Journal of Zhejiang University-SCIENCE C (Computers & Electronics)
ISSN 1869-1951 (Print); ISSN 1869-196X (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

# Statistical assessment of selection-based dual-hop semi-blind amplify-and-forward cooperative networks*

Yi LIU[†1,2], Jian-hua ZHANG[1,2], Wei XU[1,2], Ze-min LIU[2]

([1]*Wireless Technology Innovation Institute, Beijing University of Posts and Telecommunications, Beijing 100876, China*)

([2]*MOE Key Lab of Universal Wireless Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China*)

[†]E-mail: liuyi@mail.wtilabs.cn

Received Jan. 15, 2010; Revision accepted Mar. 31, 2010; Crosschecked Aug. 31, 2010

**Abstract:** For multiple-relay cooperative networks with multiple antennas deployed at source and destination nodes, we investigate the outage performance of selection based semi-blind amplify-and-forward (AF) relaying, where transmit beamforming (TB) is conducted at source transmission and maximum ratio combining (MRC) at destination reception. Based on the Kolmogorov-Smirnov test, we analyze the impact of the configuration of destination antennas on the outage performance under arbitrary Nakagami-*m* fading channels. Results reveal that increasing the number of destination antennas is not necessary for an improvement of outage performance with any Nakagami-*m* parameter. Inspired by this fact, an approximation is proposed for the optimal selection. Simulation results show that the approximation is an efficient selection method.

**Key words:** Semi-blind relaying, Transmit beamforming (TB), Maximum ratio combining (MRC), Relay selection
**doi:**10.1631/jzus.C1010020 **Document code:** A **CLC number:** TN911

## 1 Introduction

Cooperative communication, in which single-antenna users share their antennas cooperatively to create a virtual multiple-input multiple-output (MIMO) system (Sendonaris *et al*., 2003a; 2003b; Nosratinia *et al*., 2004; Zhang *et al*., 2008), has attracted a lot of attention. The spatial diversity resulting from these virtual MIMO systems leads to much higher data rates and more reliable services over a larger coverage.

Based on the fact that channel state information (CSI) assisted amplify-and-forward (AF) relaying must continuously monitor the channel to obtain the instantaneous CSI, there is often significant system complexity. Hasna and Alouini (2004) presented a semi-blind AF protocol, which does not require the instantaneous CSI of the first hop, but only a knowledge of the statistical one. This characteristic makes the use of semi-blind AF relaying attractive from a practical standpoint, especially due to its low complexity and ease of deployment. Thus far, this idea has been extensively studied and several milestones in this area have been achieved. In multiple-relay networks, researchers have provided the outage probability (OP) of the semi-blind AF relaying with partial relay selection, but a single antenna was used at each node (da Costa and Aissa, 2009a; Suraweera *et al*., 2009). Behrouz and Hjørungnes (2009b) and Behrouz *et al*. (2010) were on the performance analysis and power allocation of practical distributed space-time code (DSTC) for the semi-blind AF relay networks with multiple antennas. Furthermore, Muhaidat *et al.* (2009) and Behrouz and Hjørungnes (2009a) quantified the impact of multiple antennas deployment, although only the Rayleigh fading channel was discussed.

* Project supported by the National Natural Science Foundation (No. 60772113), the National High-Tech Research and Development Program (863) (No. 2009AA011502), and the National Basic Research Program (973) of China (No. 2009CB320406)

In this paper, we further consider the selection-based semi-blind AF relay networks with multiple-antenna source and destination but multiple single-antenna relays. The spatial diversity is investigated in an alternative way where two kinds of antenna processing techniques are applied at the source and destination nodes, namely transmit beamforming (TB) for source transmission and maximum ratio combining (MRC) for destination reception. These techniques are often utilized in point-to-point multiple-input single-output (MISO) or single-input multiple-output (SIMO) wireless links, and have been shown to achieve the optimal diversity-multiplexing tradeoff (DMT) in these cases. Based on the Kolmogorov-Smirnov test, we analyze the impact of the number of destination antennas on the outage performance, which can serve as a guideline for the configuration of destination antennas. Under arbitrarily distributed Nakagami-*m* channels, analytical results reveal that two antennas at the destination can guarantee the outage performance when the relay is close to the source node. Otherwise, a single antenna achieves nearly the same performance as multiple antennas. Motivated by this observation, we present an approximation to the optimal centralized selection scheme. Simulation results show that our proposed approximation has a comparable performance to the optimal selection. Therefore, it can be a practical selection method.

