_1^{act}, r_2^{int}] \times P_o[r_1^{act}, r_2^{int}] \\ &+ \Pr[r_1^{act}, r_2^{act}] \times P_o[r_1^{act}, r_2^{act}], \end{aligned} \quad (16)$$

where $r_1^{int/act}$ and $r_2^{int/act}$ denote the events that r_1 and r_2 are inactive/active, respectively, $P_o[r_1^{int/act}, r_2^{int/act}]$ is the outage probabilities conditioned on the corresponding state of r_1 and r_2 . Note that all the terms in (16) have already been solved

in [15] (or can be obtained by following the derivation of (15)) except the term $P_o[r_1^{act}, r_2^{act}]$ because in their system, the destination node d uses MRC technique while in this work, the SC technique is applied. Mathematically, the probability $P_o[r_1^{act}, r_2^{act}]$ can be written as

$$P_o[r_1^{act}, r_2^{act}] = \Pr[\max(\gamma_{r_1 d}, \gamma_{r_2 d}) < \Omega]. \quad (17)$$

Due to the independence of the link $r_1 \rightarrow d$ and $r_2 \rightarrow d$, (17) can be calculated as

$$\begin{aligned} P_o[r_1^{act}, r_2^{act}] &= \Pr[\gamma_{r_1 d} < \Omega, \gamma_{r_2 d} < \Omega] \\ &= \Pr[\gamma_{r_1 d} < \Omega,] \times \Pr[\gamma_{r_2 d} < \Omega,] \\ &= [1 - \exp(-\lambda_{r_1 d} \Omega)] \times [1 - \exp(-\lambda_{r_2 d} \Omega)] \\ &= Y(\bar{\gamma}_{r_1 d}, \Omega) \times Y(\bar{\gamma}_{r_2 d}, \Omega). \end{aligned} \quad (18)$$

Putting (18) into (16) and combining with the results derived in [15], the expression of P_{out}^{ADF} can be rewritten as

$$\begin{aligned} P_{out}^{ADF} &= I(\bar{\gamma}_{sr_1}, M, \Omega) \times I(\bar{\gamma}_{sr_2}, N, \Omega) \\ &\quad + I(\bar{\gamma}_{sr_1}, M, \Omega) \times \tilde{I}(\bar{\gamma}_{sr_2}, N, \Omega) \times Y(\bar{\gamma}_{r_2 d}, \Omega) \\ &\quad + \tilde{I}(\bar{\gamma}_{sr_1}, M, \Omega) \times J(\bar{\gamma}_{sr_2}, \bar{\gamma}_{r_1 r_2}, N, \Omega) \times Y(\bar{\gamma}_{r_1 d}, \Omega) \\ &\quad + \tilde{I}(\bar{\gamma}_{sr_1}, M, \Omega) \times \tilde{J}(\bar{\gamma}_{sr_2}, \bar{\gamma}_{r_1 r_2}, N, \Omega) \\ &\quad \times Y(\bar{\gamma}_{r_1 d}, \Omega) \times Y(\bar{\gamma}_{r_2 d}, \Omega). \end{aligned} \quad (19)$$

Up to here, the expressions of P_{out}^{ADF} and P_{out}^{IADF} have been solved in closed form. In next section, numerical results and discussion will be shown.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, some selected simulation results are provided to verify the analytical results and to show the performance of IADF systems under many scenarios. Besides, some comparisons of the performance between ADF and IADF systems are also represented. We consider a linear system, where all the nodes locate in a straight line with assumptions that s and d locate at (0,0) and (0,100), respectively, while r_1 and r_2 move between s and d .

In Fig. 2, the comparison of outage performance of ADF and IADF systems is shown. It is clear from this figure that IADF system outperforms ADF about 2 dB with $\varphi = 3$, $R = 1$, $l_{sr_1} = 30$, $l_{sr_2} = 60$, and $M = N = 2$. Furthermore, these plots show an excellent agreement between analytical and simulation results.

Figs. 3 and 4 show the effect of relative distance among nodes and the number of antennas employed on relays on the system. It can be concluded that in general case, the best system performance is achieved, when r_1 locates near the central point of the link $s \rightarrow d$ and r_2 locates near d , all the other positions of relays will substantially degrade the performance. The increasing the number of antennas on relays together with shifting them toward d will improve the system performance. These conclusions are similar to that in [14], [15], where their system is referred to as ADF systems in our work (note that in their works, the destination d uses MRC technique; however the using SC at d only degrades slightly the performance and does not affect the conclusions).

