Amplify-and-Forward Relaying with Optimal and Suboptimal Transmit Antenna Selection

Himal A. Suraweera, *Member, IEEE*, Peter J. Smith, *Senior Member, IEEE*, Arumugam Nallanathan, *Senior Member, IEEE*, and John S. Thompson, *Senior Member, IEEE*

***Abstract*—Antenna selection schemes offer a good complexity versus performance tradeoff for amplify-and-forward (AF) relay network implementation. In this paper, we consider a dual-hop channel state information assisted AF relay network with a direct source-destination link and investigate the performance of two antenna selection schemes (one optimal and another suboptimal). We derive analytical expressions for the systems' rate outage probabilities and the average bit error rate (BER) that match perfectly with simulation based results in the medium to high signal-to-noise ratio (SNR) regimes. We also investigate the channel capacity of the two schemes by deriving tight upper bounds. In order to gain further insights, simple high SNR approximations for the outage probability and the average BER have also been developed. Our theoretical analysis shows that the performance gap between the optimal and suboptimal schemes largely diminishes in the high SNR regime by increasing the number of antennas at the source. Since the suboptimal scheme has a near optimal performance as well as low signaling overhead compared to the optimal scheme, it seems to be a promising solution for implementing future cellular networks expecting to support relay based communications.**

***Index Terms*—Antenna selection, relay networks, amplify-and-forward, average bit error rate, channel capacity.**

I. INTRODUCTION

RELAY based systems can offer significant performance benefits, including increased spatial diversity, enhanced throughput and extended coverage [1]. As a result, future mobile broadband communication networks such as 3GPP LTE-Advanced, IEEE 802.16j and IEEE 802.16m are expected to support relay based communications [2]. Amplify-and-Forward (AF) relaying is one of the simplest techniques and uses knowledge of the source to relay channel for amplification purposes [3]. This kind of relay is widely identified as a variable gain or channel state information (CSI)-assisted relay [3], [4], [6].

Manuscript received June 29, 2010; revised December 15, 2010; accepted February 20, 2011. The associate editor coordinating the review of this paper was S. Aissa. The area editor approving it for publication was D. I. Kim.

H. A. Suraweera is with Engineering Product Development, Singapore University of Technology and Design, Singapore (e-mail: himalsuraweera@sutd.edu.sg).

P. J. Smith is with the Department of Electrical and Computer Engineering, The University of Canterbury, Private Bag 4800, Christchurch, New Zealand (e-mail: p.smith@elec.canterbury.ac.nz).

A. Nallanathan is with the Center for Telecommunications Research, King's College London, London WC2R 2LS, United Kingdom (e-mail: arumugam.nallanathan@kcl.ac.uk).

J. S. Thompson is with the Institute for Digital Communications, School of Engineering and Electronics, The University of Edinburgh, Kings Buildings, Edinburgh, United Kingdom (e-mail: john.thompson@ed.ac.uk).

Digital Object Identifier 10.1109/TWC.2011.040411.101150

The benefits of employing multiple antennas at radio terminals is now well understood. To date, a large number of papers have appeared on various aspects of multiple-input multiple-output (MIMO) AF relay systems (see for example [3], [7]–[9]). However, the improved performance gains of using MIMO processing in these systems brings a corresponding increase in hardware complexity since multiple radio frequency chains must be implemented.

Transmit antenna selection is a practical way of reducing the system complexity while achieving the full diversity order of the AF MIMO relay channel [9], [10]. In the existing point-to-point communication systems, a single transmit antenna which maximizes the signal-to-noise ratio (SNR) at the receiver output is selected [11]. However, in relay systems, selecting a single best antenna at each node (source, relay and the destination) for maximizing the end-to-end (e2e) SNR is not a trivial problem to solve[9], [10]. Finding the optimal antenna configuration that yields the maximum the e2e SNR requires regular SNR measurements on the source-destination, source-relay and relay-destination links. These SNR values must be reported to one terminal (e.g. the destination) to enable a decision to be made and then the decision must be conveyed to the source terminal. This antenna selection strategy clearly requires a significant amount of SNR estimation time slots and feedback bits.

Dual-hop networks with antenna selection techniques have been proposed in the prior literature (see for example, [9], [10], [12]–[15]). In [12], the performance of a dual-hop AF relay system with transmit antenna selection at the source and maximal ratio combining (MRC) at the destination has been investigated. In [13] and [14], a dual-hop AF MIMO relay network with the best antenna selected at the source and the destination have been considered. In [15], fast antenna selection algorithms to maximize the capacity of AF and DF MIMO relay systems have been proposed. All of the work in [12]–[15] has ignored the direct link from the source to the destination. Such an assumption reduces the complexity of the antenna selection problem in some relay network configurations since maximizing individual link SNRs separately can maximize the overall received SNR at the destination. To the best of authors' knowledge, only a few papers have considered antenna selection in relay networks those that have direct paths [9], [10]. In [9] and [10], optimal and suboptimal SNR-based transmit antenna selection rules at the source/relay nodes for the AF half-duplex MIMO relay channel have been derived.

In this paper, we consider the performance of transmit antenna selection for an AF relay system with a source-destination direct link. The system considered employs multiple antennas at the source while both the relay and the destination are equipped with a single antenna. This scenario can be directly applied to current cellular networks where the use of multiple antennas in a base station is reasonable, but the use of multiple antennas at mobile terminals and or relays may be prohibitive due to the terminal size and power constraints. Among possible antenna selection schemes in the network, we select and analytically study the rate outage probability of the optimal scheme along with another suboptimal scheme. In this suboptimal scheme, antenna selection is performed based only on the source-to-destination link channel reducing the signaling overhead compared to the optimal scheme. It should be mentioned that in this network, a suboptimal selection strategy based only on the source-relay link performs much worse than selection based only on the source-destination link, since the former has a much lower diversity order [16]. Furthermore, this also shows that not all possible suboptimal antenna selection schemes provide near optimal performance. Both the optimal and the source-destination based selection schemes achieve the highest possible diversity order of the system. To gain insights into their performance, we also derive high SNR approximations for both the optimal and the near optimal schemes. In [10], the rate outage performance of different antenna selection schemes has also been studied using a simulation based methodology. In contrast, our approach is analytically based and has the advantage of being able to show how the outage probability is affected by system and network parameters. Additionally, using the cumulative density function (cdf) expressions derived for the total received SNR, we have developed expressions for other performance measures such as the system's average bit error rate and the channel capacity. Using exhaustive Monte Carlo simulations we have confirmed the correctness of our analysis.

The rest of the paper is organized as follows. In Section II, the system model is presented. To investigate the rate outage probability, in Section III cdf expressions and high SNR approximations are derived. In Section IV, numerical results supported by simulations are presented. Finally, we conclude in Section V.

II. System Description

In the cooperative wireless network of Fig. 1, a single source, S, employs a relay, R, for information transmission to a destination, D. We assume that a direct path between S and D is also available. Thus at D, the signals received via the direct $(S-D)$ and the relayed $(S-R-D)$ paths are combined and spatial diversity gains can be obtained. We assume that S is equipped with N_t antennas while both R and D are equipped with a single antenna. This model is reasonable for a downlink mobile communication system, since the base station can be equipped with more than one antenna while the mobile stations may not be equipped with more than one antenna due to size constraints [17]–[19].

Transmission in this network is accomplished in two phases: In the first phase, S transmits its zero mean and unit variance signal x towards R and D. In the next phase, R forwards an amplified version of its received signal, y_R, to D. If S transmits using the ith antenna, $i = 1, \dots, N_t$, the received signals at D from the direct and relayed links are given by

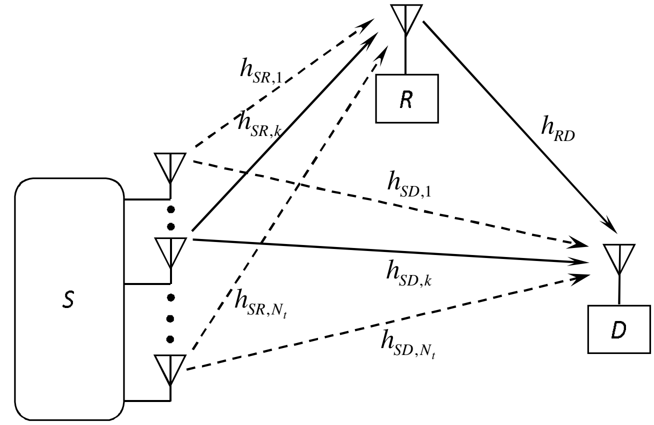

Fig. 1. System model. The source selects a single antenna, k, to communicate with the destination.

$$y_{D1} = \sqrt{P_1} h_{SD,i} x + n_{D1}, \tag{1}$$

$$y_{D2} = h_{RD} G y_R + n_{D2}, \tag{2}$$

where P_1 is the source transmit power, $h_{SD,i}$ is the channel between the ith source antenna and D, h_{RD} is the channel between R and D and G is the relay gain. All links are assumed to be subject to independent Rayleigh fading, therefore we model the channels between the ith source antenna and D, $h_{SD,i}$, for $i = 1, \dots, N_t$ as mutually independent and identically distributed (i.i.d) complex Gaussian random variables (RVs) with zero mean and average power, Ω_{SD}. Similarly the channels between the ith source antenna and R, $h_{SR,i}$, for $i = 1, \dots, N_t$ are modeled as mutually i.i.d complex Gaussian RVs with zero mean and average power, Ω_{SR}. Moreover, we model h_{RD} as an independent complex Gaussian RV with zero mean and average power, Ω_{RD}. The assumption that the coefficients $h_{SD,i}$ for $i = 1, \dots, N_t$ are identically distributed and $h_{SR,i}$ for $i = 1, \dots, N_t$ are identically distributed is reasonable since all antennas are located at the source. We denote the additive white Gaussian noise (AWGN) at D, n_D, as complex Gaussian RVs with zero mean and variance σ_D^2. The received signal at R during the first time slot, y_R, is given by

$$y_R = \sqrt{P_1} h_{SR,i} x + n_R, \tag{3}$$

where the complex AWGN at the relay is denoted by n_R with zero mean and variance, σ_R^2. In this paper we employ the so called CSI-assisted relay gain. Therefore, G is given by [4], [5]

$$G = \sqrt{\frac{P_2}{P_1 |h_{SR,i}|^2 + \sigma_R^2}}, \tag{4}$$

where P_2 is the relay transmit power.

The destination has two observations containing x and assuming that it employs a minimum mean squared error (MMSE) receiver, the e2e instantaneous SNR at D can be written as [9]

$$\gamma_i = \gamma_{SD,i} + \frac{\gamma_{SR,i} \gamma_{RD}}{\gamma_{SR,i} + \gamma_{RD} + 1}, \tag{5}$$

where $\gamma_{SD,i} = \frac{P_1}{\sigma_D^2}|h_{SD,i}|^2$, $\gamma_{SR,i} = \frac{P_1}{\sigma_R^2}|h_{SR,i}|^2$, $\gamma_{RD} = \frac{P_2}{\sigma_D^2}|h_{RD}|^2$. The e2e SNR at the destination is the summation of the direct link SNR, $\gamma_{\mathcal{D}}$, and the relayed link SNR, $\gamma_{\mathcal{R}}$.