## 2 System model

We consider a half-duplex dual-hop relay wireless network, where a source node ($\mathcal{S}$) communicates with a destination node ($\mathcal{D}$) under the help of $K_\mathrm{r}$ relays ($\mathcal{R}$). Nodes $\mathcal{S}$ and $\mathcal{D}$ are equipped with $N_\mathrm{s}$ and $N_\mathrm{d}$ antennas, respectively, while each relay has a single antenna. For simplicity, we assume that there is no direct link between the source and the destination due to the unsatisfactory quality of channel between $\mathcal{S}$ and $\mathcal{D}$. The CSI is supposed to be available at the source node. Let $\boldsymbol{h}_{\mathrm{s},i}$ represent the $1\times N_\mathrm{s}$ channel vector from the source to the $i$th relay, and $\boldsymbol{h}_{i,\mathrm{d}}$ the $N_\mathrm{d}\times 1$ channel vector from the $i$th relay to the destination. We assume flat fading channels, which are modeled as independent but not identically distributed (i.n.i.d). That is, the fading entries are independent and Nakagami-*m* distributed, with the mean power being $\Omega_{\mathrm{s},i}$ for $\boldsymbol{h}_{\mathrm{s},i}$ and $\Omega_{i,\mathrm{d}}$ for $\boldsymbol{h}_{i,\mathrm{d}}$, respectively. Moreover, $n_i$ is the complex additive white Gaussian noise (AWGN) with mean power $N_0$ at the $i$th relay, and $\boldsymbol{n}_\mathrm{d}$ stands for the $N_\mathrm{d}\times 1$ AWGN vector with mean power $N_0\boldsymbol{I}_{N_\mathrm{d}}$ at the destination. $\boldsymbol{I}_{N_\mathrm{d}}$ is the $N_\mathrm{d}\times 1$ identity vector.

The transmission from $\mathcal{S}$ to $\mathcal{D}$ can be split into two phases. In the first phase, the source broadcasts $s$ after being weighted by an $N_\mathrm{s}\times 1$ TB vector, $\boldsymbol{w}_{\mathrm{s},i}$, according to the best relay. In the second phase, only the best relay node amplifies the received signal with a fixed gain $G_i$ and forwards it to the destination. This mode can be seen as proactive cooperation, in which the specific relay, selected prior to the source transmission, participates in the cooperation. The best relay $i^*$ can be mathematically given by

$$i^* = \arg\max_{1\le i\le K_\mathrm{r}} \gamma_\mathrm{d}^i, \tag{1}$$

where $\gamma_\mathrm{d}^i$ is the received signal-to-noise ratio (SNR) with the $i$th relay selected. Different from the CSI-assisted AF protocol, the relay gain $G_i$ is a fixed gain regardless of the signal amplitude on the first hop. We assume that the destination performs MRC of the received signal through multiplying the signal with a combining vector, $\boldsymbol{w}_{i,\mathrm{d}}$. Therefore, under the best relay selected, the combined signal of the destination can be written as

$$\Gamma_\mathrm{d}^* = \boldsymbol{w}_{i^*,\mathrm{d}}\sqrt{G_{i^*}}\boldsymbol{h}_{i^*,\mathrm{d}}\left(\sqrt{\mathcal{P}_\mathrm{s}}\boldsymbol{h}_{\mathrm{s},i^*}\boldsymbol{w}_{\mathrm{s},i^*}s + n_i^*\right) + \boldsymbol{w}_{i^*,\mathrm{d}}\boldsymbol{n}_\mathrm{d}, \tag{2}$$

where $s$ is the user data with unit energy, and $\mathcal{P}_\mathrm{s}$ is the transmit power at the source node. Based on Lo (1999), we consider that $\boldsymbol{w}_{\mathrm{s},i^*} = \boldsymbol{h}_{\mathrm{s},i^*}^\dagger / \|\boldsymbol{h}_{\mathrm{s},i^*}\|_\mathrm{F}$ and $\boldsymbol{w}_{i^*,\mathrm{d}} = \boldsymbol{h}_{i^*,\mathrm{d}}^\dagger / \|\boldsymbol{h}_{i^*,\mathrm{d}}\|_\mathrm{F}$, where $\|\cdot\|_\mathrm{F}$ is the Frobenius norm, and $(\cdot)^\dagger$ denotes the conjugate transpose. Hence, the received SNR at the destination can be expressed as

$$\gamma_\mathrm{d}^* = \rho\gamma_\mathrm{d}^{i^*} = \rho\frac{\gamma_1^{i^*}\gamma_2^{i^*}}{\gamma_2^{i^*} + C_{i^*}}, \tag{3}$$

where $\rho = \mathcal{P}_{\rm s} / N_0$ and $C_{i^*} = 1/G_{i^*}$. For convenience of presentation, we define two random values, $\gamma_1^{i^*} \triangleq \sum_{k=1}^{N_{\rm s}} \left| h_{{\rm s},i^*}^k \right|^2$ and $\gamma_2^{i^*} \triangleq \sum_{k=1}^{N_{\rm d}} \left| h_{i^*,{\rm d}}^k \right|^2$.

## 3 Impact of the number of destination antennas on the outage probability

In this section, the impact of the number of destination antennas on the outage probability (OP) is first analyzed with the Kolmogorov-Smirnov test. Based on the analytical results, an approximation method is proposed for the optimal selection.

### 3.1 Brief overview of end-to-end outage performance

We provide some brief overviews about the end-to-end OP of AF relaying (i.e., semi-blind and CSI-assisted). According to the selection criterion in Eq. (1), the OP of semi-blind AF relaying can be defined by

$$P_{\rm out} = P\left(\frac{1}{2}\log_2(1+\rho\gamma_{\rm d}^{i^*}) < R\right) = P(\gamma_{\rm d}^{i^*} < \Xi) = \prod_{i=1}^{K_{\rm R}} P(\gamma_{\rm d}^{i} < \Xi), \tag{4}$$

where $\Xi = (2^{2R}-1)/\rho$ and $R$ is the data rate. With the help of identity (10) of da Costa and Aissa (2009b), Eq. (4) can be given by

