Distributed Transmit-Antenna Selection Scheme for Relaying Systems with Selection Combining

Diana C. González, Daniel B. da Costa, and José Cândido S. Santos Filho

***Abstract*— The use of multiple antennas at the node terminals of relay networks potentially improves cooperative diversity in terms of both reliability and spectral efficiency. A simple practical approach to exploit such potentials at the transmitter side is to appropriately select one out of the many transmit antennas available. In this work, we propose and analyze a dual-hop fixed-gain amplify-and-forward relaying system based on a distributed transmit antenna selection scheme, along with a selection-combining treatment of the direct and relaying signals at the destination. We derive analytical lower and upper bounds for the outage probability of the proposed scheme in single-fold integral form. In addition, asymptotic expressions for these bounds at high signal-to-noise ratio are obtained in closed form. Our results reveal that the proposed scheme achieves full diversity order. More importantly, the underlying distributed strategy of transmit antenna selection is shown to perform closely to the costly optimal centralized solution.**

***Keywords*— Cooperative diversity, outage probability, selection combining, transmit antenna selection.**

I. Introduction

Several studies have suggested the combined use of multiple-input–multiple-output (MIMO) techniques and cooperative communications in order to improve the reliability of wireless systems, by fully exploiting multipath signal diversity [1], [2], [3]. However, in practice, the implementation of such multiantenna systems is constrained by restrictions in power, complexity, and antenna size. Realistic schemes usually limit the use of multiple antennas to specific relay network nodes, or strongly restrict the total number of antennas [4].

As well known, the impairments of multipath fading on communications can be alleviated by using both transmit as well as receive diversity techniques. At the transmitter side, these techniques include, for example, space-time coding and transmit antenna selection (TAS); at the receiver side, they include many diversit-combining schemes such as maximum-ratio combining (MRC) and selection combining (SC) [2]. Many dual-hop networks with TAS at the source and MRC at the destination have been recently proposed and analyzed in the literature (see, for example, [4], [5], and the references therein). In particular, the TAS/MRC combination is widely used, because TAS reduces the complexity and power requirements at the transmitter—although it is not an optimal beamforming technique [6]—and because MRC is the optimal linear combining technique [7]. On the other hand, the MRC implementation requires many channel estimations and complex hardware resources, since each antenna needs a separate receiver chain [8]. In contrast, SC needs no channel estimation and only requires a single receiver chain. Thus, knowing that both combining techniques achieve the same diversity order, SC represents an excellent trade-off between complexity and performance.

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Very few studies have considered the TAS/SC combination in relay networks, including the following. In [2], the end-to-end performance is analyzed for a regenerative (multi-hop, decode-and-forward) MIMO relaying system. This system assumes that the receivers have perfect channel state information (CSI) in order to apply TAS at the transmission, and then the best-antenna information is fed back to the transmitter using partial CSI. Karaevli *et al.* [9] determined the performance of a cooperative system with a single relay and multiple antennas at the source and destination. In this system, TAS is employed to choose the transmit antenna with the largest end-to-end SNR at the source and relay, by using feedbacks from destination. Finally, in [3], a performance comparison between TAS/MRC and TAS/SC schemes in MIMO relay networks is performed. It was found that the SNR advantage of TAS/MRC over TAS/SC in balanced hops does not depend on the number of relays.

In systems with TAS, a feedback usually exists that informs the transmitter the best antenna to select. This feedback contains CSI of various links of the system. That is, the channel knowledge improves the overall system performance. The required bits of feedback information varies depending on the number of source and destination antennas [10].

