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# Impact of Outdated Channel Estimates on a Distributed Link-Selection Scheme for AF Relaying Networks 

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#### Abstract

We investigate the impact of outdated channel estimates on the outage performance of a distributed link-selection scheme recently proposed for variable-gain amplify-and-forward relaying networks. In this scheme, either the direct link or the relaying link is preselected before each transmission, based on a distributed mechanism. We begin by showing that an exact analysis is rather intricate, yielding a multifold integral-form solution. Motivated by this, we then derive a simple closed-form lower bound, which, importantly, proves to be a very tight approximation to the exact outage probability. We also assess the system diversity order via asymptotic analysis.


Index Terms-Cooperative diversity, distributed link selection, outdated channel state information, outage probability.

## I. Introduction

COOPERATIVE diversity schemes have received increasing attention, as they improve coverage, reliability, and throughput in wireless communication networks. Many popular cooperative schemes benefit from two basic relaying protocols: amplify-and-forward (AF) and decode-and-forward (DF). The AF protocol is particularly attractive, as it requires a less sophisticated processing at the relay and destination. Previous studies on node-selection and link-selection schemes ${ }^{1}$ for AF relaying networks include the following. In [1], the performance of a relay-destination selection scheme for the downlink of a cooperative network was analyzed. In that work, it was assumed fixed AF relaying, half-duplex operation, and transmit beamforming, so that three time slots are required per message. The resulting spectral efficiency is one third of that attained by direct transmission. To circumvent this, an optimal centralized link-selection scheme was proposed in [2], in which the best link-direct or relaying-is preselected for transmission. Accordingly, the average spectral efficiency is above one half of that attained by direct transmission, while the same full diversity order of the scheme in [1] is achieved. Aimed at re-

[^0]

Fig. 1. System model for the dual-hop relaying network.
ducing the feedback overhead due to channel state information (CSI) requirements in [2], a distributed implementation of the link-selection scheme was proposed in [3], in which a nearlyoptimal outage performance is achieved.

A common limitation of the aforementioned works is that they assumed perfect CSI, which is indeed rarely attained in practice due to the time-varying nature of the wireless channel. Many works have studied the impact of outdated CSI on various relaying schemes, including those in [4]-[6] and [7]-[10], for the DF and AF protocols, respectively. All these works have addressed outdated CSI in the context of relay selection, and many related works exist in the context of destination selection. On the other hand, to our best knowledge, outdated CSI has not been addressed yet in the context of link-selection schemes-in the sense this term is used here. This paper aims to partially fill this gap.

In the following, we analyze the impact of outdated CSI on the outage performance of the distributed link-selection scheme proposed in [3]. First, we derive a mathematical framework to compute the exact outage probability, which proves rather intricate, leading to multifold integral-form results. Alternatively, we then derive a simple, closed-form, lower-bound expression for the outage probability. More importantly, this bound turns out to be a highly accurate approximation to the exact outage probability. Also, based on an asymptotic analysis, the system diversity order is shown to be unity, as expected. These analytical results are validated through Monte Carlo simulations.

Throughout the text, $f_{Z}(\cdot)$ and $F_{Z}(\cdot)$ denote the probability density function (PDF) and the cumulative distribution function (CDF) of a generic random variable $Z$, respectively, $E\{\cdot\}$ denotes expectation, and $\operatorname{Pr}(\cdot)$ denotes probability.

## II. System Model and Link-Selection Scheme

Consider a dual-hop cooperative cellular network composed by one source ( S ) that intends to communicate with one destination (D) by using either the direct link or a variable-gain AF relay station (R), as shown in Fig. 1. All the terminals are single-antenna devices, operate on a time-division multiple access basis, and employ half-duplex transmission. All the links are subjected to (i) additive white Gaussian noise (AWGN) with mean power $N_{0}$ and (ii) Rayleigh fading, i.e., the channel coefficients are circularly symmetric Gaussian random variables with zero mean and variance $\sigma^{2}$.