$$P_{\rm out} = \prod_{i=1}^{K_{\rm r}} \left\{ 1 - \frac{2(m_2^i)^{N_{\rm d}m_2^i} \exp\left(-m_1^i \Xi / \Omega_{{\rm s},i}\right)}{(\Omega_{i,{\rm d}})^{N_{\rm d}m_2^i} \Gamma(N_{\rm d}m_2^i, 0)} \cdot \sum_{j=0}^{N_{\rm s}m_1^i-1} \left[ \frac{(m_1^i)^j \Xi^j}{(\Omega_{{\rm s},i})^j j!} \sum_{k=0}^{j} \left( C_j^k (C_i)^k \left( \frac{C_i m_1^i \Omega_{i,{\rm d}} \Xi}{m_2^i \Omega_{{\rm s},i}} \right)^{(N_{\rm d}m_2^i - k)/2} \cdot K_{N_{\rm d}m_2^i-k}\left( 2\sqrt{\frac{C_i m_1^i m_2^i \Xi}{\Omega_{{\rm s},i}\Omega_{i,{\rm d}}}} \right) \right) \right] \right\}, \tag{5}$$

where $C_u^v = \dfrac{u!}{v!(u-v)!}$, $K_v(\cdot)$ denotes the $v$th modified Bessel function, and $\Gamma(\cdot,\cdot)$ is the incomplete Gamma function (Gradshteyn and Ryzhik, 2007). For the $i$th relay, $m_1^i$ and $m_2^i$ are the Nakagami-$m$ parameters of the first and second hops, respectively. When $m_{\rm a}^i = 1$ ($a$=1, 2), the hops experience Rayleigh fading. Based on Hasna and Alouini (2004) and with the help of identity (6) of da Costa and Aissa (2009b), a reasonable choice for $G_i$ is

$$G_i = E\left(\frac{\mathcal{P}_{\rm r}}{\mathcal{P}_{\rm s}\gamma_1^i + N_0}\right) = \int_0^{+\infty} \frac{\mathcal{P}_{\rm r}}{\mathcal{P}_{\rm s}\gamma_1^i + N_0} \frac{(m_1^i)^{N_{\rm s}m_1^i} (\gamma_1^i)^{N_{\rm s}m_1^i-1}}{\Gamma(N_{\rm s}m_1^i)(\Omega_{{\rm s},i})^{N_{\rm s}m_1^i}} \exp\left(-\frac{m_1^i\gamma_1^i}{\Omega_{{\rm s},i}}\right) {\rm d}\gamma_1^i = \frac{\mathcal{P}_{\rm r} m_1^i}{\mathcal{P}_{\rm s}(N_{\rm s}m_1^i - 1)\Omega_{{\rm s},i}}, \tag{6}$$

where $E(\cdot)$ denotes the statistical average, and $\mathcal{P}_{\rm r}$ is the transmit power of the relay node.

Furthermore, the closed-form expression of OP for CSI-assisted relaying can be written by

$$P_{\rm out}^{\rm CSI} = \prod_{n=1}^{K_{\rm r}} \left\{ 1 - 2\exp\left(-\frac{m_1^n \Xi}{\rho_{\rm s}\Omega_{{\rm s},n}}\right) \exp\left(-\frac{m_2^n \Xi}{\rho_{\rm r}\Omega_{n,{\rm d}}}\right) \cdot \sum_{k=0}^{N_{\rm s}m_1^i-1} \sum_{i=0}^{k} \sum_{j=0}^{N_{\rm d}m_2^i-1} \left[ \frac{C_k^i C_{N_{\rm d}m_2^i-1}^j}{k!(N_{\rm d}m_2^i-1)!} \Xi^{\frac{2N_{\rm d}m_2^i+i-j+k-1}{2}} \cdot (\Xi+1)^{\frac{j+k-i+1}{2}} \left(\frac{m_1^i}{\rho_{\rm s}\Omega_{{\rm s},i}}\right)^{\frac{i+j+k+1}{2}} \left(\frac{m_2^i}{\rho_{\rm r}\Omega_{i,{\rm d}}}\right)^{\frac{2N_{\rm d}m_2^i-i-j+k-1}{2}} \cdot K_{i+j-k+1}\left( 2\sqrt{\frac{m_1^i m_2^i \Xi(\Xi+1)}{\rho_{\rm s}\Omega_{{\rm s},i}\rho_{\rm r}\Omega_{i,{\rm d}}}} \right) \right] \right\}, \tag{7}$$

where $\rho_{\rm s} = \mathcal{P}_{\rm s}/N_0$ and $\rho_{\rm r} = \mathcal{P}_{\rm r}/N_0$. For the detailed derivation, refer to the Appendix.

### 3.2 Analysis of impact of the number of destination antennas

For semi-blind AF relaying, the received SNR (Eq. (3)) has a special characteristic compared with CSI-assisted AF relaying (see Eq. (A2) in the Appendix). That is, when $\gamma_2^i \gg C_i$, Eq. (3) can be simplified as

$$\gamma_{\mathrm{d}}^{*}=\rho\gamma_{1}^{i^{*}}, \tag{8}$$

which means that the outage performance is independent of the second hop. Obviously, $\gamma_2^i$ depends on the number of destination antennas and $m_2^i$. Therefore, the impact of destination antennas and $m_2^i$ is worthy of being further studied. To quantify such an impact, we define the Kolmogorov-Smirnov statistic (Lehmann and Romano, 2008):