In this work, we capitalize on the distributed antenna selection (DAS) scheme proposed in [5] for a relaying network under a dual-hop, fixed-gain, amplify-and-forward (AF) scenario with a multiple-antenna source and single-antenna relay and destination. On the other hand, differently from [5], which uses MRC, we propose and analyze the use of SC at the destination, in order to reduce the system complexity. A remarkable feature of the TAS scheme used here is the requirement of CSI with low and constant delay/feedback overhead, regardless of the number of transmit antennas [5]. We derive analytical lower and upper bounds for the outage probability of the proposed scheme in single-fold integral form. In addition, asymptotic expressions for these bounds at high signal-to-noise ratio are obtained in closed form. Our results reveal that the proposed scheme achieves full diversity order. More importantly, the underlying distributed strategy of transmit antenna selection is shown to perform closely to the costly optimal centralized solution.

Throughout this paper, $f_Z(\cdot)$ denotes the probability density function (PDF) of a generic random variable Z, $E[\cdot]$ denotes expectation, and $\Pr(\cdot)$ denotes probability.

II. System Model and Antenna Selection Scheme

A. System Model

We consider a half-duplex dual-hop communication system containing a source S with N_t antennas, a single-antenna fixed-gain AF relay R, and a single-antenna destination D. Furthermore, we consider that the noise term in all of the nodes is an additive white Gaussian noise (AWGN) with mean power N_0, and that all of the links undergo independent flat Rayleigh fading. The terminals are assumed to operate on a time-division multiple access basis.

Before data transmission, TAS is employed at S, in order to find the best transmit antenna that maximizes the end-to-end SNR. After that, a conventional two-slots cooperative transmission takes place. As mentioned before, this system is similar to that presented in [5], but differs from that in the sense that the direct- and relaying-link signals are now combined at D by means of SC, instead of MRC. Accordingly, the end-to-end SNR from the ith antenna at S to D can be written as

$$\gamma_i = \max\left(\gamma_{SD,i}, \frac{\gamma_{SR,i}\gamma_{RD}}{\gamma_{RD}+C}\right), \tag{1}$$

where $\gamma_{SD,i} \triangleq \frac{P_S}{N_0}|h_{SD,i}|^2$, $\gamma_{SR,i} \triangleq \frac{P_S}{N_0}|h_{SR,i}|^2$, $\gamma_{RD} \triangleq \frac{P_R}{N_0}|h_{RD}|^2$, and $C = 1+\bar{\gamma}_{SR}$, with $\bar{\gamma}_{SR} = E[\gamma_{SR,i}]$. In these expressions, $|h_{SD_i}|^2$, $|h_{SR_i}|^2$, and $|h_{RD}|^2$ denote the channel power coefficients of the links from the ith antenna at S to D, from the ith antenna at S to R, and from R to D, respectively; and P_S and P_R denote the transmit powers at S and R, respectively. As commonly adopted in the literature [5], we assume an homogeneous network, in which $E[\gamma_{SR,i}] = \bar{\gamma}_{SR}$ and $E[\gamma_{SD,i}] = \bar{\gamma}_{SD}$, for any $i = 0, \ldots, N_t$, that is, all links from each antenna at S to D (or to R) undergo identically distributed fading conditions. Finally, the fixed-gain relaying factor G at R is adjusted according to [11]

$$G^2 = \mathrm{E}\left[\frac{P_R}{P_S|h_{SR_i}|^2 + N_0}\right]. \tag{2}$$

B. Antenna Selection Scheme

The optimal selection criterion for TAS/SC chooses the i^*th transmit antenna that maximizes the end-to-end SNR, i.e.,

$$i^* = \arg\max_i\left[\gamma_i\right]. \tag{3}$$

Although optimal, such a scheme entails a large amount of delay and feedback overhead, due to the full system CSI required for decision.