Before the transmission process takes place, a distributed link-selection scheme is carried out. To this end, let $\tilde{W}=$ $\left|\tilde{h}_{0}\right|^{2} d_{0}^{-\beta} P_{\mathrm{S}} / N_{0}, \tilde{X}=\left|\tilde{h}_{1}\right|^{2} d_{1}^{-\beta} P_{\mathrm{S}} / N_{0}$ and $\tilde{Y}=\left|\tilde{h}_{2}\right|^{2} d_{2}^{-\beta} P_{\mathrm{R}} / N_{0}$ be respectively the received signal-to-noise ratios (SNRs) of the direct link, the first-hop relaying link, and the second-hop re$\underset{\sim}{l}$ laying link, at the link-selection moment. In these expressions, $\tilde{h}_{0}, \tilde{h}_{1}$, and $\tilde{h}_{2}$ are the corresponding channel coefficients at the link-selection moment; $d_{0}, d_{1}$, and $d_{2}$ are the distances between S-D, S-R, and R-D, respectively; $\beta$ is the pathloss exponent; $P_{\mathrm{S}}$ is the transmit power at S ; and $P_{\mathrm{R}}$ is the transmit power at R.

The distributed link-selection mechanism proposed in [3] was based on a well-known upper bound for the received end-to-end SNR $\tilde{Z}=\tilde{X} \tilde{Y} /(\tilde{X}+\tilde{Y}+1)$ of the variable gain AF relaying link, namely $\tilde{Z} \leq \min \{\tilde{X}, \tilde{Y}\}$. Using this, a suboptimal decision can be made by comparing $\tilde{W}$ against $\min \{\tilde{X}, \tilde{Y}\}$ (instead of against $\tilde{Z}$ ), so that the resulting overall end-to-end received SNR $\gamma$ of the system can be written as [3]

$$
\gamma= \begin{cases}\mathrm{W}, & \text { if } \tilde{W} \geq \tilde{X} \text { or } \tilde{W} \geq \tilde{Y}  \tag{1}\\ Z=X Y /(X+Y+1), & \text { if } \tilde{W}<\tilde{X} \text { and } \tilde{W}<\tilde{Y}\end{cases}
$$

In the above, $W=\left|h_{0}\right|^{2} d_{0}^{-\beta} P_{\mathrm{S}} / N_{0}, X=\left|h_{1}\right|^{2} d_{1}^{-\beta} P_{\mathrm{S}} / N_{0}, Y=$ $\left|h_{2}\right|^{2} d_{2}^{-\beta} P_{\mathrm{R}} / N_{0}$, and $Z=X Y /(X+Y+1)$ are the received SNRs of the direct link, first-hop relaying link, second-hop relaying link, and end-to-end relaying link experienced by the signal at the transmission moment, respectively, with $h_{0}, h_{1}$, and $h_{2}$ being the corresponding channel coefficients. Remember that, due to the time-varying nature of fading channels, $\tilde{W}, \tilde{X}, \tilde{Y}$, and $\tilde{Z}$-experienced at the link-selection moment-are considered to be outdated versions of $W, X, Y$, and $Z$. Using the Jakes' model, each channel coefficient $h_{i}$ at the transmission moment and its outdated version $\tilde{h}_{i}$ at the link-selection moment $(i \in$ $\{0,1,2\})$ are autocorrelated samples of the same complexvalued Gaussian fading process. That is, $h_{i}$ and $\tilde{h}_{i}$ follow a bivariate Gaussian distribution with zero mean, variance $\sigma^{2}$, and correlation coefficient given by ${ }^{2}$

$$
\begin{equation*}
\rho_{i}=J_{0}\left(2 \pi f_{d, i} T_{D}\right) \tag{2}
\end{equation*}
$$

where $f_{d, i}$ is the maximum Doppler frequency ${ }^{3}, T_{D}$ is the time delay between the link-selection and transmission moments, and $J_{0}(\cdot)$ is the zero-order Bessel function of the first kind [11, Eq. (8.411)]. In particular, it is assumed that the relay has instantaneous CSI of the first-hop relaying link, so that it can select the amplification gain accordingly.