Unfortunately (5) is not mathematically tractable. No closed-form cdf or probability density function (pdf) expressions for the e2e SNR exist. These are required to analytically study the system performance[1]. As a solution, previous literature has adopted a tight upper bound to (5) given by [4], [21] as

$$\gamma_i \leq \gamma_{SD,i} + \min\{\gamma_{SR,i}, \gamma_{RD}\}. \tag{6}$$

Our subsequent analysis relies on this upper bound and using this bound, the statistics of γ_i can be evaluated conveniently. Moreover, in Section IV we provide extensive simulation results to complement the analysis.

We now describe the transmit antenna selection schemes in detail.

Scheme (a) Optimal Antenna Selection: The optimal transmit antenna selection scheme maximizes the instantaneous post-processing SNR at D by selecting a single best antenna at the source. Mathematically, transmit antenna k is selected according to

$$k = \arg\max_i \{\gamma_i\}, \tag{7}$$

and the e2e SNR under the optimal antenna selection scheme is given by

$$\gamma = \gamma_k. \tag{8}$$

Using (6), the e2e SNR given in (8) can be tightly upper bounded as

$$\gamma_{\text{ub1}} = \gamma_{SD,k} + \min\{\gamma_{SR,k}, \gamma_{RD}\}. \tag{9}$$

This scheme can achieve the maximum possible diversity order of this system which is equal to $N_t + 1$.

Scheme (b) Antenna Selection Based on the $S-D$ Link: A simple solution to reduce the signaling overhead is to employ an alternative antenna selection scheme whose operation is based on maximizing $\gamma_{\mathcal{D}}$ [10]. In other words, we can select a single antenna at the source, based only on the $S-D$ channel information.

Consider the selection strategy based only on the $S-D$ link. Transmit antenna k is selected according to

$$k = \arg\max_i \{\gamma_{SD,i}\}. \tag{10}$$

Therefore, the e2e SNR at D is given by

$$\gamma = \gamma_{SD,k} + \frac{\gamma_{SR,k}\gamma_{RD}}{\gamma_{SR,k} + \gamma_{RD} + 1}. \tag{11}$$

Now the e2e SNR given in (11) can be tightly upper bounded as

$$\gamma_{\text{ub2}} = \gamma_{SD,k} + \min\{\gamma_{SR,k}, \gamma_{RD}\}. \tag{12}$$

Note that the diversity order of this scheme is also $N_t + 1$. This motivates us to analytically compare the performance of the system under *Schemes (a)* and *(b)*.

[1]Exact closed-form cdf/pdf expressions for $\gamma_{\mathcal{D}}$ and $\gamma_{\mathcal{R}}$ can be found. However, no closed-form expressions for the cdf/pdf of the total e2e SNR, $\gamma = \gamma_{\mathcal{D}} + \gamma_{\mathcal{R}}$, are known to exist [4], [20].

Scheme (a): An antenna selection decision can be made at D. A decision made at D needs $2N_t$ time slots and $\lceil \log_2(N_t) \rceil$ bits. This results from each of the N_t source antennas requiring two time slots to signal and D requiring $\lceil \log_2(N_t) \rceil$ bits, to convey the selected antenna index to S.

Scheme (b): D implements an antenna selection decision using N_t time slots and $\lceil \log_2(N_t) \rceil$ bits. This results from each of the N_t source antennas requiring a single time slot to signal and D requiring $\lceil \log_2(N_t) \rceil$ bits, to convey the selected antenna index to S.

In both schemes, the required feedback from D to S can be efficiently implemented in practice. For example, in many wireless systems, such as 3GPP HSPA, LTE etc use high rate feedback of CSI for selecting data transmission rates and also for identifying handover opportunities. Also, IEEE 802.16m and LTE Advanced standards address relay networks, hence signaling mechanisms established there could be exploited.

III. Performance Analysis

In this section we investigate important performance measures when transmit antenna selection *Schemes (a)* and *(b)* are implemented. This includes the outage probability, average BER and the channel capacity. We also present simple high SNR approximations.

A. Outage Probability

The instantaneous mutual information of the considered system is given by

$$\mathcal{I} = \frac{1}{2}\log_2(1+\gamma). \tag{13}$$

Note that the pre-log factor $\frac{1}{2}$ is due to the two time slots employed in the relay protocol. The outage probability can be defined as the probability that $\mathcal{I}$ falls below the required rate, R_0. Mathematically, the probability, $\Pr(\mathcal{I} < R_0)$, is given by

$$P_o = F_\gamma\left(2^{2R_0} - 1\right), \tag{14}$$

where $F_\gamma(\cdot)$ is the cdf of the e2e SNR. In order to derive the outage probability, next we will develop cdf expressions for *Schemes (a)* and *(b)*.

Scheme (a): Consider the cdf of the e2e SNR, $F_\gamma(z)$, given by

$$\Pr[\gamma < z] = \Pr\left[\gamma_{SD,k} + \frac{\gamma_{SR,k}\gamma_{RD}}{\gamma_{SR,k} + \gamma_{RD} + 1} < z\right]. \tag{15}$$

Conditioned upon $\gamma_{RD} = \upsilon$, the cdf in (15) can be rewritten as

$$F_\gamma(z) = E_\upsilon\left[\Pr\left(\gamma_{SD,k} + \frac{\gamma_{SR,k}\upsilon}{\gamma_{SR,k} + \upsilon + 1} < z\right)\right], \tag{16}$$

where $E_\upsilon[\cdot]$ denotes the expectation operator with respect to the RV υ. Using the upper bound in (9) gives the corresponding version of (16) as

$$\begin{aligned} F_{\gamma_{\text{ub1}}}(z) &= E_\upsilon\left[\Pr\left(\gamma_{SD,k} + \min(\gamma_{SR,k}, \upsilon) < z\right)\right] \qquad (17) \\ &= E_\upsilon\left[\Pr\left(\gamma_{SD,i} + \min(\gamma_{SR,i}, \upsilon) < z\right)^{N_t}\right]. \end{aligned}$$

To proceed further, we define $X = \gamma_{SD,i}$, $Y = \gamma_{SR,i}$ and $Z = X + \min(Y, \upsilon)$. Also the pdfs of $\gamma_{SD,i}, \gamma_{SR,i}$

and γ_{RD} are given by $f_{\gamma_{SD,i}}(x) = \frac{1}{\bar{\gamma}_{SD}} e^{-\frac{x}{\bar{\gamma}_{SD}}}$, $f_{\gamma_{SR,i}}(x) = \frac{1}{\bar{\gamma}_{SR}} e^{-\frac{x}{\bar{\gamma}_{SR}}}$ and $f_{\gamma_{RD}}(x) = \frac{1}{\bar{\gamma}_{RD}} e^{-\frac{x}{\bar{\gamma}_{RD}}}$, respectively where $\bar{\gamma}_{SD} = \frac{P_1 \Omega_{SD}}{\sigma_D^2}$, $\bar{\gamma}_{SR} = \frac{P_1 \Omega_{SR}}{\sigma_R^2}$ and $\bar{\gamma}_{RD} = \frac{P_2 \Omega_{RD}}{\sigma_D^2}$.

In order to obtain an expression for $F_{\gamma_{\mathrm{ub1}}}(z)$, we will first derive an expression for the cdf of the RV, Z. The cdf of Z, $F_Z(z)$, can be written as

$$\begin{aligned} F_Z(z) &= \Pr\left(X < z - \min(Y, \upsilon)\right) \\ &= \frac{1}{\bar{\gamma}_{SR}} \int_0^\infty \Pr\left(X < z - \min(y, \upsilon)\right) e^{-\frac{y}{\bar{\gamma}_{SR}}} dy. \end{aligned} \tag{18}$$

To simplify the integral in (18) let us define the two domains, $\mathcal{D}_1 = \{\min(y, \upsilon) > z\}$ and $\mathcal{D}_2 = \{\min(y, \upsilon) < z\}$. In $\mathcal{D}_1$, $\upsilon > z$ and $y > z$. In $\mathcal{D}_2$, $\upsilon < z$ or $y < z$. Note that if $\upsilon > z$, $\mathcal{D}_1 = \{y > z\}$ and $\mathcal{D}_2 = \{y < z\}$. If $\upsilon < z$, $\mathcal{D}_1 = \{\emptyset\}$ and $\mathcal{D}_2 = \{y > 0\}$.

First consider the case of $\upsilon < z$; $F_Z(z)$ can be written as

$$F_Z(z) = \frac{1}{\bar{\gamma}_{SR}} \int_0^\infty \left(1 - e^{-\frac{(z - \min(y,\upsilon))}{\bar{\gamma}_{SD}}}\right) e^{-\frac{y}{\bar{\gamma}_{SR}}} dy. \tag{19}$$

Equation (19) can be re-expressed as

$$\begin{aligned} F_Z(z) = 1 &- \frac{1}{\bar{\gamma}_{SR}} \int_0^\upsilon e^{-\frac{z-y}{\bar{\gamma}_{SD}}} e^{-\frac{y}{\bar{\gamma}_{SR}}} dy \\ &- \frac{1}{\bar{\gamma}_{SR}} \int_\upsilon^\infty e^{-\frac{z-\upsilon}{\bar{\gamma}_{SD}}} e^{-\frac{y}{\bar{\gamma}_{SR}}} dy. \end{aligned} \tag{20}$$

Simplifying (20) yields

$$\begin{aligned} F_Z(z) &= 1 - \bar{\gamma}_{SD} e^{-\frac{z}{\bar{\gamma}_{SD}}} \left(\frac{1 - e^{-\left(\frac{\bar{\gamma}_{SD} - \bar{\gamma}_{SR}}{\bar{\gamma}_{SD}\bar{\gamma}_{SR}}\right)\upsilon}}{\bar{\gamma}_{SD} - \bar{\gamma}_{SR}} \right) \\ &\quad - e^{-\frac{z-\upsilon}{\bar{\gamma}_{SD}} - \frac{\upsilon}{\bar{\gamma}_{SR}}} \\ &\stackrel{\text{def}}{=} \mathcal{F}(\upsilon, z). \end{aligned} \tag{21}$$

Next consider the case of $\upsilon > z$; Since $\Pr(X < 0) = 0$, we have $y < z$ and $\min(y, \upsilon) = y$. Now using (18), $F_Z(z)$ is given by

$$\begin{aligned} F_Z(z) &= \frac{1}{\bar{\gamma}_{SR}} \int_0^z \left(1 - e^{-\frac{(z - \min(y,\upsilon))}{\bar{\gamma}_{SD}}}\right) e^{-\frac{y}{\bar{\gamma}_{SR}}} dy \\ &= \frac{1}{\bar{\gamma}_{SR}} \int_0^z e^{-\frac{y}{\bar{\gamma}_{SR}}} dy - \frac{1}{\bar{\gamma}_{SR}} \int_0^z e^{\frac{-z+y}{\bar{\gamma}_{SD}}} e^{-\frac{y}{\bar{\gamma}_{SR}}} dy. \end{aligned} \tag{22}$$