$$D_{N_{\mathrm{d}}}=\sup_{0<\Omega_{i,\mathrm{d}}<+\infty}\left|F_{N_{\mathrm{d}}-1}(\Omega_{i,\mathrm{d}})-F_{N_{\mathrm{d}}}(\Omega_{i,\mathrm{d}})\right|, \tag{9}$$

where sup(·) denotes supremum. With the help of identity (6) of da Costa and Aissa (2009b), $F_{N_{\mathrm{d}}}(\Omega_{i,\mathrm{d}})$ can be given by

$$\begin{aligned}F_{N_{\mathrm{d}}}(\Omega_{i,\mathrm{d}})&=P(\gamma_2^i>\lambda)\\&=1-\int_0^{\lambda}\frac{(m_2^i)^{N_{\mathrm{d}}m_2^i}(\gamma_2^i)^{N_2m_2^i-1}}{\Gamma(N_{\mathrm{d}}m_2^i)(\Omega_{i,\mathrm{d}})^{N_{\mathrm{d}}m_2^i}}\exp\left(-\frac{m_2^i\gamma_2^i}{\Omega_{i,\mathrm{d}}}\right)\mathrm{d}\gamma_2^i\\&=\exp\left(-\frac{m_2^i\lambda}{\Omega_{i,\mathrm{d}}}\right)\sum_{k=0}^{N_{\mathrm{d}}m_2^i-1}\frac{(m_2^i\lambda)^k}{k!(\Omega_{i,\mathrm{d}})^k},\end{aligned} \tag{10}$$

where $\lambda=\beta C_i$, $\beta$ is a constant. Substitution of Eq. (10) into Eq. (9) yields

$$D_{N_{\mathrm{d}}}=\exp\left(-\frac{m_2^i\lambda}{\Omega_{i,\mathrm{d}}}\right)\sum_{k=(N_{\mathrm{d}}-1)m_2^i}^{N_{\mathrm{d}}m_2^i-1}\frac{(m_2^i\lambda)^k}{k!(\Omega_{i,\mathrm{d}})^k}. \tag{11}$$

We assume that the mean channel gain between the $i$th relay and the destination is $\Omega_{i,\mathrm{d}}=1/(1+d_{i,\mathrm{d}})^{\eta}$, where $d_{i,\mathrm{d}}$ denotes the distance from the relay to the destination, and $\eta$ is the path loss exponent. Given the $i$th relay, Fig. 1 shows the Kolmogorov-Smirnov statistic against distance $d_{i,\mathrm{d}}$ for different transmit power. We select $\beta$=10, which means that $\gamma_2^i$ should be much larger than $C_i$. Under significance level $\alpha$=0.1, we compare two scenarios, $m_1^i=m_2^i=1$ and $m_1^i=m_2^i=2$. With the Kolmogorov-Smirnov test (Lehmann and Romano, 2008), we conclude that $N_{\mathrm{d}}$=1 can guarantee $\gamma_2^i\gg C_i$ when the relay is close to the destination.

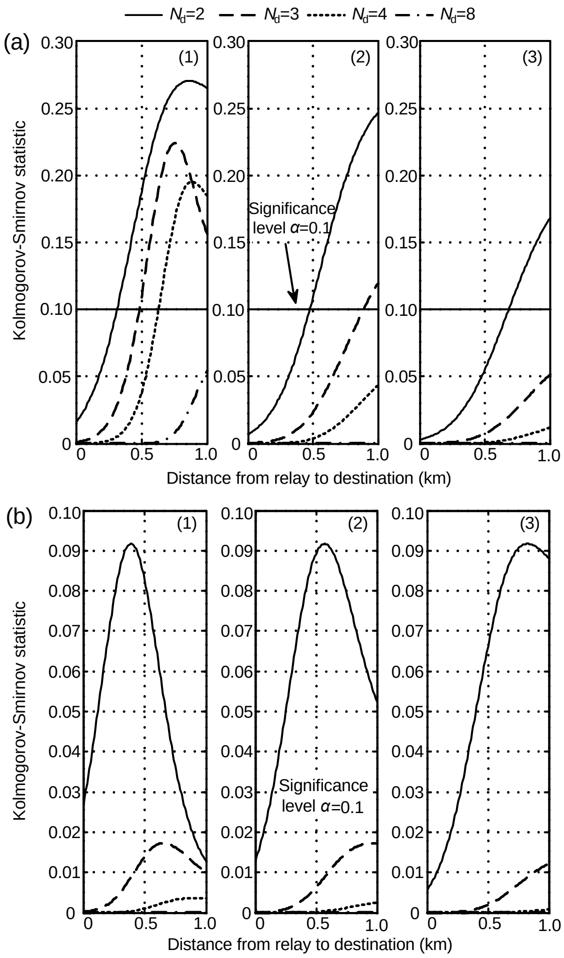


**Fig. 1 Kolmogorov-Smirnov statistic against the distance from the relay to the destination, where the distance from the source to the destination is 1 km, $\eta$=3, and significance level $\alpha$=0.1**

(1) $\mathcal{P}_{\mathrm{s}}=\mathcal{P}_{\mathrm{r}}=4$ dB; (2) $\mathcal{P}_{\mathrm{s}}=\mathcal{P}_{\mathrm{r}}=5$ dB; (3) $\mathcal{P}_{\mathrm{s}}=\mathcal{P}_{\mathrm{r}}=6$ dB. (a) Nakagami-$m$ parameter $m_1^i=m_2^i=1$; (b) Nakagami-$m$ parameter $m_1^i=m_2^i=2$

Simultaneously, $N_{\mathrm{d}}$=2 is sufficient for $\gamma_2^i\gg C_i$ when the relay is located adjacent to the source node. Moreover, this conclusion will have a better approximation with the increase of transmit power and the number of destination antennas. Therefore, according to the specific significance level, there will always be a minimum antenna configuration for $\gamma_2^i\gg C_i$. This fact means that increasing the number of destination antennas is not necessary for the improvement of outage performance. Also, it provides a guideline to reduce the complexity of relay selection and system design without performance degradation.