It is noteworthy that the approach in (1) enables the linkselection scheme to be implemented in a perfectly distributed manner through an efficient use of the local CSIs at S and D . More specifically, before each transmission, S first compares its local CSIs $\tilde{W}$ and $\tilde{X}$. If $\tilde{W} \geq \tilde{X}$, the direct link is selected for transmission. Otherwise, $S$ sends a 1-bit signaling message (e.g., a binary symbol " 0 ") to D to indicate that $\tilde{W}<\tilde{X}$. Upon hearing this message, D compares its local CSIs $\tilde{W}$ and $\tilde{Y}$. If $\tilde{W} \geq \tilde{Y}, \mathrm{D}$ broadcasts a 1-bit signaling message (e.g., a binary symbol " 1 ") to notify S that the direct link should be selected for transmission. Otherwise, D sends a 1-bit signaling message

[^1]to S (e.g., a binary symbol " 0 ") to indicate that $\tilde{W}<\tilde{Y}$, and that the dual-hop relaying link should be selected instead, once $\tilde{W}<$ $\min \{\tilde{X}, \tilde{Y}\}$. After the link-selection process, the information transmission is carried out in one or two time slots, depending on whether the direct link or the dual-hop relaying link was selected, respectively.

## III. Outage Probability

## A. Preliminaries

In this section, the outage probability of the proposed system is analyzed. By definition, the system is in outage if the received SNR at the destination (i.e., D) from the selected link (either the direct link or the dual-hop relaying link) falls bellow a certain threshold $\tau \stackrel{\Delta}{=} 2^{2 \Re_{s}}-1$, where $\mathfrak{R}_{s}$ is a predefined target spectral efficiency given in bits/s/Hz. From the previous section, note that the received SNRs ( $W, X$, and $Y$ ) and their respective outdated versions ( $\tilde{W}, \tilde{X}$, and $\tilde{Y}$ ) follow exponential distributions. In addition, $W$ and $\tilde{W}$ are correlated variates following a bivariate exponential distribution, as well as $X$ and $\tilde{X}$, and $Y$ and $\tilde{Y}$. Thus, the respective joint PDFs can be written as [4]

$$
\begin{equation*}
f_{M, \tilde{M}}(m, \tilde{m})=\frac{1}{\bar{\gamma}_{i}^{2}\left(1-\rho_{i}^{2}\right)} e^{-\frac{(m+\tilde{m})}{\bar{\gamma}_{i}\left(1-\rho_{i}^{2}\right)}} I_{0}\left(\frac{2 \sqrt{\rho_{i}^{2} m \tilde{m}}}{\bar{\gamma}_{i}\left(1-\rho_{i}^{2}\right)}\right), \tag{3}
\end{equation*}
$$

where $M \in\{W, X, Y\}$ and $i \in\{1,2,3\}$, as required, $\bar{\gamma}_{0}=$ $E\{W\}=E\{\tilde{W}\}, \bar{\gamma}_{1}=E\{X\}=E\{\tilde{X}\}, \bar{\gamma}_{2}=E\{Y\}=E\{\tilde{Y}\}, \rho_{i}$ is given in (2), and $I_{0}(\cdot)$ is the zero-order modified Bessel function of the first kind [11, Eq. (8.447.1)].

## B. Exact Analysis

From (1), and by defining the auxiliary random variable $\Phi \stackrel{\Delta}{=}$ $\min \{\tilde{X}, \tilde{Y}\}$, the outage probability can be formulated as

$$
\begin{equation*}
P_{\text {out }}=\underbrace{\operatorname{Pr}(\Phi<\tilde{W}, W<\tau)}_{I_{1}}+\underbrace{\operatorname{Pr}\left(\Phi>\tilde{W}, \frac{X Y}{X+Y+1}<\tau\right)}_{I_{2}} \tag{4}
\end{equation*}
$$