Equation (22) can be re-expressed as

$$F_Z(z) = 1 - e^{-\frac{z}{\bar{\gamma}_{SR}}} - \frac{e^{-\frac{z}{\bar{\gamma}_{SD}}}}{\bar{\gamma}_{SR}} \int_0^z e^{-\left(\frac{\bar{\gamma}_{SD} - \bar{\gamma}_{SR}}{\bar{\gamma}_{SD}\bar{\gamma}_{SR}}\right) y} dy. \tag{23}$$

Simplifying the integral in (23) we get

$$\begin{aligned} F_Z(z) &= 1 - e^{-\frac{z}{\bar{\gamma}_{SR}}} - \frac{\bar{\gamma}_{SD}\left(e^{-\frac{z}{\bar{\gamma}_{SD}}} - e^{-\frac{z}{\bar{\gamma}_{SR}}}\right)}{\bar{\gamma}_{SD} - \bar{\gamma}_{SR}} \\ &\stackrel{\text{def}}{=} \mathcal{G}(z). \end{aligned} \tag{24}$$

Since $F_{\gamma_{\mathrm{ub1}}}(z) = E_\upsilon\left[\Pr\left(Z < z\right)^{N_t}\right]$, the cdf of the e2e SNR can be written as

$$\begin{aligned} F_{\gamma_{\mathrm{ub1}}}(z) &= \frac{1}{\bar{\gamma}_{RD}} \int_0^z \left(\mathcal{F}(\upsilon, z)\right)^{N_t} e^{-\frac{\upsilon}{\bar{\gamma}_{RD}}} d\upsilon \\ &\quad + \frac{1}{\bar{\gamma}_{RD}} \int_z^\infty \left(\mathcal{G}(z)\right)^{N_t} e^{-\frac{\upsilon}{\bar{\gamma}_{RD}}} d\upsilon. \end{aligned} \tag{25}$$

Equation (25) can be simplified as

$$\begin{aligned} F_{\gamma_{\mathrm{ub1}}}(z) &= \frac{1}{\bar{\gamma}_{RD}} \int_0^z \left(p + q e^{-\omega \upsilon}\right)^{N_t} e^{-\frac{\upsilon}{\bar{\gamma}_{RD}}} d\upsilon \\ &\quad + \left(\mathcal{G}(z)\right)^{N_t} e^{-\frac{z}{\bar{\gamma}_{RD}}}, \end{aligned} \tag{26}$$

where

$$p = 1 - \frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SD} - \bar{\gamma}_{SR}} e^{-\frac{z}{\bar{\gamma}_{SD}}}, \tag{27}$$

$$q = \frac{\bar{\gamma}_{SR}}{\bar{\gamma}_{SD} - \bar{\gamma}_{SR}} e^{-\frac{z}{\bar{\gamma}_{SD}}}, \tag{28}$$

and

$$\omega = \frac{\bar{\gamma}_{SD} - \bar{\gamma}_{SR}}{\bar{\gamma}_{SD}\bar{\gamma}_{SR}}. \tag{29}$$

We can rewrite (26) using the binomial theorem as

$$\begin{aligned} F_{\gamma_{\mathrm{ub1}}}(z) &= \left(\mathcal{G}(z)\right)^{N_t} e^{-\frac{z}{\bar{\gamma}_{RD}}} \\ &\quad + \frac{1}{\bar{\gamma}_{RD}} \sum_{j=0}^{N_t} \binom{N_t}{j} p^{N_t - j} q^j \int_0^z e^{-\left(\frac{1}{\bar{\gamma}_{RD}} + j\omega\right)\upsilon} d\upsilon. \end{aligned} \tag{30}$$

After simplifying the integral, the cdf of the e2e SNR in *Scheme (a)* can be expressed as

$$\begin{aligned} F_\gamma(z) \geq F_{\gamma_{\mathrm{ub1}}}(z) &= \left(\mathcal{G}(z)\right)^{N_t} e^{-\frac{z}{\bar{\gamma}_{RD}}} \\ &\quad + \frac{1}{\bar{\gamma}_{RD}} \sum_{j=0}^{N_t} \binom{N_t}{j} p^{N_t - j} q^j \left(\frac{1 - e^{-\left(\frac{1}{\bar{\gamma}_{RD}} + j\omega\right) z}}{1/\bar{\gamma}_{RD} + j\omega} \right). \end{aligned} \tag{31}$$

Finally, the outage probability of *Scheme (a)* can be obtained from (31) by substituting $z = 2^{2R_0} - 1$.

Scheme (b): We now derive an expression for $F_{\gamma_{\mathrm{ub2}}}(z)$ which is a tight lower bound to outage probability of the system when *Scheme (b)* is implemented. Let $\tilde{X} = \gamma_{SD,k}$ and $\tilde{Y} = \min\{\gamma_{SR,k}, \gamma_{RD}\}$. First we will obtain an expression for the e2e SNR pdf. Since $\tilde{X}$ and $\tilde{Y}$ are independent, the pdf of the e2e SNR given by their sum, can be obtained using the convolution integral as

$$f_{\gamma_{\mathrm{ub2}}}(z) = \int_0^z f_{\tilde{X}}(y) f_{\tilde{Y}}(z - y) dy, \tag{32}$$

where $f_{\tilde{X}}(\cdot)$ and $f_{\tilde{Y}}(\cdot)$ denote the pdfs of $\tilde{X}$ and $\tilde{Y}$ respectively. The pdf of $\tilde{X}$ can be found using the cdf expression of [22, Eq. (9.344)] and is given by

$$f_{\tilde{X}}(y) = \frac{N_t}{\bar{\gamma}_{SD}} \sum_{n=0}^{N_t - 1} (-1)^n \binom{N_t - 1}{n} e^{-\frac{n+1}{\bar{\gamma}_{SD}} y}. \tag{33}$$

In *Scheme (b)* selection of k leads to a random selection of the $S - R$ channel and therefore, $\gamma_{SR,k}$ is an exponential RV. Noting that the minimum of two exponential RVs is also another exponential RV, $\tilde{Y}$ is distributed as

$$f_{\tilde{Y}}(y) = \frac{\bar{\gamma}_{SR} + \bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}} e^{-\left(\frac{\bar{\gamma}_{SR} + \bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right) y}. \tag{34}$$

We rewrite (32) after substituting (33) and (34) as

$$\begin{aligned} f_{\gamma_{\mathrm{ub2}}}(z) &= \frac{N_t}{\bar{\gamma}_{SD}} \left(\frac{\bar{\gamma}_{SR} + \bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right) e^{-\left(\frac{\bar{\gamma}_{SR} + \bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right) z} \\ &\quad \times \sum_{n=0}^{N_t - 1} (-1)^n \binom{N_t - 1}{n} \int_0^z e^{-\left(\frac{n+1}{\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{SR} + \bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right) y} dy. \end{aligned} \tag{35}$$

Simplifying the integral in (35), the pdf can be expressed in closed-form as

$$f_{\gamma_{\text{ub2}}}(z) = \frac{N_t}{\bar{\gamma}_{SD}} \left(\frac{\bar{\gamma}_{SR} + \bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}} \right) \times \sum_{n=0}^{N_t-1} \frac{(-1)^n \binom{N_t-1}{n} \left(e^{-\left(\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right)z} - e^{-\frac{n+1}{\bar{\gamma}_{SD}}z} \right)}{\frac{n+1}{\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}. \tag{36}$$

Now it is easy to obtain the cdf, $F_{\gamma_{\text{ub2}}}(z) = \int_0^z f_{\gamma_{\text{ub2}}}(z)dz$. The cdf of γ_{ub2} is given by

$$\begin{aligned} F_\gamma(z) &\geq F_{\gamma_{\text{ub2}}}(z) \\ &= \frac{N_t}{\bar{\gamma}_{SD}} \sum_{n=0}^{N_t-1} \frac{(-1)^n \binom{N_t-1}{n}}{\frac{n+1}{\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} \Bigg(1 - e^{-\left(\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right)z} \\ &\quad - \frac{\bar{\gamma}_{SD}}{n+1} \left(\frac{1}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}} \right) \left(1 - e^{-\left(\frac{n+1}{\bar{\gamma}_{SD}}\right)z} \right) \Bigg). \end{aligned} \tag{37}$$

The outage probability of *Scheme (b)* can be obtained from (37) by substituting $z = 2^{2R_0} - 1$.

B. High SNR Outage Approximations

Although the outage expressions of *Schemes (a)* and *(b)* given by (31) and (37) are valid for arbitrary SNR, it is difficult to obtain further insights. For example, it is interesting to know how system and network parameters such as N_t and SNR imbalances among $\bar{\gamma}_{SD}$, $\bar{\gamma}_{RS}$ and $\bar{\gamma}_{RD}$ influence the system's outage performance. Such information can not be *directly* obtained from (31) or (37). Along these lines, we have developed simple high SNR approximations, whose derivations can be found in the Appendix.

Scheme (a): At high SNR, the system's outage probability is given by[2]

$$P_{o/a}^{\infty} = \frac{1}{\mu_1\mu_2(N_t+1)} \left(\frac{2^{2R_0}-1}{\bar{\gamma}_{SD}} \right)^{N_t+1} + o\left(\left(\frac{2^{2R_0}-1}{\bar{\gamma}_{SD}} \right)^{N_t+2} \right), \tag{38}$$

where $\mu_1 = \frac{\bar{\gamma}_{SR}}{\bar{\gamma}_{SD}}$ and $\mu_2 = \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}}$.

Scheme (b): At high SNR, the system's outage probability is given by

$$P_{o/b}^{\infty} = \frac{1+\mu_2}{\mu_1\mu_2(N_t+1)} \left(\frac{2^{2R_0}-1}{\bar{\gamma}_{SD}} \right)^{N_t+1} + o\left(\left(\frac{2^{2R_0}-1}{\bar{\gamma}_{SD}} \right)^{N_t+2} \right). \tag{39}$$

Clearly, (38) and (39) show that both *Schemes (a)* and *(b)* achieve the same diversity order of $N_t + 1$. The reason for this is that the relay-destination link in the relayed path acts as the bottleneck. In other words, in *Scheme (a)*, although the best source-relay link is selected, due the single antenna relay-destination link, the relayed path does not provide a diversity gain (i.e., diversity is one). In *Scheme (b)*, we totally ignore the relayed path meaning that the diversity is again one. However, in both schemes, the source-destination direct path offers the full spatial degrees of freedom and is equal to the total number of transmit antennas (since the destination employs a single antenna). As a result combining the relayed and direct paths, both schemes provide the same diversity order.