Specifically, as the values of $m_1^i$ and $m_2^i$ increase, the same conclusions can be obtained. Thus, variations of the Nakagami parameter have no effect on the behavior of the destination antennas.

### 3.3 Approximation of relay selection for semi-blind AF relaying

The selection scheme in Eq. (1) is centralized. From the view of the source node, it needs to compare the value of $\gamma_{\rm d}^i$ across each cooperative link (i.e., source-*i*th relay-destination) to determine which relay will participate in the cooperation. Although the source can obtain the CSI of the forward link $\boldsymbol{h}_{{\rm s},i}$, based on the assumption of time-division-duplex (TDD) mode, it still needs to know $\boldsymbol{h}_{i,{\rm d}}$. This fact requires extra information exchange from the destination to the source, which will lead to tremendous feedback.

For practical reasons, one may want to reduce the amount of information exchange among the nodes. Based on the previous discussion, a proper configuration of destination antennas will lead to $\gamma_2^i \gg C_i$. Therefore, Eq. (3) can be approximated by Eq. (8) and CSI of the first hop could determine the selected relay, which is given by

$$j^* = \arg\max_{1\le j\le K_{\rm r}} (\gamma_1^j)\ . \tag{12}$$

This is the same as the partial relay selection in Krikidis *et al.* (2008). Thus, OP can be reformulated as

$$P_{\rm out} = \prod_{i=1}^{K_{\rm r}}\left[1-\exp\left(-\frac{m_1^i\varXi}{\varOmega_{\rm s,i}}\right)\sum_{k=0}^{N_{\rm s}m_1^i-1}\frac{1}{k!}\left(\frac{m_1^i\varXi}{\varOmega_{{\rm s},i}}\right)^k\right]$$
$$=\prod_{i=1}^{K_{\rm r}}\left[\exp\left(-\frac{m_1^i\varXi}{\varOmega_{\rm s,i}}\right)\sum_{k=0}^{+\infty}\frac{(m_1^i\varXi)^{k+N_{\rm s}m_1^i}}{(\varOmega_{{\rm s},i})^{k+N_{\rm s}m_1^i}(k+N_{\rm s}m_1^i)!}\right]. \tag{13}$$

We further study the DMT performance of this approximation. Consider the cooperative system operating at SNR $\rho$ and having rate $R(\rho)$. If $P_{\rm out}$ denotes the OP for rate $R$, the DMT can be defined by

$$d(r) = -\lim_{\rho\to+\infty}\frac{\log_2 P_{\rm out}(R)}{\log_2\rho}, \tag{14}$$

where $d(\cdot)$ is the diversity order and $r$ is the multiplexing order. To obtain the DMT of the proposed cooperative scheme, define the data rate $R$ as the function of $\rho$:

$$R = r\log_2\rho. \tag{15}$$

Substituting Eqs. (13) and (15) into Eq. (14), we have

$$d(r) = -\lim_{\rho\to+\infty}\left\{\frac{1}{\log_2\rho}\log_2\prod_{i=1}^{K_{\rm r}}\left[\exp\left(-\frac{m_1^i(2^{2r\log\rho}-1)}{\varOmega_{{\rm s},i}\rho}\right)\right.\right.$$
$$\left.\left.\cdot\sum_{k=0}^{+\infty}\frac{(m_1^i)^{k+N_{\rm s}m_1^i}\left((2^{2r\log_2\rho}-1)/\rho\right)^{k+N_{\rm s}m_1^i}}{(\varOmega_{{\rm s},i})^{k+N_{\rm s}m_1^i}(k+N_{\rm s}m_1^i)!}\right]\right\}$$
$$\le -\lim_{\rho\to+\infty}\left\{\frac{1}{\log_2\rho}\left[\sum_{i=1}^{K_{\rm r}}\log_2\left(\exp\left(-\frac{m_1^i\rho^{2r-1}}{\varOmega_{{\rm s},i}}\right)\right)\right.\right.$$
$$\left.\left.+\sum_{i=1}^{K_{\rm r}}\log_2\left(\sum_{k=0}^{+\infty}\frac{(m_1^i)^{k+N_{\rm s}m_1^i}\rho^{(2r-1)(k+N_{\rm s})}}{(\varOmega_{{\rm s},i})^{k+N_{\rm s}}(k+N_s)!}\right)\right]\right\}$$
$$\le -\lim_{\rho\to+\infty}\left\{\frac{1}{\log_2\rho}\sum_{i=1}^{K_{\rm r}}\log_2\left(\sum_{k=0}^{+\infty}\frac{(m_1^i)^{k+N_{\rm s}m_1^i}\rho^{(2r-1)(k+N_{\rm s})}}{(\varOmega_{{\rm s},i})^{k+N_{\rm s}}(k+N_{\rm s})!}\right)\right\}$$
$$\le -\lim_{\rho\to+\infty}\left\{\frac{1}{\log_2\rho}\sum_{i=1}^{K_{\rm r}}\log_2\left(\rho^{(2r-1)N_{\rm s}}+O(\rho)\right)\right\}$$
$$=(1-2r)K_{\rm r}N_{\rm s}, \tag{16}$$