In the above, the term $I_{1}$ can be expressed as

$$
\begin{equation*}
I_{1}=\int_{\tilde{w}=0}^{\infty} \int_{w=0}^{\tau} f_{W, \tilde{W}}(w, \tilde{w}) F_{\Phi}(\tilde{w}) d w d \tilde{w} \tag{5}
\end{equation*}
$$

where $f_{W, \tilde{W}}(\cdot, \cdot)$ is given by (3), and the CDF of $\Phi$ can be obtained as

$$
\begin{equation*}
F_{\Phi}(\phi)=F_{\tilde{X}}(\phi)+F_{\tilde{Y}}(\phi)-F_{\tilde{X}}(\phi) F_{\tilde{Y}}(\phi)=1-e^{-\frac{\phi\left(\bar{\gamma}_{1}+\bar{\gamma}_{2}\right)}{\bar{\gamma}_{1} \tilde{\gamma}_{2}}} . \tag{6}
\end{equation*}
$$

With the help of [11, Eq. (6.614.3)] and [11, Eq. (9.220.2)], it can be shown that $\int_{0}^{\infty} e^{-\alpha z} I_{0}\left(2 \sqrt{\beta z} d z=\frac{1}{\alpha} e^{\frac{\beta}{\alpha}}\right.$. Applying this into (5), a closed-form expression for $I_{1}$ can be attained as

$$
\begin{align*}
I_{1}=\frac{\bar{\gamma}_{2} \bar{\gamma}_{0}+\bar{\gamma}_{1} \bar{\gamma}_{0}}{\bar{\gamma}_{1} \bar{\gamma}_{2}+\bar{\gamma}_{0}\left(\bar{\gamma}_{2}+\bar{\gamma}_{1}\right)}- & e^{-\frac{\tau}{\bar{\gamma}_{0}}} \\
& +\frac{\bar{\gamma}_{1} \bar{\gamma}_{2} e^{-\frac{\tau}{\gamma_{0}}}\left[\frac{\bar{\gamma}_{1} \bar{\gamma}_{2}+\bar{\gamma}_{2} \bar{\gamma}_{0}+\bar{\gamma}_{1} \bar{\gamma}_{0}}{\bar{\gamma}_{1} \bar{\gamma}_{2}+\bar{\gamma}_{0}\left(\bar{\gamma}_{2}+\bar{\gamma}_{1}\right)\left(1-\rho_{0}^{2}\right)}\right]}{\bar{\gamma}_{1} \bar{\gamma}_{2}+\bar{\gamma}_{2} \bar{\gamma}_{0}+\bar{\gamma}_{1} \bar{\gamma}_{0}} . \tag{7}
\end{align*}
$$

On the other hand, the term $I_{2}$ in (4) can be expressed as

$$
\begin{equation*}
I_{2}=\int_{0}^{\infty} \int_{0}^{\frac{\tau(x+1)}{x-\tau}} \int_{0}^{\infty} \int_{\tilde{w}}^{\infty} \int_{\tilde{w}}^{\infty} f_{\tilde{W}}(\tilde{w}) f_{X, \tilde{X}}(x, \tilde{x}) f_{Y, \tilde{Y}}(y, \tilde{y}) d \tilde{y} d \tilde{x} d \tilde{w} d y d x, \tag{8}
\end{equation*}
$$

where $f_{X, \tilde{X}}(\cdot, \cdot)$ and $f_{Y, \tilde{Y}}(\cdot, \cdot)$ are given by (3). Unfortunately, an exact closed-form solution for (8) proves to be extremely intricate, if not unfeasible. Moreover, numerical integration using standard computing softwares such as Mathematica and Matlab requires a heavy processing, experiencing sometimes slow-convergence issues that may lead to inaccurate results. Alternatively, a highly accurate closed-form lower bound for $I_{2}$ is attained next. ${ }^{4}$

## C. Bound/Approximate Analysis

By using $X Y /(X+Y+1)<\min \{X, Y\}$ into (4), a lower bound for $I_{2}$ can be formulated as

$$
\begin{equation*}
I_{2}^{\mathrm{LB}}=\operatorname{Pr}(\min \{\tilde{X}, \tilde{Y}\}>\tilde{W}, \min \{X, Y\}<\tau) . \tag{9}
\end{equation*}
$$