When the outage probability is plotted on a log scale against $\bar{\gamma}_{SD}$ in dB, the high SNR penalty, δ, of *Scheme (b)* compared to *Scheme (a)* can be expressed as[3]

$$\delta = \frac{10}{N_t+1} \log(1+\mu_2) \quad \text{dB}. \tag{40}$$

To see this, for *Schemes (a)* and *(b)* we write

$$\log\left(P_{o/a}^{\infty}\right) = \log\left(\frac{1}{\mu_1\mu_2(N_t+1)} \right) - (N_t+1)\log\left(\frac{\bar{\gamma}_{SD}}{2^{2R_0}-1} \right), \tag{41}$$

and

$$\log\left(P_{o/b}^{\infty}\right) = \log\left(\frac{1+\mu_2}{\mu_1\mu_2(N_t+1)} \right) - (N_t+1)\log\left(\frac{\bar{\gamma}_{SD}}{2^{2R_0}-1} \right), \tag{42}$$

respectively. Now equating (41) and (42), simplifying and noting that what we require is an expression for $10(\log(\bar{\gamma}_{SD}|_{\text{Scheme (a)}} - \log(\bar{\gamma}_{SD}|_{\text{Scheme (b)}})$ yields the desired result in (40).

The high SNR performances of both schemes are governed by N_t, μ_1 and μ_2. Clearly, in both schemes, we see that increasing these parameters has a positive effect on the outage probability. On the other hand, (40) shows that δ depends on N_t and μ_2. We see that the performance loss for large N_t and small μ_2 is marginal.

C. Average BER

In this subsection we analyze the average BER of *Schemes (a)* and *(b)*. For many modulation formats used in wireless applications, the average BER can be expressed as [23]

$$\begin{aligned} P_e &= E\left[a\, Q(\sqrt{b\gamma}) \right], \\ &= \frac{a}{\sqrt{2\pi}} \int_0^\infty F_\gamma\left(\frac{t^2}{b} \right) e^{-\frac{t^2}{2}} dt. \end{aligned} \tag{43}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{y^2}{2}} dy$ is the Gaussian Q-function and $a, b > 0$ are determined by specific constellations. Some example modulation schemes for which (43) apply include binary phase shift keying (BPSK) modulation, $a = 1$, and $b = 2$, and Quadrature phase shift keying (QPSK), $a = 1$ and $b = 1$. Our results also provide the approximate BER for M-ary phase-shift keying (M-PSK), $a = 1$, and $b = 2\sin^2(\pi/M)$). Moreover, the following BER derivations can also be trivially extended to square/rectangular M-QAM, for which P_e can be written as a weighted sum of $a\, Q\left(\sqrt{b\gamma}\right)$ terms [24].

[2] A function of x, $f(x)$, is represented as $o(x)$ if $\lim_{x\to 0} \frac{f(x)}{x} = 0$.

[3] Throughout the paper, the logarithm of x to the base 10 is written as $\log(x)$.

Scheme (a): By substituting (31) into (43) system's average BER can be tightly lower bounded as

$$\begin{aligned} P_e &\geq \tilde{P}_{e/a} \quad (44)\\ &= \frac{a}{\sqrt{2\pi}}\int_0^\infty \left(1-\frac{e^{-\frac{t^2}{b\bar\gamma_{SD}}}}{1-\frac{\bar\gamma_{SR}}{\bar\gamma_{SD}}}-\frac{e^{-\frac{t^2}{b\bar\gamma_{SR}}}}{1-\frac{\bar\gamma_{SD}}{\bar\gamma_{SR}}}\right)^{N_t}\\ &\quad\times e^{-\left(\frac{1}{b\bar\gamma_{RD}}+\frac{1}{2}\right)t^2}dt\\ &\quad+\frac{a}{\sqrt{2\pi}}\sum_{j=0}^{N_t}\binom{N_t}{j}\int_0^\infty\left(1-\frac{e^{-\frac{t^2}{b\bar\gamma_{SD}}}}{\omega\bar\gamma_{SR}}\right)^{N_t-j}\\ &\quad\times\frac{e^{-\left(\frac{j}{b\bar\gamma_{SD}}+\frac{1}{2}\right)t^2}}{(\omega\bar\gamma_{SD})^j}\left(\frac{1-e^{-\left(\frac{1}{\bar\gamma_{RD}}+j\omega\right)\frac{t^2}{b}}}{1+j\omega\bar\gamma_{RD}}\right)dt. \end{aligned}$$

Next, we apply the binomial expansion to simplify (44) and obtain

$$\begin{aligned} \tilde{P}_{e/a} &= \frac{a}{\sqrt{2\pi}}\sum_{j=0}^{N_t}\frac{\binom{N_t}{j}}{(\omega\bar\gamma_{SD})^j}\sum_{k=0}^{N_t-j}\binom{N_t-j}{k}\frac{(-1)^k}{(\omega\bar\gamma_{SR})^k} \quad (45)\\ &\quad\times\int_0^\infty e^{-\left(\frac{j}{\bar\gamma_{SR}}+\frac{1}{\bar\gamma_{RD}}+\frac{k}{\bar\gamma_{SD}}+\frac{b}{2}\right)\frac{t^2}{b}}dt\\ &\quad+\frac{a}{\sqrt{2\pi}}\sum_{j=0}^{N_t}\frac{\binom{N_t}{j}}{(\omega\bar\gamma_{SD})^j(1+j\omega\bar\gamma_{RD})}\\ &\quad\times\sum_{k=0}^{N_t-j}\binom{N_t-j}{k}\frac{(-1)^k}{(\omega\bar\gamma_{SR})^k}\\ &\quad\times\int_0^\infty\left(1-e^{-\left(\frac{1}{\bar\gamma_{RD}}+j\omega\right)\frac{t^2}{b}}\right)e^{-\left(\frac{j+k}{\bar\gamma_{SD}}+\frac{b}{2}\right)\frac{t^2}{b}}dt. \end{aligned}$$

Finally, using the following integral result from [25]

$$\mathcal{J}_1=\int_0^\infty e^{-q^2x^2}dx=\frac{\sqrt{\pi}}{2q},\quad [q>0] \quad (46)$$

$\tilde{P}_{e/a}$ can be evaluated in closed-form as

$$\begin{aligned} \tilde{P}_{e/a} &= \frac{a}{2}\sum_{j=0}^{N_t}\frac{\binom{N_t}{j}}{(\omega\bar\gamma_{SD})^j} \quad (47)\\ &\times\sum_{k=0}^{N_t-j}\frac{(-1)^k\binom{N_t-j}{k}}{(\omega\bar\gamma_{SR})^k\sqrt{1+\frac{2j}{b\bar\gamma_{SR}}+\frac{2}{b\bar\gamma_{RD}}+\frac{2k}{b\bar\gamma_{SD}}}}\\ &+\frac{a}{2}\sum_{j=0}^{N_t}\frac{\binom{N_t}{j}}{(\omega\bar\gamma_{SD})^j(1+j\omega\bar\gamma_{RD})}\sum_{k=0}^{N_t-j}\binom{N_t-j}{k}\frac{(-1)^k}{(\omega\bar\gamma_{SR})^k}\\ &\times\left(\frac{1}{\sqrt{1+\frac{2(j+k)}{b\bar\gamma_{SD}}}}-\frac{1}{\sqrt{1+\frac{2}{b\bar\gamma_{RD}}+\frac{2j\omega}{b}+\frac{2(j+k)}{b\bar\gamma_{SD}}}}\right). \end{aligned}$$

Scheme (b): Substituting (37) into (43), the average BER of *Scheme (b)* can be expressed as

$$\begin{aligned} P_e &\geq \tilde{P}_{e/b}=\frac{aN_t}{2\bar\gamma_{SD}}\sum_{n=0}^{N_t-1}\frac{(-1)^n\binom{N_t-1}{n}}{\frac{n+1}{\bar\gamma_{SD}}-\frac{\bar\gamma_{SR}+\bar\gamma_{RD}}{\bar\gamma_{SR}\bar\gamma_{RD}}} \quad (48)\\ &\quad-\frac{aN_t}{\sqrt{2\pi}\bar\gamma_{SD}}\sum_{n=0}^{N_t-1}\frac{(-1)^n\binom{N_t-1}{n}}{\frac{n+1}{\bar\gamma_{SD}}-\frac{\bar\gamma_{SR}+\bar\gamma_{RD}}{\bar\gamma_{SR}\bar\gamma_{RD}}}\\ &\quad\times\left(\int_0^\infty e^{-\left(\frac{\bar\gamma_{SR}+\bar\gamma_{RD}}{b\bar\gamma_{SR}\bar\gamma_{RD}}+\frac{1}{2}\right)t^2}dt+\frac{\bar\gamma_{SD}}{n+1}\left(\frac{1}{\bar\gamma_{SR}}+\frac{1}{\bar\gamma_{RD}}\right)\right.\\ &\quad\left.\times\left(1-\int_0^\infty e^{-\left(\frac{n+1}{b\bar\gamma_{SD}}+\frac{1}{2}\right)t^2}\right)dt\right). \end{aligned}$$

The integrals in (48) can be evaluated in closed-form using (46). Finally, a lower bound on the average BER of *Scheme (b)* is given by

$$\begin{aligned} \tilde{P}_{e/b} &= \frac{aN_t}{2\bar\gamma_{SD}}\sum_{n=0}^{N_t-1}\frac{(-1)^n\binom{N_t-1}{n}}{\frac{n+1}{\bar\gamma_{SD}}-\frac{\bar\gamma_{SR}+\bar\gamma_{RD}}{\bar\gamma_{SR}\bar\gamma_{RD}}} \quad (49)\\ &\times\left(1-\frac{1}{\sqrt{1+\frac{2(\bar\gamma_{SR}+\bar\gamma_{RD})}{b\bar\gamma_{SR}\bar\gamma_{RD}}}}\right.\\ &\left.-\frac{\bar\gamma_{SD}}{n+1}\left(\frac{1}{\bar\gamma_{SR}}+\frac{1}{\bar\gamma_{RD}}\right)\left(1-\frac{1}{\sqrt{1+\frac{2(n+1)}{b\bar\gamma_{SD}}}}\right)\right). \end{aligned}$$

D. Average BER at High SNR

We now analyze the BER in the high SNR regime in order to derive the array gain. Using a general single-input single-output (SISO) result from [26], the BER can be approximated in the high SNR regime by considering the first order expansion of the e2e SNR pdf around the origin. Therefore, employing (38) and (39), the average BER in the high SNR regime can be closely approximated as

$$P_{e/a}^\infty\approx\frac{2^{N_t}\,\Gamma(N_t+\frac{3}{2})a}{\sqrt{\pi}\mu_1\mu_2(N_t+1)}(b\bar\gamma_{SD})^{-(N_t+1)}, \quad (50)$$

and

$$P_{e/b}^\infty\approx\frac{2^{N_t}\,\Gamma(N_t+\frac{3}{2})(1+\mu_2)a}{\sqrt{\pi}\mu_1\mu_2(N_t+1)}(b\bar\gamma_{SD})^{-(N_t+1)}, \quad (51)$$

for *Schemes (a)* and *(b)* respectively. From (50) and (51) we see that the array gains of *Schemes (a)* and *(b)* are given by

$$G_{a/a}=b\left(\frac{2^{N_t}\,\Gamma(N_t+\frac{3}{2})a}{\sqrt{\pi}\mu_1\mu_2(N_t+1)}\right)^{-\frac{1}{N_t+1}}, \quad (52)$$

and

$$G_{a/b}=b\left(\frac{2^{N_t}\,\Gamma(N_t+\frac{3}{2})(1+\mu_2)a}{\sqrt{\pi}\mu_1\mu_2(N_t+1)}\right)^{-\frac{1}{N_t+1}}, \quad (53)$$

respectively.