Alternatively, a much simpler suboptimal and distributed solution is provided in [5]. In this DAS scheme, the local CSI available at S is exploited to its furthest extent in order to assist the decision, incurring a negligible delay and feedback overhead. In that work, the DAS concept is motivated and supported by an important inequality involving the end-to-end SNR of the MRC reception and the SNRs of the various links [5, Eq. (4)]. Here, since we use SC, the corresponding motivation and support is given by the following inequality [12], [13]

$$\gamma_i < \max\left[\gamma_{SD,i}, \gamma_{SR,i}\min\left[\frac{\gamma_{RD}}{C}, 1\right]\right] \triangleq \widetilde{\gamma}_i. \tag{4}$$

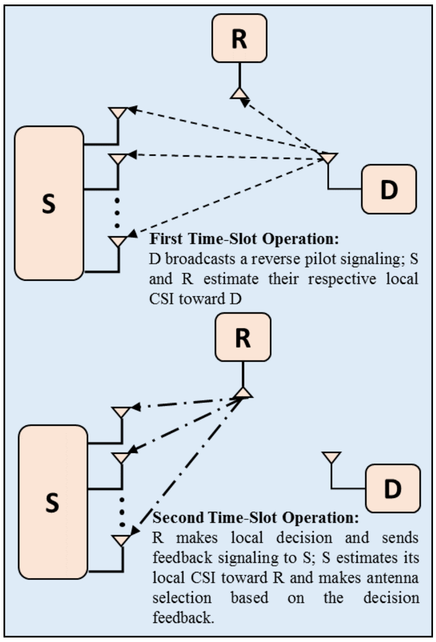

Fig. 1. Operation of the DAS scheme (reproduced from [5, Fig. 1]).

The DAS scheme is performed in two time slots [5], as shown in Fig. 1. In the first time slot, D sends to R and S a 1-bit reverse pilot signaling. Then, R and S use this bit to estimate their respective local CSIs γ_{RD} and $\gamma_{SD,i}$. In the second time slot, R compares its local CSI with C, which may produce two outputs: $\gamma_{RD} \geq C$ or $\gamma_{RD} < C$. In the first case, R sends to S a 1-bit message "1" to indicate that $\gamma_{RD} \geq C$ and, in this case, $\gamma_{SD,i}$ and $\gamma_{SR,i}$, which are available at S ($\gamma_{SR,i}$ can be readily estimated from the 1-bit message), are sufficient to apply the selection rule $\max\widetilde{\gamma}_i$. In the second case, R sends to S a 1-bit message "0" to indicate that $\gamma_{RD} < C$. In this case, from (4), the application of $\max\widetilde{\gamma}_i$ would depend on the additional knowledge of γ_{RD}, which is unavailable at S. Then, a suboptimal decision can be attained from the available CSI as proposed by [4], by performing the solely maximization of $\gamma_{SD,i}$. In summary, the transmit-antenna selection rule of the proposed DAS/SC scheme is given as follows:

$$i^* = \begin{cases} \bar{i} = \arg\max_i\left[\max\left[\gamma_{SD,i}, \gamma_{SR,i}\right]\right] & \gamma_{RD} \geq C \\ \underline{i} = \arg\max_i\left[\gamma_{SD,i}\right] & \gamma_{RD} < C \end{cases} \tag{5}$$

The great advantage of DAS/SC over other TAS/SC schemes is its greatly reduced delay/feedback overhead. In conventional TAS schemes, $O(\log N_t)$ bits of feedback information are required, as shown in [10], [4], and [7]. In contrast, in the DAS scheme, only a 2-bit pilot/feedback signaling is required, at the cost of some additional hardware complexity at the source.

III. Outage Analysis

The outage probability is the probability that the maximum mutual information between source and destination drops below a predefined spectral efficiency R_0 (bits/s/Hz). In our system, it can be formulated as

$$P_{out}^{\text{DAS}} = \underbrace{\Pr\left(\gamma_{RD} \geq C, \max\left[\gamma_{SD,\bar{i}}, \frac{\gamma_{SR,\bar{i}}\gamma_{RD}}{\gamma_{RD}+C}\right] < z \triangleq 2^{2R_0}-1\right)}_{P_1} + \underbrace{\Pr\left(\gamma_{RD} < C, \max\left[\gamma_{SD,\underline{i}}, \frac{\gamma_{SR,\underline{i}}\gamma_{RD}}{\gamma_{RD}+C}\right] < z\right)}_{P_2}. \tag{6}$$