where 0≤*r*≤0.5. Notice that, the relays can periodically transmit pilots at the beginning of each coherent time interval of $\mathcal{S}\to\mathcal{R}$ channel. Therefore, using the channel reciprocity property, $\mathcal{S}$ can estimate CSI for the forward $\mathcal{S}\to\mathcal{R}_i$ channel and select the relay node with maximum $\gamma_1^i$. This method will be more meaningful considering the tremendous feedback and additional network delays for monitoring the global connectivity among different links. It can be called 'cooperative relay selection' (CRS). In the next section, simulation results will evaluate the performance gap between the optimal selection and this approximation one.

## 4 Numerical and simulation results

In this section, Monte-Carlo simulation results are provided to validate our theoretical analysis. It was assumed that the variance of AWGN at relay and destination nodes was $N_0$=0 dB. The target data rate was set as $R$=1.5 bits/(s·Hz). Relay gain $G_i$ was calculated with Eq. (6).

Fig. 2 shows the analytical and simulation results of the end-to-end OP against the average SNR per hop. We compared the OP between semi-blind and CSI-assisted AF relaying for two cases, in which $N_s$, $K_r$, $N_d$, and $m_a^i$ ($a$=1, 2) have different configurations. The analytical OP exactly matched the simulation results for both symmetric and asymmetric scenarios. Note that, networks with semi-blind AF relays slightly outperformed networks with CSI-assisted AF relays under Nakagami-$m$ channels.

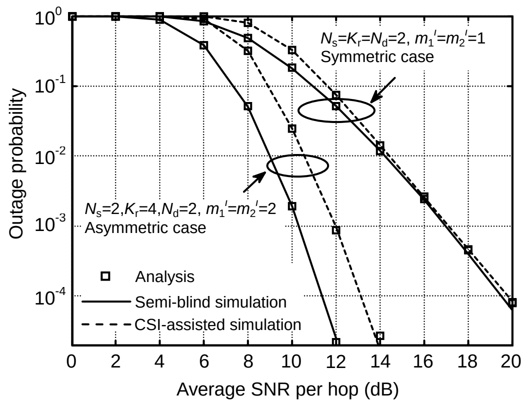


**Fig. 2 Outage probability against the average signal-to-noise ratio (SNR) per hop for a symmetric scenario ($\{\Omega_{s,i}\}_{i=1}^{K_r}=\{\Omega_{i,d}\}_{i=1}^{K_r}$=0 dB) and an asymmetric scenario ($\{\Omega_{s,i}\}_{i=1}^{K_r}=\{\Omega_{i,d}\}_{i=1}^{K_r}$={0.5, 1, 1.5, 2} dB)**

Under different transmit power, we compared the outage performance of semi-blind AF relaying between the configurations with the same $N_s$ and $K_r$, but different $N_d$ and $m_a^i$ ($a$=1, 2), for the optimal selection in Eq. (1) and CRS in Eq. (12), respectively (Figs. 3a and 3b). Both figures show that a single antenna can guarantee the outage performance when the relay was close to the destination node (i.e., $d_{i,d}$=0–0.3 km). Otherwise, two antennas at the destination almost achieved the same performance as many more antennas. This observation supports the conclusion of Section 3. Comparison of Figs. 3a and 3b shows that: (1) the number of destination antennas has much less impact on the outage performance for the optimal selection; (2) CRS has a comparable outage performance to the optimal selection when a single antenna is used at the destination; (3) with the increase of the number of destination antennas, the performance gap between these two methods can almost be neglected; and (4) the variations of $m_1^i$ and $m_2^i$ almost have no effect on the behavior of destination antennas. Thus, CRS can be a practical selection scheme with less feedback for obtaining the global CSI of different links. The DMT is plotted in Fig. 4. The proposed scheme had a better DMT performance over other cooperative ones and the maximum diversity gain was $K_r \times N_s$.

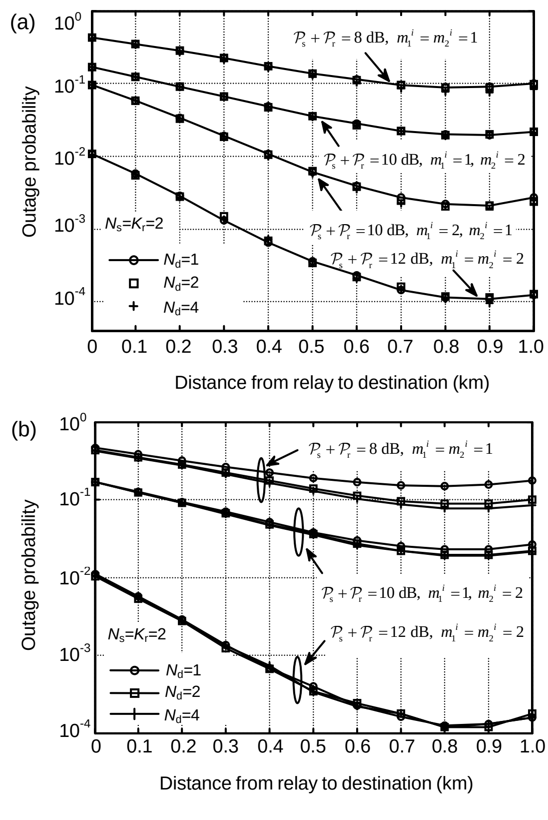


**Fig. 3 Impact of the configuration of destination antennas on the end-to-end outage probability against the distance from the relay to the destination for the optimal selection scenario (a) and the cooperative relay selection (CRS) method scenario (b)**