E. Mean Channel Capacity

The mean channel capacity is defined as the expected value of the instantaneous mutual information between S and D. The mean capacity C (in bits/second) per unit bandwidth can be expressed as [27]–[29]

$$C=E_\gamma\left[\frac{1}{2}\log_2(1+\gamma)\right]. \quad (54)$$

Scheme (a): Using the pdf of γ_{ub1}, $f_{\gamma_{\text{ub1}}}(x)$, the exact C can be tightly upper bounded by solving the following integral

$$C_a=\frac{1}{2\ln 2}\int_0^\infty \ln(1+x)f_{\gamma_{\text{ub1}}}(x)dx. \quad (55)$$

$$f_{\gamma_{\text{ub1}}}(z) = \sum_{j=0}^{N_t} \frac{\binom{N_t}{j}}{(\omega\bar{\gamma}_{SD})^j} \sum_{k=0}^{N_t-j} \frac{(-1)^{k-1}\binom{N_t-j}{k}\left(\frac{j}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}} + \frac{k}{\bar{\gamma}_{SD}}\right)}{(\omega\bar{\gamma}_{SR})^k} e^{-\left(\frac{j}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}} + \frac{k}{\bar{\gamma}_{SD}}\right)z}$$
$$+ \sum_{j=0}^{N_t} \frac{\binom{N_t}{j}}{(\omega\bar{\gamma}_{SD})^j(1+j\omega\bar{\gamma}_{RD})} \sum_{k=0}^{N_t-j} \frac{(-1)^{k-1}\binom{N_t-j}{k}}{(\omega\bar{\gamma}_{SR})^k}$$
$$\times \left(\frac{j+k}{\bar{\gamma}_{SD}} e^{-\left(\frac{j+k}{\bar{\gamma}_{SD}}\right)z} - \left(\frac{1}{\bar{\gamma}_{RD}} + j\omega + \frac{j+k}{\bar{\gamma}_{SD}}\right) e^{-\left(\frac{1}{\bar{\gamma}_{RD}} + j\omega + \frac{j+k}{\bar{\gamma}_{SD}}\right)z}\right). \quad (56)$$

$$C \le C_a = \frac{1}{2\ln(2)} \sum_{j=0}^{N_t} \frac{\binom{N_t}{j}}{(\omega\bar{\gamma}_{SD})^j} \sum_{k=0}^{N_t-j} \frac{(-1)^{k-1}\binom{N_t-j}{k}\left(\frac{j}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}} + \frac{k}{\bar{\gamma}_{SD}}\right)}{(\omega\bar{\gamma}_{SR})^k}$$
$$\times \int_0^\infty \ln(1+x) e^{-\left(\frac{j}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}} + \frac{k}{\bar{\gamma}_{SD}}\right)x} dx + \frac{1}{2\ln(2)} \sum_{j=0}^{N_t} \frac{\binom{N_t}{j}}{(\omega\bar{\gamma}_{SD})^j(1+j\omega\bar{\gamma}_{RD})}$$
$$\times \sum_{k=0}^{N_t-j} \frac{(-1)^{k-1}\binom{N_t-j}{k}}{(\omega\bar{\gamma}_{SR})^k} \left(\frac{j+k}{\bar{\gamma}_{SD}} \int_0^\infty \ln(1+x) e^{-\left(\frac{j+k}{\bar{\gamma}_{SD}}\right)x} dx\right.$$
$$\left.- \left(\frac{1}{\bar{\gamma}_{RD}} + j\omega + \frac{j+k}{\bar{\gamma}_{SD}}\right) \int_0^\infty \ln(1+x) e^{-\left(\frac{1}{\bar{\gamma}_{RD}} + j\omega + \frac{j+k}{\bar{\gamma}_{SD}}\right)x} dx\right). \quad (57)$$

In order to derive the capacity we first need an expression for the pdf of γ_{ub1}. This can be easily obtained using the cdf of γ_{ub1} given in (31). Therefore, by differentiating (31) with respect to z we obtain the pdf of γ_{ub1} as (56). Now substituting (56) into (55) we write (57). Using the closed-form expression for the integral[4]

$$\mathcal{J}_2 = \int_0^\infty \ln(1+\beta x) e^{-sx} dx = \frac{e^{\frac{s}{\beta}}}{s} E_1\left(\frac{s}{\beta}\right) \quad (58)$$

given in [25], where $E_1(x) = \int_x^\infty \frac{e^{-t}}{t} dt$ is the exponential integral function of order one, the mean capacity can be tightly upper bounded as (59) where

$$\Im = \begin{cases} 0, & j = k = 0, \\ 1, & \text{else.} \end{cases}$$

Scheme (b): We substitute (36) into (55) and express the upper bound for the mean channel capacity as (60). The integrals in (60) can be evaluated in closed-form using (58) to yield

$$C_b = \frac{N_t}{2\ln(2)\bar{\gamma}_{SD}} e^{\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} E_1\left(\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right) \quad (61)$$
$$\times \sum_{n=0}^{N_t-1} \frac{(-1)^n\binom{N_t-1}{n}}{\frac{n+1}{\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} - \frac{N_t}{2\ln(2)}\left(\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right)$$
$$\times \sum_{n=0}^{N_t-1} \frac{(-1)^n\binom{N_t-1}{n} e^{\frac{n+1}{\bar{\gamma}_{SD}}}}{\left(\frac{n+1}{\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right)(n+1)} E_1\left(\frac{n+1}{\bar{\gamma}_{SD}}\right).$$

IV. Numerical Results and Comparisons

This section presents the numerical and simulation results for the system's rate outage probability, average BER and the mean channel capacity.

[4]Note that $E_1(x) = -\text{Ei}(-x)$.

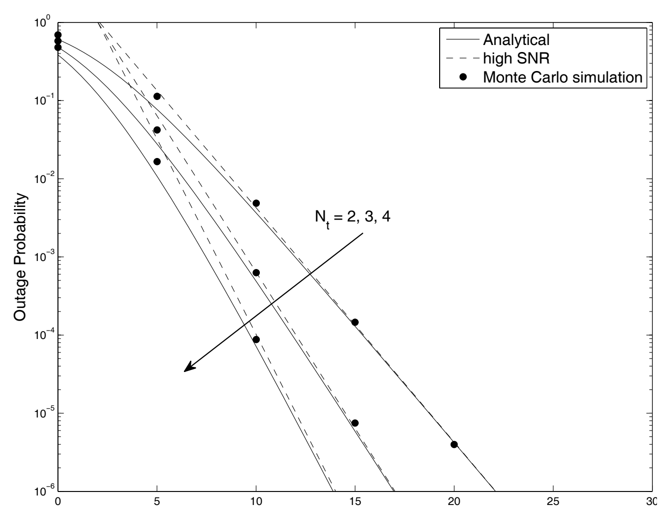

Fig. 2. *Scheme (a)*: Outage probability versus $\bar{\gamma}_{SD}$ for different N_t. $\mu_1 = 1.25$ and $\mu_2 = 0.5$.

Figs. 2 and 3 show the outage probability for *Scheme (a)* and *Scheme (b)* respectively. The target rate, $R_0 = 1$ bit/s/Hz. The analytical results are plotted using Eqs. (31) and (37) respectively, while the high SNR approximations correspond to Eqs. (38) and (39). In order to verify our analytical results, we have also plotted simulation based results. We see that the analytical results obtained by employing the tight bound match perfectly with the simulations in the medium to high SNR regimes. Furthermore, it is observed that the high-SNR approximation curves converge to the analytical ones in the medium to high SNR regimes. As expected, increasing the number of antennas has a positive effect on reducing the outage probability. However, the reduction of outage probability

$$C_a = \frac{1}{2\ln(2)} \sum_{j=0}^{N_t} \frac{\binom{N_t}{j}}{(\omega\bar{\gamma}_{SD})^j} \sum_{k=0}^{N_t-j} \frac{(-1)^{k-1}\binom{N_t-j}{k}}{(\omega\bar{\gamma}_{SR})^k} e^{\left(\frac{j}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}+\frac{k}{\bar{\gamma}_{SD}}\right)} E_1\left(\frac{j}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}+\frac{k}{\bar{\gamma}_{SD}}\right)$$
$$+ \frac{1}{2\ln(2)} \sum_{j=0}^{N_t} \frac{\binom{N_t}{j}}{(\omega\bar{\gamma}_{SD})^j(1+j\omega\bar{\gamma}_{RD})} \sum_{k=0}^{N_t-j} \frac{(-1)^{k-1}\binom{N_t-j}{k}}{(\omega\bar{\gamma}_{SR})^k}$$
$$\times \left(\Im e^{\left(\frac{j+k}{\bar{\gamma}_{SD}}\right)} E_1\left(\frac{j+k}{\bar{\gamma}_{SD}}\right) - e^{\left(\frac{1}{\bar{\gamma}_{RD}}+j\omega+\frac{j+k}{\bar{\gamma}_{SD}}\right)} E_1\left(\frac{1}{\bar{\gamma}_{RD}}+j\omega+\frac{j+k}{\bar{\gamma}_{SD}}\right)\right), \quad (59)$$

$$C_b = \frac{N_t}{2\ln(2)\bar{\gamma}_{SD}} \left(\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right) \sum_{n=0}^{N_t-1} \frac{(-1)^n\binom{N_t-1}{n}}{\frac{n+1}{\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}$$
$$\times \left(\int_0^\infty \ln(1+x) e^{-\left(\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}\right)x} dx - \int_0^\infty \ln(1+x) e^{-\frac{n+1}{\bar{\gamma}_{SD}}x} dx\right). \quad (60)$$

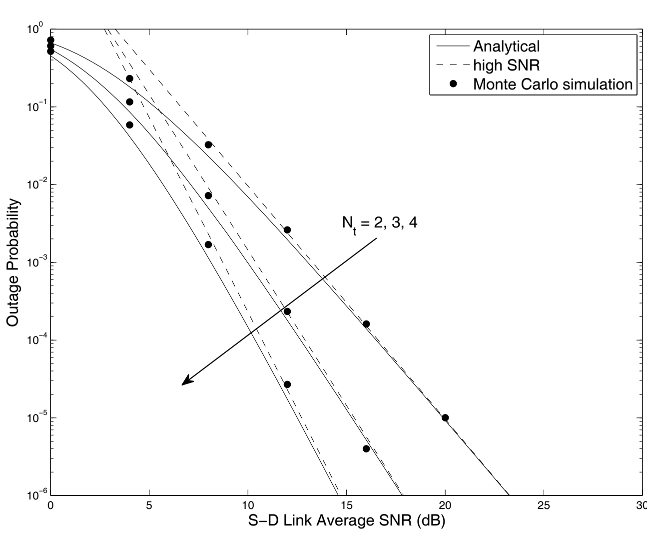

Fig. 3. *Scheme (b)*: Outage probability versus $\bar{\gamma}_{SD}$ for different N_t. $\mu_1 = 0.5$ and $\mu_2 = 1.25$.