An integral-form representation for $I_{2}^{\mathrm{LB}}$ can be written similarly to (8), with the integration limits being changed accordingly. But again no exact closed-form solution seems to exist. On the other hand, a relaxed lower bound can be obtained in closed form, as follows. Consider the series expansion of the Bessel function in (3), as given in [11, Eq. (8.447.1)]. Then, by dropping the terms beyond the $N_{1}$-th for $f_{X, \tilde{X}}(\cdot, \cdot)$, and beyond the $N_{2}$-th for $f_{Y, \tilde{Y}}(\cdot, \cdot)$, and using this into the integrand for the computation of $I_{2}^{\mathrm{LB}}$-which is identical to that of (8)-a new lower bound $\tilde{I}_{2}^{L \mathrm{~L}}$ is attained, somewhat looser than the original bound in (9). This is because both the series expansion as well as the referred integrand consist of strictly positivevalued terms. For the same reason, as $N_{1}$ and $N_{2}$ increase, $\tilde{I}_{2}^{\mathrm{LB}}$ approaches $I_{2}^{\mathrm{LB}}$. In particular, $\tilde{I}_{2}^{\mathrm{LB}}=I_{2}^{\mathrm{LB}}$ for $N_{1}=N_{2}=\infty$. Taking all this into account with use of [11, Eq. (3.351-2)], [11, Eq. (3.351-1)], and [11, Eq. (8.352-2)], a closed-form lower bound for $I_{2}$ can be obtained by dividing the integration region into three: (a) $0<x<\tau$ and $0<y<\tau$, (b) $0<x<\tau$ and $\tau<y<\infty$, and (c) $\tau<x<\infty$ and $0<y<\tau$. The final result can be expressed as

$$
\begin{equation*}
\tilde{I}_{2}^{\mathrm{LB}}=T_{a}+T_{b}+T_{c}, \tag{10}
\end{equation*}
$$

where

$$
\begin{gather*}
T_{s}=\sum_{i=0}^{N_{1}} \sum_{j=0}^{N_{2}} \sum_{k=0}^{i} \sum_{l=0}^{j} \rho_{1}^{2 i}\left(1-\rho_{1}^{2}\right)^{1-k} \rho_{2}^{2 j}\left(1-\rho_{2}^{2}\right)^{1-l} \phi_{s} \\
\times \frac{\left(\frac{1}{\bar{\gamma}_{0}}+\frac{1}{\bar{\gamma}_{1}\left(1-\rho_{1}^{2}\right)}+\frac{1}{\bar{\gamma}_{2}\left(1-\rho_{2}^{2}\right)}\right)^{-1-k-l} \Gamma(1+k+l)}{\bar{\gamma}_{0} \bar{\gamma}_{1}^{-} \bar{\gamma}_{2}^{l} k!l!\Gamma(1+i) \Gamma(1+j)}, \tag{11}
\end{gather*}
$$

[^2]for $s \in\{a, b, c\}$, as required, and
\[

$$
\begin{align*}
& \phi_{a}=\gamma\left(i+1, \frac{\tau}{\overline{\gamma_{1}\left(1-\rho_{1}^{2}\right)}}\right) \gamma\left(j+1, \frac{\tau}{\overline{\gamma_{2}\left(1-\rho_{2}^{2}\right)}}\right),  \tag{12}\\
& \phi_{b}=\gamma\left(i+1, \frac{\tau}{\bar{\gamma}_{1}\left(1-\rho_{1}^{2}\right)}\right) \Gamma\left(j+1, \frac{\tau}{\bar{\gamma}_{2}\left(1-\rho_{2}^{2}\right)}\right),  \tag{13}\\
& \phi_{c}=\Gamma\left(i+1, \frac{\tau}{\bar{\gamma}_{1}\left(1-\rho_{1}^{2}\right)}\right) \gamma\left(j+1, \frac{\tau}{\bar{\gamma}_{2}\left(1-\rho_{2}^{2}\right)}\right), \tag{14}
\end{align*}
$$
\]

with $\Gamma(\cdot, \cdot)$ and $\gamma(\cdot, \cdot)$ being the upper and lower incomplete gamma functions, respectively. Finally, by substituting (7) and (10) into $P_{\text {out }}^{\mathrm{LB}}=I_{1}+\tilde{I}_{2}^{\mathrm{LB}}$, a simple and useful closed-form lower-bound expression for the outage probability of the proposed system under the impact of outdated channel estimates is attained.