Considering the extreme complexity of obtaining an exact closed-form expression for the above outage probability, we derive instead lower and upper bounds of it, based on the inequality in (4). The analysis is performed separately for each term P_1 and P_2. We begin by deriving a lower bound for P_1, which can be expressed as

$$\begin{aligned} P_1 &> \Pr\left(\gamma_{RD} \geq C, \max\left[\gamma_{SD,\bar{i}}, \gamma_{SR,\bar{i}} \min\left[\frac{\gamma_{RD}}{C}, 1\right]\right] < z\right) \\ &\overset{(a)}{=} \Pr\left(\gamma_{RD} \geq C, \max_i\left[\max\left[\gamma_{SD,i}, \gamma_{SR,i}\right]\right] < z\right) \triangleq P_1^{\text{LB}} \\ &= \Pr\left(\gamma_{RD} \geq C\right) \Pr\left(\gamma_{SD,i} < z\right)^{N_t} \Pr\left(\gamma_{SR,i} < z\right)^{N_t} \\ &= e^{-\frac{C}{\bar{\gamma}_{RD}}} \left(1 - e^{-\frac{z}{\bar{\gamma}_{SD}}}\right)^{N_t} \left(1 - e^{-\frac{z}{\bar{\gamma}_{SR}}}\right)^{N_t}. \end{aligned} \tag{7}$$

where, in step (a), we apply the DAS rule given in (5) for $\gamma_{RD} \geq C$. Focusing on the high-SNR behavior, an asymptotic analysis of P_1^{LB} is performed. As a result, at high SNR, (7) can be expressed, after some algebraic manipulations, as

$$P_1^{\text{LB}} \simeq e^{-\frac{C}{\bar{\gamma}_{RD}}} \left(\frac{z^2}{\bar{\gamma}_{SD}\bar{\gamma}_{SR}}\right)^{N_t}. \tag{8}$$

In a similar way, an upper bound for P_1 can be obtained as [12][1]

$$\begin{aligned} P_1 &< \Pr\left(\gamma_{RD} \geq C, \max\left[\gamma_{SD,\bar{i}}, \frac{\gamma_{SR,\bar{i}}}{2} \min\left[\frac{\gamma_{RD}}{C}, 1\right]\right] < z\right) \\ &< \Pr\left(\gamma_{RD} \geq C, \max\left[\frac{\gamma_{SD,\bar{i}}}{2}, \frac{\gamma_{SR,\bar{i}}}{2} \min\left[\frac{\gamma_{RD}}{C}, 1\right]\right] < z\right) \\ &= \Pr\left(\gamma_{RD} \geq C, \max_i\left[\max\left[\gamma_{SD,i}, \gamma_{SR,i}\right]\right] < 2z\right) \triangleq P_1^{\text{UB}} \\ &\simeq e^{-\frac{C}{\bar{\gamma}_{RD}}} \left(\frac{(2z)^2}{\bar{\gamma}_{SD}\bar{\gamma}_{SR}}\right)^{N_t}. \end{aligned} \tag{9}$$

We now focus on the analysis of the term P_2. Using again the inequality in (4) and the DAS rule in (5) for $\gamma_{RD} < C$, a lower bound for P_2 is obtained as

$$\begin{aligned} P_2 &> \Pr\left(\gamma_{RD} < C, \max\left[\gamma_{SD,\underline{i}}, \gamma_{SR,\underline{i}} \min\left[\frac{\gamma_{RD}}{C}, 1\right]\right] < z\right) \\ &= \Pr\left(\gamma_{RD} < C, \max\left[\gamma_{SD,\underline{i}}, \frac{\gamma_{SR,\underline{i}}\gamma_{RD}}{C}\right] < z\right) = P_2^{\text{LB}} \\ &= \Pr\left(\gamma_{RD} < C, \max\left[\max_j\left[\gamma_{SD,j}\right], \frac{\gamma_{SR,i}\gamma_{RD}}{C}\right] < z\right). \end{aligned} \tag{10}$$