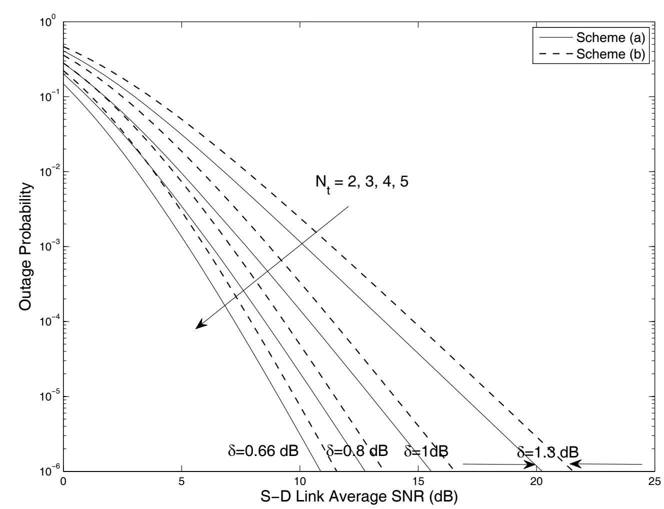

Fig. 4. Outage probability versus $\bar{\gamma}_{SD}$ of *Schemes (a)* and *(b)* for different N_t, $\mu_1 = \mu_2 = 1.5$.

decreases for higher N_t. Since in practice, adding an extra antenna element attracts extra system costs, this number of antennas/performance tradeoff is useful in selecting a desirable value for N_t.

In Fig. 4 we compare the theoretical rate outage performance of *Scheme (a)* and *Scheme (b)* by varying the number of antennas, N_t, with $\mu_1 = \mu_2 = 1.5$. The plots are based on Eqs. (31) and (37) respectively. To avoid clutter, we have not plotted the high SNR and simulation based results. In all cases, as expected, *Scheme (a)* has a better outage performance in all SNR regimes. However, the performance gap between *Schemes (a)* and *(b)* is marginal and decreases when N_t is increased as predicted by our analysis. Thus, in this network, if a small performance loss is tolerable, *Scheme (b)* which has a low signaling overhead can be employed to realize the cooperative diversity gains. In Fig. 4, δ values obtained using (40) an outage probability of $\approx 10^{-6}$ are also shown. These values perfectly matched simulated system outages (not shown here). When N_t is increased from 2 to 5, we see that the relative performance difference between the schemes drops from 1.3 dB to 0.66 dB.

Figure 5 shows the average BER of *Scheme (a)* with 4-QAM modulation and $N_t = 2$. Four different values of μ_1 and μ_s have been considered to illustrate the impact of SNR imbalance on the system's error probability. In addition to the simulated BER, analytical and high SNR results are also shown in Fig. 5. We observe that the analytical results from (47) match the simulations very well except at low SNRs given by $\bar{\gamma}_{SD} < 5$ dB. High SNR results calculated from (50) are also useful to predict system's error performance accurately in the regimes of $\bar{\gamma}_{SD} > 15$ dB and in some cases, as low as $\bar{\gamma}_{SD} > 10$ dB. High values of μ_1 and μ_2 improve the BER as expected. However, relative performance gains become marginal as μ_1 and μ_2 are increased. This can be seen from plots for $[\mu_1 = \mu_2 = 1.5 \text{ and } 5]$ and $[\mu_1 = \mu_2 = 5 \text{ and } 10]$.

Figure 6 compares the average BER of *Schemes (a)* and *(b)* for $N_t = 2$ and $N_t = 3$ respectively. As expected, in both schemes increasing the number of antennas, N_t, has a positive effect on the error performance since the achievable diversity order is increased from three to four. For both values

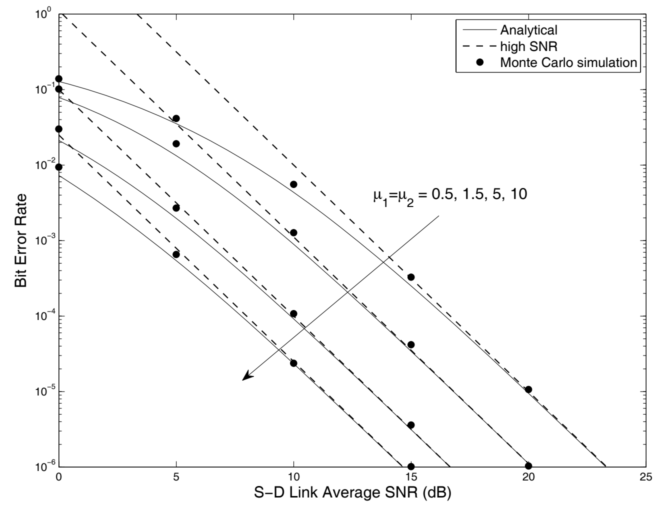

Fig. 5. *Scheme (a)*: Average BER versus $\bar{\gamma}_{SD}$ with 4-QAM modulation, $N_t = 2$ antennas.

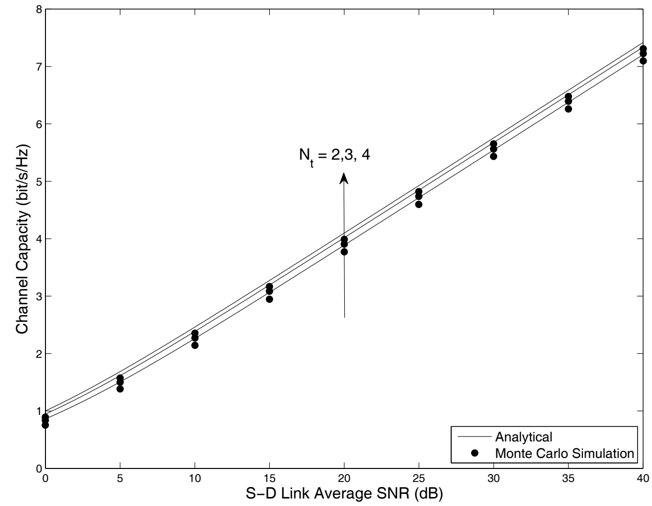

Fig. 7. Channel capacity versus $\bar{\gamma}_{SD}$ of *Scheme (a)*. $\mu_1 = \mu_2 = 1.5$.

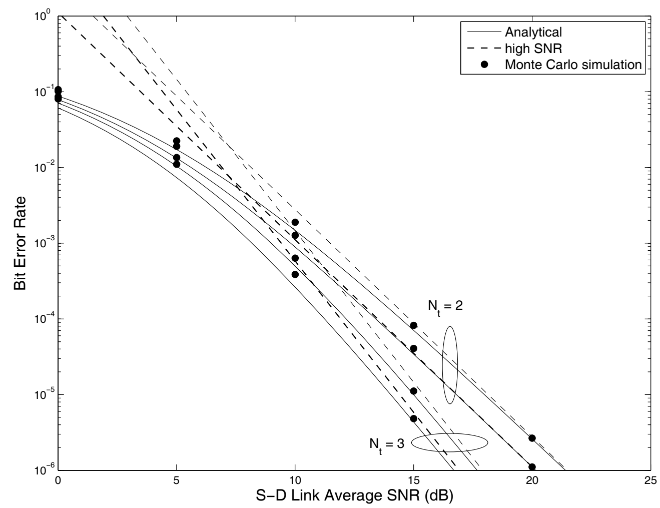

Fig. 6. Average BER versus $\bar{\gamma}_{SD}$ of *Schemes (a)* and *(b)* with 4-QAM modulation. $\mu_1 = \mu_2 = 1.5$.

of N_t, *Scheme (a)* compared to *Scheme (b)* only shows a slight performance advantage.

Fig 7 shows the mean channel capacity of *Scheme (a)*. As expected, when $\bar{\gamma}_{SD}$ and N_t are increased, the capacity improves. For example, when $\bar{\gamma}_{SD}$ is increased from 0 dB to 40 dB, in the case of $N_t = 4$ the mean capacity is increased from 1 bit/s/Hz to 7.4 bit/s/Hz. However, capacity improvement when N_t is increased from two to four is marginal at all SNR. Also by comparing plots for $N_t = [2, 3]$ and $N_t = [3, 4]$ we see that the relative capacity gains reduces. Simulation results shown in Fig. 7 again confirm the tightness of the derived capacity bounds.

Finally, we make some remarks on optimal and suboptimal antenna selection performance when all terminals have multiple antennas, i.e., R and D are also equipped with N_r and N_d antennas respectively. In [9] it has been shown that the diversity order of such a system equals, $N_tN_d + N_r \min(N_t, N_d)$. First assume that $N_d = 1$; This situation may be the case in some infrastructure based networks with fixed relays where the relay has the functionality of a mini base station. The optimal scheme achieves a diversity order of $N_t + N_r$. Under this configuration, the suboptimal antenna scheme can only achieve a same diversity order of $N_t = N_r$, if R deploys hybrid signal processing techniques such as MRC/antenna selection [12] or MRC/transmit beamforming. Suboptimal antenna selection is only capable of achieving a diversity order of $N_t + 1$. This is because selecting a single antenna at S only based on the $S - D$ link will yield a random selection of the $S - D$ link and thus would not yield any diversity gains in the relayed link. The diversity order of the system when $N_d > 1$ with suboptimal antenna selection and antenna selection/diversity combining is $N_tN_d + 1$ and $N_tN_d + N_r$. Therefore, the performance of these schemes will be very much inferior to the optimal antenna selection scheme, especially for a "square" $S - D$ link, i.e, large $\min(N_t, N_d)$.

V. CONCLUSIONS

Antenna selection is a simple way of improving the performance of AF relaying while maintaining a low hardware complexity. In this paper, we analytically investigated and compared the performance of two transmit antenna selection schemes in a dual-hop AF relay network. Using a tight upper bound, we derived expressions for the SNR cdf. These expressions were next utilized to study important performance measures such as the outage probability, average BER and the mean channel capacity of the two schemes. In order to gain further insights, we also developed simple high SNR outage approximations. From the developed expressions, it is easy to see that when a large number of antennas at the source are deployed or μ_2 is small, the performance gap between the suboptimal and optimal antenna selection schemes is marginal. Since the suboptimal scheme also has a low feedback overhead, it seems to be a promising solution for implementing future cellular networks expecting to support relay based communications.