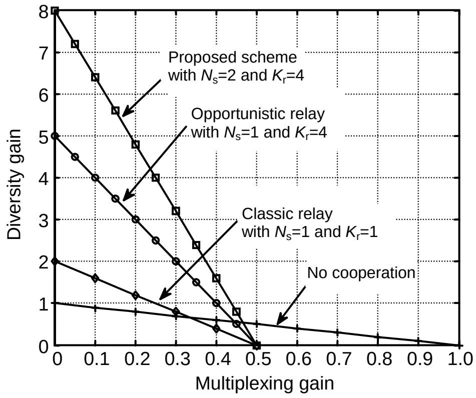


**Fig. 4 Diversity-multiplexing tradeoff of different protocols with $N_d$=1**

## 5 Conclusions

In this paper, we investigate the outage performance for selection based semi-blind amplify-and-forward relay networks under arbitrary Nakagami-*m* channels. To further improve the end-to-end outage performance, transmit beamforming and maximum ratio combining are used at source and destination nodes, respectively. Through the Kolmogorov-Smirnov test, we further analyze the impact of the number of destination antennas on the outage performance. Results show that a single antenna can guarantee the outage performance when the relay is close to the destination. Otherwise, two antennas achieve the same performance as many more antennas. Based on this observation, an approximation is proposed for the optimal selection. Numerical results show that the theoretical analysis exactly matches the simulation results and confirm that our proposed approximation is a practical selection scheme.

## References


Behrouz, M., Hjørungnes, A., 2009a. Opportunistic Relaying for Space-Time Coded Cooperation with Multiple Antennas Terminals. Proc. IEEE Personal Indoor and Mobile Radio Communications Symp., p.1-5.

Behrouz, M., Hjørungnes, A., 2009b. Power allocation strategies for distributed space-time codes in amplify-and-forward mode. *EURASIP J. Adv. Signal Process.*, **2009**, Article No. 612719, p.1-13. [doi:10.1155/2009/612719]

Behrouz, M., Hjørungnes, A., Rajan, B.S., 2010. Quasi-Orthogonal Design and Performance Analysis of Amplify-and-Forward Relay Networks with Multiple-Antennas. Proc. IEEE Wireless Communications and Networking Conf., p.1-6.

da Costa, D.B., Aissa, S., 2009a. Cooperative dual-hop relaying systems with beamforming over Nakagami-*m* fading channels. *IEEE Trans. Wirel. Commun.*, **8**(8):3950-3954. [doi:10.1109/TWC.2009.081353]

da Costa, D.B., Aissa, S., 2009b. End-to-end performance of dual-hop semi-blind relaying systems with partial relay selection. *IEEE Trans. Wirel. Commun.*, **8**(8):4306-4315. [doi:10.1109/TWC.2009.081262]

Gradshteyn, I.S., Ryzhik, I.M., 2007. Table of Integrals, Series, and Products (7th Ed.). Academic Press, California, USA, p.340-341, 368.

Hasna, M.O., Alouini, M.S., 2004. A performance study of dual-hop transmissions with fixed gain relays. *IEEE Trans. Wirel. Commun.*, **3**(6):1963-1968. [doi:10.1109/TWC.2004.837470]

Krikidis, I., Thompson, J., McLaughlin, S., Goertz, N., 2008. Amplify-and-forward with partial relay selection. *IEEE Commun. Lett.*, **12**(4):235-237. [doi:10.1109/LCOMM.2008.071987]

Lehmann, E.L., Romano, J.P., 2008. Testing Statistical Hypotheses (Springer Texts in Statistics) (3rd Ed.). Springer, USA, p.584.

Lo, T.K.Y., 1999. Maximum ratio transmission. *IEEE Trans. Commun.*, **47**(10):1458-1461. [doi:10.1109/26.795811]

Muhaidat, S., Uysal, M., Adve, R., 2009. Blind Amplify-and-Forward Relaying in Multiple-Antenna Relay Networks. Proc. IEEE Wireless Communications and Networking Conf., p.1-6. [doi:10.1109/WCNC.2009.4917613]

Nosratinia, A., Hunter, T.E., Hedayat, A., 2004. Cooperative communication in wireless networks. *IEEE Commun. Mag.*, **42**(10):74-80. [doi:10.1109/MCOM.2004.1341264]

Sendonaris, A., Erkip, E., Aazhang, B., 2003a. User cooperation diversity-part I: system description. *IEEE Trans. Commun.*, **51**(11):1927-1938. [doi:10.1109/TCOMM.2003.818096]

Sendonaris, A., Erkip, E., Aazhang, B., 2003b. User cooperation diversity-part II: implementation aspects and performance analysis. *IEEE Trans. Commun.*, **51**(11):1939-1948. [doi:10.1109/TCOMM.2003.819238]

Suraweera, H.A., Michalopoulos, D.S., Karagiannidis, G.K., 2009. Semi-blind amplify-and-forward with partial relay selection. *IET Electron. Lett.*, **45**(6):317-319. [doi:10.1049/el.2009.3089]

Zhang, L., Chuai, G., Lin, L.F., Wen, X.J., 2008. Power allocation for cooperative decode-and-forward transmission with multiple cooperative relays and multiple received antennas. *J. Beijing Univ. Posts Telecommun.*, **31**(6):104-108 (in Chinese).