Using the concepts of probability theory presented in [4], P_2^{LB} can be further obtained in a single-fold integral form as

$$\begin{aligned} &P_2^{\text{LB}} \\ &= \int_0^C f_{\gamma_{RD}}(x) \Pr\left(\max\left[\max_j\left[\gamma_{SD,j}\right], \frac{x}{C}\gamma_{SR,i}\right] < z\right) dx \\ &= \int_0^1 \frac{C}{\bar{\gamma}_{RD}} e^{-\frac{Cy}{\bar{\gamma}_{RD}}} \Pr\left(\max\left[\max_j\left[\gamma_{SD,j}\right], y\gamma_{SR,i}\right] < z\right) dy \\ &= \int_0^1 \frac{C}{\bar{\gamma}_{RD}} e^{-\frac{Cy}{\bar{\gamma}_{RD}}} \Pr\left(\max_j\left[\gamma_{SD,j}\right] < z\right) \Pr\left(y\gamma_{SR,i} < z\right) dy \\ &= \left(1 - e^{-\frac{z}{\bar{\gamma}_{SD}}}\right)^{N_t} \underbrace{\int_0^1 \frac{C}{\bar{\gamma}_{RD}} e^{-\frac{Cy}{\bar{\gamma}_{RD}}} \left(1 - e^{-\frac{z}{y\bar{\gamma}_{SR}}}\right) dy}_{\varphi} \end{aligned} \tag{11}$$

In the appendix, we have derived a simple high-SNR asymptotic expression for φ. Accordingly, after some algebraic manipulations, P_2^{LB} can be asymptotically expressed as

$$\begin{aligned} P_2^{\text{LB}} &\simeq \left(\frac{z}{\bar{\gamma}_{SD}}\right)^{N_t} \left(\frac{z}{\bar{\gamma}_{SR}\mu_2}\left(\ln z - \ln\bar{\gamma}_{RD} - \psi(1) - \psi(2)\right)\right) \\ &= \frac{z^{N_t+1}}{(\bar{\gamma}_{SD})^{N_t}\bar{\gamma}_{RD}\mu_2}\left(\ln\frac{z}{\bar{\gamma}_{RD}} - \psi(1) - \psi(2)\right) \end{aligned} \tag{12}$$

where $\mu_2 \triangleq \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}}$. By following a similar procedure, an upper bound for P_2 can be written as [13]

$$\begin{aligned} P_2 &< \Pr\left(\gamma_{RD} < C, \max\left[\gamma_{SD,\underline{i}}, \gamma_{SR,\underline{i}} \min\left[\frac{\gamma_{RD}}{C}, 1\right]\right] < 2z\right) \\ &= P_2^{\text{UB}}, \end{aligned} \tag{13}$$

which is seen to have an identical form to P_2^{LB} in (10), with z replaced by $2z$. Accordingly, an asymptotic expression for P_2^{UB} can be readily obtained from (12) as

$$P_2^{\text{UB}} \simeq \frac{(2z)^{N_t+1}}{(\bar{\gamma}_{SD})^{N_t}\bar{\gamma}_{RD}\mu_2}\left(\ln\frac{2z}{\bar{\gamma}_{RD}} - \psi(1) - \psi(2)\right) \tag{14}$$