APPENDIX
HIGH SNR ANALYSIS

Scheme (a): To obtain a first order expansion of $F_\gamma(z)$ we note that at high SNR

$$F_\gamma(z) = F_{\gamma_{\text{ub1}}}(z). \tag{62}$$

Therefore, consider the cdf $F_{\gamma_{\text{ub1}}}(z)$ given in (31). To proceed, we substitute $\mu_1 = \frac{\bar{\gamma}_{SR}}{\bar{\gamma}_{SD}}$ and $\mu_2 = \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}}$ in (31) which gives

$$\begin{aligned} F_{\gamma_{\text{ub1}}}(z) &= \left(1 - e^{-\frac{z}{\mu_1\bar{\gamma}_{SD}}} - \frac{\left(e^{-\frac{z}{\bar{\gamma}_{SD}}} - e^{-\frac{z}{\mu_1\bar{\gamma}_{SD}}}\right)}{1-\mu_1}\right)^{N_t} \\ &\quad \times e^{-\frac{z}{\mu_1\mu_2\bar{\gamma}_{SD}}} \\ &\quad + \frac{1}{\mu_1\mu_2\bar{\gamma}_{SD}} \sum_{j=0}^{N_t} \binom{N_t}{j} \left(1 - \frac{e^{-\frac{z}{\bar{\gamma}_{SD}}}}{1-\mu_1}\right)^{N_t-j} \\ &\quad \times \left(\frac{\mu_1}{1-\mu_1} e^{-\frac{z}{\bar{\gamma}_{SD}}}\right)^j \left(\frac{1 - e^{-\left(\frac{1}{\mu_1\mu_2\bar{\gamma}_{SD}} + j\omega\right)z}}{\frac{1}{\mu_1\mu_2\bar{\gamma}_{SD}} + j\omega}\right). \end{aligned} \tag{63}$$

Employing the Maclaurin series for the exponential function we obtain (64) where (65). We simplify (65) to obtain (66). Now as $A(z)$ contains higher powers of z than (N_t+1), we see that $B(z)$ will accurately describe the behavior of $F_{\gamma_{\text{ub1}}}(z)$ around $z = 0$.

Consider $B(z)$ given by

$$\begin{aligned} B(z) &= \frac{1}{\mu_1\mu_2\bar{\gamma}_{SD}} \sum_{j=0}^{N_t} \binom{N_t}{j} \left(1 - \frac{\sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}}{1-\mu_1}\right)^{N_t-j} \\ &\quad \times \left(\frac{\mu_1}{1-\mu_1} \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}\right)^j \left(\frac{1 - e^{-\left(\frac{1}{\mu_1\mu_2\bar{\gamma}_{SD}} + j\omega\right)z}}{\frac{1}{\mu_1\mu_2\bar{\gamma}_{SD}} + j\omega}\right). \end{aligned} \tag{67}$$

It can be shown that

$$\begin{aligned} B(z) &= \frac{z}{\mu_1\mu_2\bar{\gamma}_{SD}} \sum_{j=0}^{N_t} \binom{N_t}{j} \left(1 - \frac{\sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}}{1-\mu_1}\right)^{N_t-j} \\ &\quad \times \left(\frac{\mu_1}{1-\mu_1} \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}\right)^j. \end{aligned} \tag{68}$$

Since the summation in (68) is the binomial expansion of $(p+q)^{N_t}$, we get

$$B(z) = \frac{z}{\mu_1\mu_2\bar{\gamma}_{SD}} \left(1 - e^{-\frac{z}{\bar{\gamma}_{SD}}}\right)^{N_t}. \tag{69}$$

We apply the binomial theorem to yield

$$B(z) = \frac{z}{\mu_1\mu_2\bar{\gamma}_{SD}} \sum_{l=0}^{N_t} \binom{N_t}{l} (-1)^l \sum_{n=0}^{\infty} \frac{\left(\frac{lz}{\bar{\gamma}_{SD}}\right)^n}{n!}. \tag{70}$$

Once again, after several manipulations (70) can be written as

$$B(z) = \frac{1}{\mu_1\mu_2(N_t+1)} \left(\frac{z}{\bar{\gamma}_{SD}}\right)^{N_t+1} + o\left(\left(\frac{z}{\bar{\gamma}_{SD}}\right)^{N_t+2}\right). \tag{71}$$

We see that $B(z)$ accurately describes the behavior of $F_{\gamma_{\text{ub1}}}(z)$ around $z = 0$ and therefore $F_\gamma(z)$ around $z = 0$. Now substituting $z = 2^{2R_0-1}$ into (38) yields the desired result.

Scheme (b): At high SNR, the outage probability of *Scheme (b)* can be obtained by deriving a first order expression for $F_\gamma(z)$. To this end, we begin by finding an exact expression for $F_{\gamma_\mathcal{R}}(z)$. Conditioned on the RV, γ_{RD}, $F_{\gamma_\mathcal{R}}(z)$ is given by

$$\begin{aligned} F_{\gamma_\mathcal{R}}(z) &= \int_0^\infty \Pr\left(\frac{\gamma_{SR,k} w}{\gamma_{SR,k} + w + 1} < z\right) f_{\gamma_{RD}}(w) dw \\ &= \int_0^z \Pr\left(\gamma_{SR,k} > \frac{z(w+1)}{w-z}\right) f_{\gamma_{RD}}(w) dw \\ &\quad + \int_z^\infty \Pr\left(\gamma_{SR,k} \le \frac{z(w+1)}{w-z}\right) f_{\gamma_{RD}}(w) dw. \end{aligned} \tag{72}$$

After some manipulations it can be shown that

$$F_{\gamma_\mathcal{R}}(z) = 1 - \int_0^\infty P_{\gamma_{SR,k}}\left(z + \frac{z^2+z}{w}\right) f_{\gamma_{RD}}(z+w) dw, \tag{73}$$

where $P_{\gamma_{SR,k}}(x) = 1 - F_{\gamma_{SR,k}}(x)$ denotes the complementary cdf of $\gamma_{SR,k}$.

Simplifying (73) we get

$$\begin{aligned} F_{\gamma_\mathcal{R}}(z) &= 1 - \frac{e^{-\left(\frac{1}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}}\right)z}}{\bar{\gamma}_{RD}} \int_0^\infty e^{-\frac{z^2+z}{\bar{\gamma}_{RD} w} - \frac{w}{\bar{\gamma}_{RD}}} dw \\ &= 1 - 2\sqrt{\frac{z^2+z}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}} e^{-\left(\frac{1}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}}\right)z} K_1\left(2\sqrt{\frac{z^2+z}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right), \end{aligned} \tag{74}$$

where we have used [25, Eq. (3.471.9)] and $K_1(x)$ is the first order modified Bessel function of the second kind [30, Sec. (9.6)]. When $\nu > 0$ is fixed and $x \to 0$, using the following approximation,

$$K_\nu(x) \simeq \frac{2^{\nu-1}\Gamma(\nu)}{x^\nu}, \tag{75}$$

it can be shown that at high SNR

$$\begin{aligned} F_{\gamma_\mathcal{R}}(z) &= 1 - e^{-\left(\frac{1}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}}\right)z} \\ &= \left(1 + \frac{1}{\mu_2}\right)\left(\frac{z}{\bar{\gamma}_{SR}}\right) + o\left(\left(\frac{z}{\bar{\gamma}_{SR}}\right)^2\right). \end{aligned} \tag{76}$$

Similarly consider $F_{\gamma_\mathcal{D}}(z)$ given by

$$\begin{aligned} F_{\gamma_\mathcal{D}}(z) &= 1 - N_t \sum_{l=0}^{N_t-1} \frac{(-1)^l}{1+l} \binom{N_t-1}{l} e^{-\frac{(1+l)z}{\bar{\gamma}_{SD}}} \\ &= 1 - N_t \sum_{l=0}^{N_t-1} \frac{(-1)^l}{1+l} \binom{N_t-1}{l} \sum_{n=0}^{\infty} (-1)^n \frac{\left(\frac{(1+l)z}{\bar{\gamma}_{SD}}\right)^n}{n!} \\ &= \left(\frac{z}{\bar{\gamma}_{SD}}\right)^{N_t} + o\left(\left(\frac{z}{\bar{\gamma}_{SD}}\right)^{N_t+1}\right). \end{aligned} \tag{77}$$

Finally, employing [31, Lemma 1] it can be shown that the high SNR cdf of $\gamma = \gamma_\mathcal{R} + \gamma_\mathcal{D}$ in terms of $\bar{\gamma}_{SD}$ can be written as

$$F_\gamma(z) = \frac{1 + \frac{1}{\mu_2}}{\mu_1(N_t+1)} \left(\frac{z}{\bar{\gamma}_{SD}}\right)^{N_t+1} + o\left(\left(\frac{z}{\bar{\gamma}_{SD}}\right)^{N_t+2}\right). \tag{78}$$

$$
\begin{aligned}
F_{\gamma_{\text{ub1}}}(z) = & \left(1 - \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\mu_1 \bar{\gamma}_{SD}}\right)^n}{n!} - \left(\frac{1}{1-\mu_1}\right)\right. \\
& \times \left.\left(\sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!} - \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\mu_1 \bar{\gamma}_{SD}}\right)^n}{n!}\right)\right)^{N_t} \sum_{n=0}^{\infty} \frac{\left(\frac{-z}{\mu_1 \mu_2 \bar{\gamma}_{SD}}\right)^n}{n!} \\
& + \frac{1}{\mu_1 \mu_2 \bar{\gamma}_{SD}} \sum_{j=0}^{N_t} \binom{N_t}{j} \left(1 - \frac{\sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}}{1-\mu_1}\right)^{N_t - j} \\
& \times \left(\frac{\mu_1}{1-\mu_1} \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}\right)^j \left(\frac{1 - e^{-\left(\frac{1}{\mu_1 \mu_2 \bar{\gamma}_{SD}} + j\omega\right) z}}{\frac{1}{\mu_1 \mu_2 \bar{\gamma}_{SD}} + j\omega}\right) \\
& = A(z) + B(z).
\end{aligned} \tag{64}
$$

$$
\begin{aligned}
A(z) = & \left(1 - \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\mu_1 \bar{\gamma}_{SD}}\right)^n}{n!} - \left(\frac{1}{1-\mu_1}\right)\right. \\
& \times \left.\left(\sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!} - \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\mu_1 \bar{\gamma}_{SD}}\right)^n}{n!}\right)\right)^{N_t} \sum_{n=0}^{\infty} \frac{\left(\frac{-z}{\mu_1 \mu_2 \bar{\gamma}_{SD}}\right)^n}{n!} \\
= & \left(1 + \frac{\mu_1}{1-\mu_1} \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\mu_1 \bar{\gamma}_{SD}}\right)^n}{n!} - \frac{1}{1-\mu_1} \sum_{n=0}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}\right)^{N_t} \sum_{n=0}^{\infty} \frac{\left(\frac{-z}{\mu_1 \mu_2 \bar{\gamma}_{SD}}\right)^n}{n!}.
\end{aligned} \tag{65}
$$

$$
A(z) = \left(\frac{\mu_1}{1-\mu_1} \sum_{n=2}^{\infty} \frac{\left(-\frac{z}{\mu_1 \bar{\gamma}_{SD}}\right)^n}{n!} - \frac{1}{1-\mu_1} \sum_{n=2}^{\infty} \frac{\left(-\frac{z}{\bar{\gamma}_{SD}}\right)^n}{n!}\right)^{N_t} \sum_{n=0}^{\infty} \frac{\left(\frac{-z}{\mu_1 \mu_2 \bar{\gamma}_{SD}}\right)^n}{n!}. \tag{66}
$$

REFERENCES

[1] R. Pabst, B. H. Walke, D. C. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. D. Falconer, and G. P. Fettweis, "Relay-based deployment concepts for wireless and mobile broadband radio," *IEEE Commun. Mag.*, vol. 42, pp. 80-89, Sep. 2004.