As known from previous works, upper bounding the harmonic mean by the minimum leads to a tight approximation at medium-to-high SNR, so that $I_{2}^{\mathrm{LB}} \approx I_{2}$. More importantly, as shall be seen from the numerical results, small values of $N_{1}$ and $N_{2}$ (below 15) suffice to render $\tilde{I}_{2}^{\text {LB }}$ a very tight approximation to $I_{2}$ for most values of $\rho_{i}$ (below 0.9). A tight approximation can also be attained for higher values of $\rho_{i}$, under higher values of $N_{1}$ and $N_{2}$.

## D. Diversity Order

In order to assess the system diversity order, we start by defining $\bar{\gamma} \xlongequal{\Delta} 1 / N_{0}$ as the system SNR, from which it is observed that $1 / \bar{\gamma}_{0}, 1 / \bar{\gamma}_{1}$, and $1 / \bar{\gamma}_{2}$ go to zero as $\bar{\gamma} \rightarrow \infty$. In addition, by using the Maclaurin series expansion of the exponential function [11, Eq. (0.318.2)], it follows that $e^{-b} \simeq 1-b$ for $b \ll 1$. From this, a high-SNR asymptotic expression for $I_{1}$ can be derived as

$$
\begin{equation*}
I_{1} \simeq \frac{\tau\left(1-\rho_{0}^{2}\right)\left(\bar{\gamma}_{1}+\bar{\gamma}_{2}\right)}{\bar{\gamma}_{1} \bar{\gamma}_{2}+\bar{\gamma}_{0}\left(\bar{\gamma}_{2}+\bar{\gamma}_{1}\right)\left(1-\rho_{0}^{2}\right)} \propto \frac{1}{\bar{\gamma}} . \tag{15}
\end{equation*}
$$

As for $I_{2}$, we start by specializing (10) to $N_{1}=N_{2}=0$. In such a case, by using again the Maclaurin series expansion of the exponential function, after some algebraic manipulations, a lower bound for $I_{2}$ can be asymptotically obtained as

$$
\begin{align*}
\tilde{I}_{2}^{\mathrm{LB}} & \simeq \frac{\tau\left(1-\rho_{1}^{2}\right)\left(1-\rho_{2}^{2}\right)\left[\bar{\gamma}_{1}\left(1-\rho_{1}^{2}\right)+\bar{\gamma}_{2}\left(1-\rho_{2}^{2}\right)\right]}{\bar{\gamma}_{1} \bar{\gamma}_{2}\left(1-\rho_{1}^{2}\right)\left(1-\rho_{2}^{2}\right)+\bar{\gamma}_{0}\left[\bar{\gamma}_{1}\left(1-\rho_{1}^{2}\right)+\bar{\gamma}_{2}\left(1-\rho_{2}^{2}\right)\right]} \\
& \propto \frac{1}{\bar{\gamma}} . \tag{16}
\end{align*}
$$

In addition, an asymptotic upper bound $I_{2}^{\mathrm{UB}}$ for $I_{2}$ can be derived very similarly, by using the known relationship $(1 / 2) \min \{X, Y\} \leq X Y /(X+Y)$. More specifically, this is obtained as $I_{2}^{\mathrm{UB}}=2 \times \tilde{I}_{2}^{\mathrm{LB}} \propto 1 / \bar{\gamma}$, with $\tilde{I}_{2}^{\mathrm{LB}}$ given in (16). Therefore, using the Pinching Theorem [12], we conclude that $I_{2} \propto 1 / \bar{\gamma}$.

From the above, $P_{\text {out }} \propto 1 / \bar{\gamma}$, that is, in the presence of outdated CSI, the diversity order of the investigated system degrades from 2 (as shown in [3]) to 1 . This is in accordance with previous related results in the literature.