The derived exact and asymptotic bounds for P_1 and P_2 can be now added as in (6) to yield corresponding bounds for P_{out}. In particular, asymptotic lower and upper bounds at high SNR are obtained respectively as

$$P_{out}^{\text{DAS,LB}} \simeq \begin{cases} e^{-\frac{1}{\mu_2}}\left(\frac{z^2}{\bar{\gamma}_{SD}\bar{\gamma}_{SR}}\right)^{N_t} + \frac{z^{N_t+1}}{(\bar{\gamma}_{SD})^{N_t}\bar{\gamma}_{RD}\mu_2} \\ \times\left(\ln\frac{z}{\bar{\gamma}_{RD}} - \psi(1) - \psi(2)\right) & \text{if } N_t = 1 \\ \frac{z^{N_t+1}}{(\bar{\gamma}_{SD})^{N_t}\bar{\gamma}_{RD}\mu_2} \\ \times\left(\ln\frac{z}{\bar{\gamma}_{RD}} - \psi(1) - \psi(2)\right) & \text{if } N_t \geq 2 \end{cases} \tag{15}$$

[1] Note that the exact expression of P_1^{UB} has been omitted. Similarly to P_1^{LB}, this is given by (7), but with z replaced by $2z$.

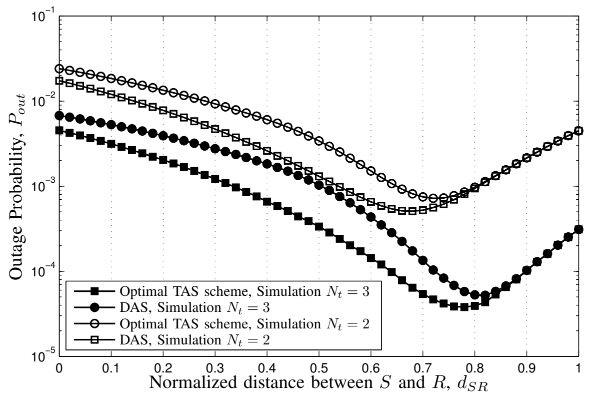

Fig. 2. Comparison of different TAS/SC schemes in terms of outage probability (P = 10 dB).

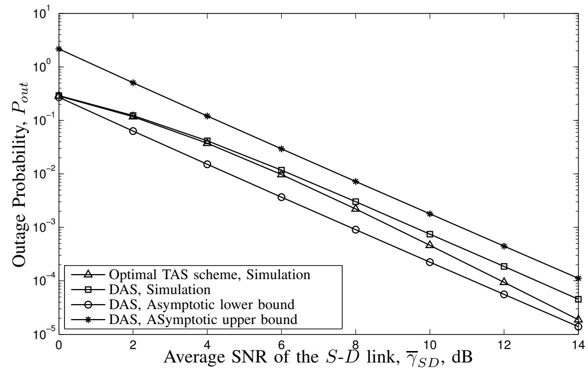

Fig. 3. Outage probability versus average SNR of the $S \rightarrow D$ link for different TAS/SC schemes ($d_{SR} = 0.7$, $N_t = 2$).

$$P_{out}^{\text{DAS,UB}} \simeq \begin{cases} e^{-\frac{1}{\mu_2}} \left(\frac{(2z)^2}{\overline{\gamma}_{SD}\overline{\gamma}_{SR}} \right)^{N_t} + \frac{(2z)^{N_t+1}}{(\overline{\gamma}_{SD})^{N_t}\overline{\gamma}_{RD}\mu_2} \\ \times \left(\ln \frac{2z}{\overline{\gamma}_{RD}} - \psi(1) - \psi(2) \right) & \text{if } N_t = 1 \\ \frac{(2z)^{N_t+1}}{(\overline{\gamma}_{SD})^{N_t}\overline{\gamma}_{RD}\mu_2} \\ \times \left(\ln \frac{2z}{\overline{\gamma}_{RD}} - \psi(1) - \psi(2) \right) & \text{if } N_t \geq 2. \end{cases} \tag{16}$$

Finally, from (15) and (16), it can be seen that DAS/SC exhibits a full diversity order of $N_t + 1$, the same achieved by DAS/MRC [5]. This, allied to the simplicity of SC, renders the proposed DAS/SC scheme highly attractive in practice.