[2] Y. Yang, H. Hu, J. Xu, and G. Mao, "Relay technologies for WiMAX and LTE-Advanced mobile systems," *IEEE Commun. Mag.*, vol. 47, pp. 100-105, Oct. 2009.

[3] H. Mheidat and M. Uysal, "Impact of receive diversity on the performance of amplify-and-forward relaying under APS and IPS power constraints," *IEEE Commun. Lett.*, vol. 10, pp. 468-470, June 2006.

[4] T. Nechiporenko, P. Kalansuriya, and C. Tellambura, "Performance of optimum switching adaptive M-QAM for amplify-and-forward relays," *IEEE Trans. Veh. Technol.*, vol. 58, pp. 2258-2268, June 2009.

[5] D. Senaratne and C. Tellambura, "Unified exact performance analysis of two-hop amplify-and-forward relaying in Nakagami fading," *IEEE Trans. Veh. Technol.*, vol. 59, pp. 1529-1534, Mar. 2010.

[6] M. O. Hasna and M.-S. Alouini, "A performance study of dual-hop transmissions with fixed gain relays," *IEEE Trans. Wireless Commun.*, vol. 3, pp. 1963-1968, Nov. 2004.

[7] Y. Fan and J. Thompson, "MIMO configurations for relay channels: theory and practice," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 1774-1786, May 2007.

[8] A. Adinoyi and H. Yanikomeroglu, "Cooperative relaying in multi-antenna fixed relay networks," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 533-544, Feb. 2007.

[9] S. W. Peters and R. W. Heath Jr., "Nonregenerative MIMO relaying with optimal transmit antenna selection," *IEEE Signal Process. Lett.*, vol. 15, pp. 421-424, 2008.

[10] L. Cao, X. Zhang, Y. Wang, and D. Yang, "Transmit antenna selection strategy in amplify-and-forward MIMO relaying," in *Proc. IEEE WCNC*, Apr. 2009, pp. 1-4.

[11] Z. Chen, J. Yuan, and B. Vucetic, "Analysis of transmit antenna selection/maximal-ratio combining in Rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 54, pp. 1312-1321, July 2005.

[12] S. Chen, W. Wang, X. Zhang, and D. Zhao, "Performance of amplify-and-forward MIMO relay channels with transmit antenna selection and maximal-ratio combining," in *Proc. IEEE WCNC*, Apr. 2009, pp. 1-6.

[13] J.-B. Kim and D. Kim, "BER analysis of dual-hop amplify-and-forward MIMO relaying with best antenna selection in Rayleigh fading channels," *IEICE Trans. Commun.*, vol. E91-B, pp. 2772-2775, Aug. 2008.

[14] H. A. Suraweera, G. K. Karagiannidis, Y. Li, H. K. Garg, A. Nallanathan, and B. Vucetic, "Amplify-and-forward relay transmission with end-to-end antenna selection," in *Proc. IEEE WCNC*, Apr. 2010, pp. 1-6.

[15] G. Zhang, G. Li, and J. Qin, "Fast antenna subset selection algorithms for multiple-input multiple-output relay systems," *IET Commun.*, vol. 3, pp. 1693-1703, Nov. 2009.

[16] I. Krikidis, J. S. Thompson, S. McLaughlin, and N. Goertz, "Amplify and forward with partial relay selection," *IEEE Commun. Lett.*, vol. 12, pp. 235-237, Apr. 2008.

[17] H. Min, S. Lee, K. Kwak, and D. Hong, "Effect of multiple antennas at the source on outage probability for amplify-and-forward relaying systems," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 633-637, Feb. 2009.

[18] A. Agustin and J. Vidal, "Amplify-and-forward cooperation under interference-limited spatial reuse of the relay slot," *IEEE Trans. Wireless Commun.*, vol. 7, pp. 1952-1962, May 2008.

[19] S. Chen, W. Wang, X. Zhang, and Z. Sun "Performance analysis of OSTBC transmission in amplify-and-forward cooperative relay networks," *IEEE Trans. Veh. Technol.*, vol. 59, pp. 105-113, Jan. 2010.

[20] S. Ikki and M. H. Ahmed, "Performance analysis of dual-hop relaying

communications over generalized Gamma fading channels," in *Proc. IEEE GLOBECOM*, Dec. 2007, pp. 3888-3893.
[21] S. Ikki and M. H. Ahmed, "Performance analysis of cooperative diversity wireless networks over Nakagami-m fading channel," *IEEE Commun. Lett.*, vol. 11, pp. 334-336, Apr. 2007.
[22] M. K. Simon and M.-S. Alouini, *Digital Communications over Fading Channels*, 1st edition. Wiley, 2001.
[23] J. G. Proakis, *Digital Communications*, 4th edition. McGraw-Hill, 2001.
[24] K. Cho and D. Yoon, "On the general BER expression of one and two dimensional amplitude modulations," *IEEE Trans. Commun.*, vol. 50, pp. 1074-1080, July 2002.
[25] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*, 6th edition. Academic Press, 2000.
[26] Z. Wang and G. B. Giannakis, "A simple and general parameterization quantifying performance in fading channels," *IEEE Trans. Commun.*, vol. 51, pp. 1389-1398, Aug. 2003.
[27] S. Chen, W. Wang, X. Zhang, M. Peng, and D. Zhao, "Capacity performance of amplify-and-forward MIMO relay with transmit antenna selection and maximal-ratio combining," in *Proc. IEEE GLOBECOM*, Nov. 2009, pp 1-6.
[28] S. S. Ikki and M. H. Ahmed, "Exact error probability and channel capacity of the best-relay cooperative-diversity networks," *IEEE Signal Process. Lett.*, vol. 16, pp. 1051-1054, Dec. 2009.
[29] D. B. da Costa and S. Aïssa, "Capacity analysis of cooperative systems with relay selection in Nakagami-m fading," *IEEE Commun. Lett.*, vol. 13, pp. 637-639, Sep. 2009.
[30] M. Abramovitz and I. A. Stegun, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, 9th edition. Dover, 1972.
[31] Y. Li and S. Kishore, "Asymptotic analysis of amplify-and-forward relaying in Nakagami-fading environments," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 4256-4262, Dec. 2007.

Himal A. Suraweera (M'07) was born in Kurunegala, Sri Lanka. He received the B.Sc. degree (first class honors) in electrical and electronics engineering, Peradeniya University, Peradeniya, Sri Lanka, in 2001 and the Ph.D. degree from Monash University, Melbourne, Australia, in 2007. He was also awarded the 2007 Mollie Holman Doctoral and 2007 Kenneth Hunt Medals for his doctoral thesis upon graduating from Monash University.

From 2001 to 2002, he was with the Department of Electrical and Electronics Engineering, Peradeniya University, as an Instructor. From October 2006 to January 2007 he was at Monash University as a Research Associate. From February 2007 to June 2009, he was at the center for Telecommunications and Microelectronics, Victoria University, Melbourne, Australia as a Research Fellow. From July 2009 to January 2011, he was with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore as a Research Fellow. He is now a Research Fellow at the Singapore University of Technology and Design, Singapore. His main research interests include relay networks, cognitive radio, MIMO and OFDM.

Dr. Suraweera is an Editor of the IEEE COMMUNICATIONS LETTERS. He serves as a Technical Program Committee Member for international conferences such as ICC '12, GLOBECOM '11 and WCNC '11. He was a recipient of an International Postgraduate Research Scholarship from the Australian Commonwealth during 2003-2006. He received an IEEE COMMUNICATIONS LETTERS exemplary reviewer certificate for 2009.

Peter J. Smith (SM'03) received the B.Sc degree in Mathematics and the Ph.D degree in Statistics from the University of London, London, U.K., in 1983 and 1988, respectively. From 1983 to 1986 he was with the Telecommunications Laboratories at GEC Hirst Research Center. From 1988 to 2001 he was a lecturer in statistics at Victoria University, Wellington, New Zealand. Since 2001 he has been a Senior Lecturer and Associate Professor in Electrical and Computer Engineering at the University of Canterbury in New Zealand. His research interests include the statistical aspects of design, modeling and analysis for communication systems, especially antenna arrays, MIMO, cognitive radio and relays.

Arumugam Nallanathan (S'97−M'00−SM'05) is a Reader in Communications at King's College London, United Kingdom. He was an Assistant Professor in the Department of Electrical and Computer Engineering, National University of Singapore, Singapore from August 2000 to December 2007. His research interests include smart grid, cognitive radio and relay networks. In these areas, he has published over 160 journal and conference papers. He is a co-recipient of the Best Paper Award presented at 2007 IEEE International Conference on Ultra-Wideband (ICUWB'2007).

He currently serves on the Editorial Board of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and IEEE SIGNAL PROCESSING LETTERS as an Associate Editor. He served as a Guest Editor for *EURASIP Journal of Wireless Communications and Networking* special issue on UWB Communication Systems-Technology and Applications. He served as the General Track Chair for the IEEE VTC'2008-Spring, Co-Chair for the IEEE GLOBECOM'2008 Signal Processing for Communications Symposium and IEEE ICC'2009 Wireless Communications Symposium. He currently serves as Co- Chair for the IEEE GLOBECOM'2011 and IEEE ICC'2012 Signal Processing for Communications Symposium and Technical program Co-Chair for IEEE International Conference on Ultra-Wideband'2011 (IEEE ICUWB'2011). He also currently serves as the Vice-Chair for the Signal Processing for Communication Electronics Technical Committee of IEEE Communications Society.

John S. Thompson was appointed as a lecturer at what is now the School of Engineering at the University of Edinburgh in 1999. In October 2005, he was promoted to the position of reader. His research interests currently include energy efficient communications systems, antenna array techniques and multihop wireless communications. He has published over 200 papers to date including a number of invited papers, book chapters and tutorial talks, as well as co-authoring an undergraduate textbook on digital signal processing. He is overall project leader for the £1.2 EPSRC Islay project involving four Universities which investigates efficient hardware implementation of complex algorithms. He is also the external liasion for the £2M EPSRC/Mobile VCE Green Radio project, which involves a number of international communication companies. He is currently editor-in-chief of the IET Signal Processing journal and is a technical programme co-chair for the Globecom conference in Miami in December 2010.