Fig. 2. Outage probability versus transmit SNR for different severities of outdated CSI.

## IV. Numerical Results and Discussions

In this section, our analytical expressions are applied to sample numerical examples and validated by Monte Carlo simulations. For illustration purposes, we use $\beta=4, \Re_{s}=1$ $\mathrm{bit} / \mathrm{s} / \mathrm{Hz}$, and $P_{\mathrm{S}}=P_{\mathrm{R}}$. The sample network is generated in a linear topology, in which the distance between S and D is normalized to unity, i.e., $d_{0}=1$, and R is placed at the midpoint between $S$ and D.

Fig. 2 shows the outage probability versus the transmit SNR for different values of $\rho_{0}=\rho_{1}=\rho_{2} \triangleq \rho$. For comparison, the lower bound for the special case of perfect CSI $(\rho=1)$ as obtained in [3, Eqs. (8) and (10)] is also shown, as well as two simulated curves for the cases of fixed relaying with maximalratio combining (MRC) or selection combining (SC) at the destination, as studied in [13]. Note how the proposed lower bound is extremely close to the exact outage probability in all of the cases. As $\rho$ approaches unity, higher values of $N_{1}$ and $N_{2}$ are required to render a good approximation. On the other hand, low values of $N_{1}$ and $N_{2}$ suffice for most practical cases. In our examples, we have used $N_{1}=N_{2}=\{2,3,5,15,150\}$ for $\rho=\{0.3,0.5,0.7,0.9,0.99\}$, respectively. It can also be seen that, regardless of the severity of the outdated CSI (that is, $\forall \rho \neq 1$ ), the system diversity order reduces from 2 to 1 . As a result, a strong performance degradation is observed even for a minimum level of outdated CSI (e.g., $\rho=0.99$ ), achieving around 10 dB at an outage probability of $10^{-4}$. In contrast, under perfect CSI, the performance of the link-selection scheme is quite similar to that of fixed relaying with SC. As expected, fixed relaying with MRC is the best scheme.

Fig. 3 depicts the outage probability versus the transmit SNR for different mobility scenarios: (a) all nodes move ( $\rho_{0}=\rho_{1}=$ $\rho_{2}=0.1$ ); (b) S moves $\left(\rho_{0}=\rho_{1}=0.1, \rho_{2}=0.99\right)$; (c) D moves ( $\rho_{0}=\rho_{2}=0.1, \rho_{1}=0.99$ ); (d) R moves $\left(\rho_{0}=0.99, \rho_{1}=\rho_{2}=\right.$ 0.1 ); and (e) none of the nodes move ( $\rho_{0}=\rho_{1}=\rho_{2}=0.99$ ). In the examples, note that $\rho=0.99$ has been used to approximate the no-mobility scenario, because $\rho=1$ renders our expressions indeterminate. As expected, the worst performance is attained when all the nodes are moving. In addition, a moving $S$ is equivalent to a moving D and is outperformed by a moving R . In other words, the movement of $R$ is less critical for the system performance than the movement of $S$ or $D$.


Fig. 3. Outage probability versus transmit SNR for different mobility scenarios.

## V. Conclusion

We derived a highly accurate closed-form lower bound for the outage probability of a distributed link-selection scheme recently proposed for variable-gain amplify-and-forward relaying networks, when affected by outdated channel estimates.

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    ${ }^{1}$ Herein, the term node selection refers to a scheme that selects a source, relay, and/or destination for transmission, out of a set of nodes available. In contrast, the term link selection refers to a scheme that, for a given source, relay, and destination, preselects either the direct link or the relaying link before each transmission.

[^1]:    ${ }^{2}$ An isotropic propagation scenario has been assumed here.
    ${ }^{3}$ According to the mobility scenario, the maximum Doppler frequency-and thus the correlation coefficient-may vary among the links, as it depends on the relative speed between transmitter and receiver.

[^2]:    ${ }^{4}$ An upper bound could also be attained by following a similar rationale and would be indeed preferred from an engineering design perspective. However, it turns out to be very loose, as revealed by exhaustive tests we have performed. This is why we have focused our analysis on the lower bound.