IV. Numerical Results and Discussions

In this section, we assess the outage performance of the proposed DAS/SC scheme by investigating some representative examples and scenarios. Monte Carlo simulation is performed to provide the exact performance as well as to support our analytical bounds. Without loss of generality, we assume that the end-to-end spectral efficiency is R_0 = 1 bit/s/Hz and that the path loss exponent is $\beta = 4$. We also assume that the channel mean power is proportional to $d^{-\beta}$, with d being the distance between the transceivers. The distance between S and D is normalized to unity, as in [5].[2]

Fig. 2 presents the outage performance versus d_{SR} for both DAS/SC and optimal TAS/SC schemes using two and three antennas at the source. From this figure, we observe that the outage performance of DAS/SC improves when the relay is closer to destination, approaching the performance of optimal TAS. This behavior is due to the probability of $\gamma_{RD} \geq C$ being higher when d_{SR} is close to unity, thus causing the DAS selection rule being indeed optimal during most of the time. A similar behavior is reported for DAS/MRC in [5]. In particular, when $N_t = 2$, the DAS/SC is observed to achieve its best performance with $d_{SR} \simeq 0.7$; when $N_t = 3$, the best performance is observed with $d_{SR} \simeq 0.8$. In both cases, the outage probability of DAS/SC is seen to be very close to that of the optimal TAS/SC scheme.

[2]Again, as in [5], we assume a linear network topology, in which S and R transmit with the same SNR P, and $d_{SD} = d_{SR} + d_{RD}$, where d_{SD}, d_{SR}, and d_{RD} represent the distance of the links $S \rightarrow D$, $S \rightarrow R$, and $R \rightarrow D$, respectively. The corresponding average link SNRs can be formulated as $\overline{\gamma}_{SD} = P d_{SD}^{-\beta}$, $\overline{\gamma}_{SR} = P d_{SR}^{-\beta}$, and $\overline{\gamma}_{RD} = P d_{RD}^{-\beta}$.

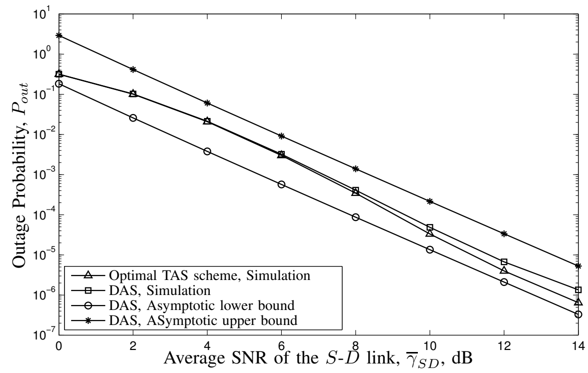

Fig. 4. Outage probability versus average SNR of the $S \rightarrow D$ link for different TAS/SC schemes ($d_{SR} = 0.75$, $N_t = 3$).

We now address two representative scenarios in order to assess the outage performance of DAS while varying the average SNR. The distance values used were established based on the results of several Monte Carlo simulations, which confirmed the observation from Fig. 2 that, for relays placed at $0.6 - 0.8$, the outage performance of DAS/SC is improved and close to the optimal TAS/SC scheme. In other words, the relay has been positioned to comply with these best-performance cases. Fig. 3 depicts the outage probability of the first proposed scenario, configured with $d_{SR} = 0.7$ and $N_t = 2$, and Fig. 4 depicts a second scenario with $d_{SR} = 0.8$ and $N_t = 3$. In both scenarios, we see that the performance of the proposed DAS/SC is comparable to that of the optimal TAS/SC scheme, while widely outperforming this in terms of feedback overhead. Moreover, when compared to the corresponding cases ($d_{SR} = 0.7$, $N_t = 2$; $d_{SR} = 0.8$, $N_t = 3$) of the DAS/MRC scheme presented in [5, Figs. 3 and 4], the DAS/SC scheme proposed here represents an SNR loss of approx. 1.3 and 1.4 dB, respectively.