## Appendix

For CSI-assisted AF relaying, the received SNR can be reformulated as

$$\gamma_{\mathrm{d}}=\frac{\left(\rho_{\mathrm{s}}\sum_{k=1}^{N_{\mathrm{s}}}\left|h_{\mathrm{s},i}^{k}\right|^{2}\right)\left(\rho_{\mathrm{r}}\sum_{k=1}^{N_{\mathrm{d}}}\left|h_{i,\mathrm{d}}^{k}\right|^{2}\right)}{\left(\rho_{\mathrm{s}}\sum_{k=1}^{N_{\mathrm{s}}}\left|h_{\mathrm{s},i}^{k}\right|^{2}\right)+\left(\rho_{\mathrm{r}}\sum_{k=1}^{N_{\mathrm{d}}}\left|h_{i,\mathrm{d}}^{k}\right|^{2}\right)+1}, \quad \text{(A1)}$$

where $\rho_{\mathrm{s}}=\mathcal{P}_{\mathrm{s}}/N_0$ and $\rho_{\mathrm{r}}=\mathcal{P}_{\mathrm{r}}/N_0$. Plugging the gains' expressions into Eq. (A1), it follows that

$$\gamma_{\mathrm{d}}=\frac{\gamma_1^i\gamma_2^i}{\gamma_1^i+\gamma_2^i+1}, \quad \text{(A2)}$$

where $\gamma_1^i=\rho_{\mathrm{s}}\sum_{k=1}^{N_{\mathrm{s}}}\left|h_{\mathrm{s},i}^{k}\right|^{2}$. Based on da Costa and Aissa (2009b), the cumulative density function of $\gamma_1^i$ can be denoted as

$$P(\gamma_1^i<\varXi)=1-\exp\left(-\frac{m_1^i\varXi}{\rho_{\mathrm{s}}\varOmega_{\mathrm{s},i}}\right)\sum_{k=0}^{N_{\mathrm{s}}m_1^i-1}\frac{1}{k!}\left(\frac{m_1^i\varXi}{\rho_{\mathrm{s}}\varOmega_{\mathrm{s},i}}\right)^{k}, \quad \text{(A3)}$$

and $\gamma_2^i=\rho_{\mathrm{r}}\sum_{k=1}^{N_{\mathrm{d}}}\left|h_{i,\mathrm{d}}^{k}\right|^{2}$ obeys the distribution

$$f(\gamma_2^i)=\frac{(m_2^i)^{N_{\mathrm{d}}m_2^i}(\gamma_2^i)^{N_{\mathrm{d}}m_2^i-1}}{\Gamma(N_{\mathrm{d}}m_2^i)(\rho_{\mathrm{r}}\varOmega_{i,\mathrm{d}})^{N_{\mathrm{d}}m_2^i}}\exp\left(-\frac{m_2^i\gamma_2^i}{\rho_{\mathrm{r}}\varOmega_{i,\mathrm{d}}}\right). \quad \text{(A4)}$$

Therefore, the following equation can be followed:

$$\begin{aligned}P\left(\frac{\gamma_1^i\gamma_2^i}{\gamma_1^i+\gamma_2^i+1}<\varXi\right)&=P(\gamma_2^i<\varXi)+P\left(\gamma_1^i<\frac{(\gamma_2^i+1)\varXi}{\gamma_2^i-\varXi}\middle|\gamma_2^i\right)\\&=1-\int_0^{\infty}\left\{\exp\left(-\frac{m_1^i}{\rho_{\mathrm{s}}\varOmega_{\mathrm{s},i}}\frac{(\gamma_2^i+1)\varXi}{\gamma_2^i-\varXi}\right)\right.\\&\quad\cdot\sum_{k=0}^{N_{\mathrm{s}}m_1^i-1}\frac{1}{k!}\left(\frac{m_1^i}{\rho_{\mathrm{s}}\varOmega_{\mathrm{s},i}}\frac{(\gamma_2^i+1)\varXi}{\gamma_2^i-\varXi}\right)^{k}\\&\quad\left.\cdot\frac{(m_2^i)^{N_{\mathrm{d}}m_2^i}(\gamma_2^i)^{N_{\mathrm{d}}m_2^i-1}}{\Gamma(N_{\mathrm{d}}m_2^i)(\rho_r\varOmega_{i,\mathrm{d}})^{N_{\mathrm{d}}m_2^i}}\exp\left(-\frac{m_2^i\gamma_2^i}{\rho_{\mathrm{r}}\varOmega_{i,\mathrm{d}}}\right)\right\}\mathrm{d}\gamma_2^i, \quad \text{(A5)}\end{aligned}$$

where $\varXi=2^{2R-1}$. With the help of (3.351.1) and (3.471.9) of Gradshteyn and Ryzhik (2007) and through some algebraic manipulations, Eq. (7) can be easily deduced from Eq. (A5).