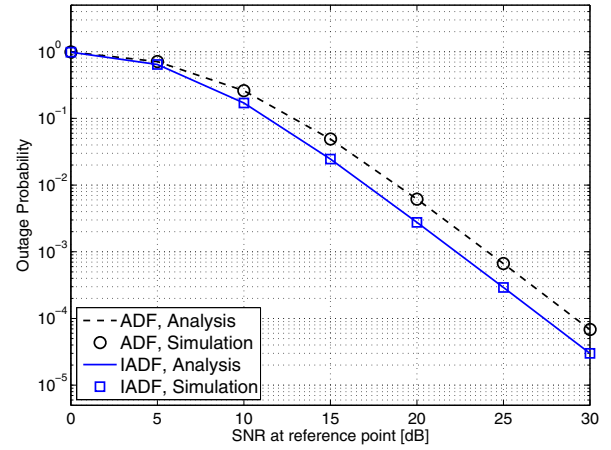


Fig. 2. Outage probability comparison between ADF and IADF systems with $\varphi = 3$, $R = 1$, $l_{sr_1} = 30$, $l_{sr_2} = 60$, $M = N = 2$.

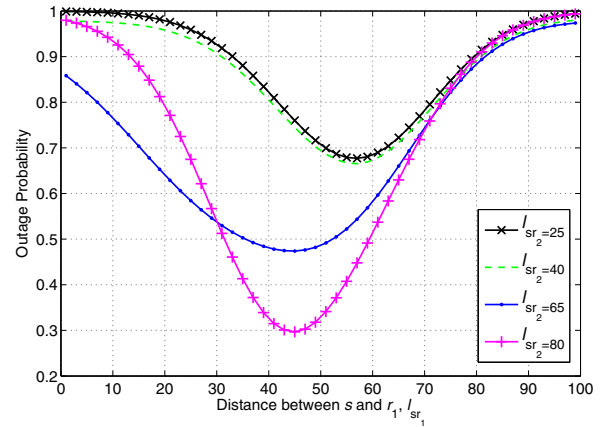


Fig. 3. Outage probability versus the distance between s and r_1, r_2 with $\rho = 5$ dB, $\varphi = 3$, $R = 1$, $M = N = 2$ for IADF system.

It is well-known that incremental cooperative relaying systems will attain much higher spectral efficiency as compared to the others such as fixed DF or adaptive DF systems by only using the additional time slot (the third time slot in this work) if needed [18]. So it is meaningful to compare the spectral efficiency between ADF and IADF systems as shown in Fig. 5. From this figure, it is obviously observed that in terms of spectral efficiency, the IADF systems outperform the ADF system but at a cost of the feedback channels in the IADF system.

V. CONCLUSION

In this paper, we have studied multi-receive-antenna fixed relay networks with incremental adaptive decode-and-forward relaying scheme (referred as IADF) and shown a comparison with the same system without using incremental relaying phase (using fixed three transmission time slots instead and referred as ADF). Specially, the direct link (between the source and destination) is omitted while the link between two

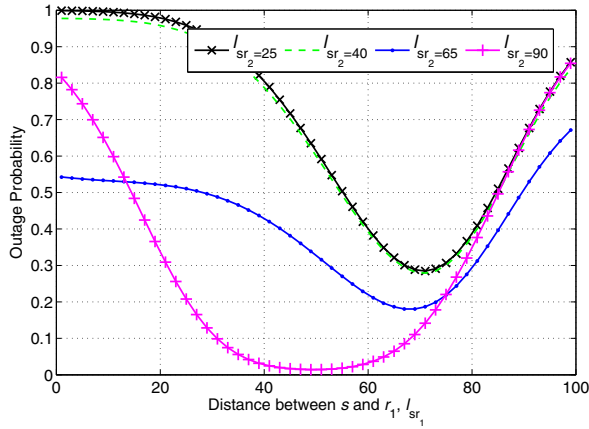


Fig. 4. Outage probability versus the distance between s and r_1, r_2 with $\rho = 5$ dB, $\varphi = 3$, $R = 1$, $M = N = 5$ for IADF system.

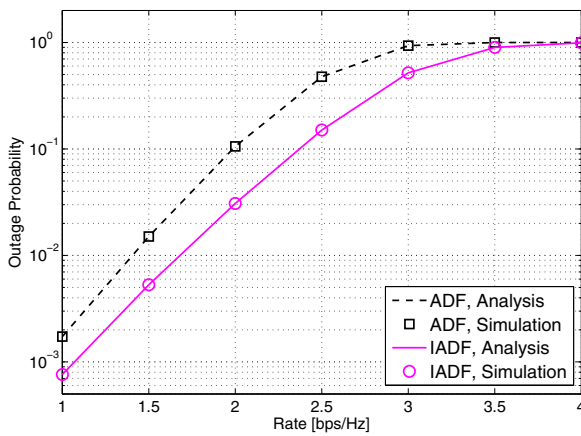


Fig. 5. Spectral efficiency comparison between ADF and IADF systems with $\rho = 20$ dB, $\varphi = 3$, $l_{sr1} = 40$, $l_{sr2} = 70$, $M = N = 2$.

relays is present in the two systems. With IADF systems, the exact closed-form expression of the end-to-end system outage probability was obtained. The effect of the relay positions and the number of antennas on relays on the system performance was represented. It is concluded that the system will provide the best performance when relay 1 locates near the central point between the source and destination while the relay 2 locates near the destination. It is interesting to show that ADF systems have the same characteristics. The comparison in terms of spectral efficiency between two systems was represented as well, and as expected, IADF systems outperforms ADF systems for the same network and channel settings.

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