V. CONCLUSIONS

In this paper, we presented an analysis of the outage performance for a dual-hop fixed-gain AF relaying system that combines DAS and SC techniques for distributed transmit antenna selection and diversity exploitation. We derived closed-form expressions for lower and upper high-SNR asymptotic bounds of the outage probability. Monte Carlo simulations have been performed to support the derived analytical expressions. Our results reveal that the proposed scheme achieves full diversity order. More importantly, the underlying distributed strategy of transmit antenna selection is shown to perform closely to the costly optimal centralized solution.

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APPENDIX

Here we derive the high-SNR behavior of φ. From its definition, we have

$$\begin{aligned}\varphi &= \int_0^1 \frac{C}{\bar{\gamma}_{RD}} e^{-\frac{Cy}{\bar{\gamma}_{RD}}}\, dy - \frac{C}{\bar{\gamma}_{RD}} \int_0^1 e^{-\frac{Cy}{\bar{\gamma}_{RD}} - \frac{z}{y\bar{\gamma}_{SR}}}\, dy \\ &= \left(1 - e^{-\frac{C}{\bar{\gamma}_{RD}}}\right) - \frac{C}{\bar{\gamma}_{RD}} \underbrace{\int_0^1 e^{-\frac{Cy}{\bar{\gamma}_{RD}} - \frac{z}{y\bar{\gamma}_{SR}}}\, dy}_{\rho},\end{aligned} \quad (17)$$

where ρ can be expressed as

$$\begin{aligned}\rho &\overset{(b)}{=} 2\sqrt{\frac{z\bar{\gamma}_{RD}}{C\bar{\gamma}_{SR}}} K_1\left(2\sqrt{\frac{Cz}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right) \\ &- \int_1^\infty e^{-\frac{Cy}{\bar{\gamma}_{RD}}} \sum_{l=0}^{\infty} \frac{\left(-\frac{z}{y\bar{\gamma}_{SR}}\right)^l}{l!}\, dy \\ &\overset{(c)}{=} \left(2\sqrt{\frac{z\bar{\gamma}_{RD}}{C\bar{\gamma}_{SR}}}\right)\left(\frac{1}{2}\sqrt{\frac{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}{Cz}}\right) + \left(2\sqrt{\frac{z\bar{\gamma}_{RD}}{C\bar{\gamma}_{SR}}}\right) \\ &\times \sum_{k=0}^{\infty} \frac{\sqrt{\frac{Cz}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}}{k!(k+1)} \left(\ln\sqrt{\frac{Cz}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} - \psi(k+1) - \psi(k+2)\right) \\ &- \sum_{l=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SR}}\right)^l}{l!} \int_1^\infty y^{-l} e^{-\frac{Cy}{\bar{\gamma}_{RD}}}\, dy.\end{aligned} \quad (18)$$

Steps (b) and (c) follow from [14, eq.(3.471.9)] and [14, eq. (8.446)], respectively, where $K_1(\cdot)$ is the first-order modified Bessel function of second kind. Hence, by keeping only to the lowest-order terms in $\bar{\gamma}_{SR}$ and $\bar{\gamma}_{RD}$, ρ can be asymptotically written as

$$\begin{aligned}\rho \simeq \frac{\bar{\gamma}_{RD}}{C} + \frac{1}{2}\frac{z}{\bar{\gamma}_{SR}} \left(\ln z - \ln \bar{\gamma}_{RD} - \psi(1) - \psi(2)\right) \\ - \frac{\bar{\gamma}_{RD}}{C} e^{-\frac{C}{\bar{\gamma}_{RD}}}\end{aligned} \quad (19)$$

Finally, replacing (19) into (17), we obtain, after some algebraic manipulations, the high-SNR asymptote of φ as

$$\varphi \simeq \frac{z}{\bar{\gamma}_{SR}\mu_2} \left(\ln z - \ln \bar{\gamma}_{RD} - \psi(1) - \psi(2)\right). \quad (20)$$