www.ietdl.org

Published in IET Communications
Received on 24th October 2012
Revised on 16th February 2013
Accepted on 12th March 2013
doi: 10.1049/iet-com.2012.0659

ISSN 1751-8628

A low-complexity relay selection scheme based on switch-and-examine diversity combining for AF relay systems

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Abstract: In this study, the authours present a low-complexity relay selection scheme for channel-state information (CSI)-assisted dual-hop amplify-and-forward cooperative systems. The scheme is mainly based on the switch-and-examine diversity combining (SEC) and SEC post-selection (SECps) techniques in which a relay out of multiple relays is selected to forward the source signal to destination. The selection process is performed such that the selected relay signal-to-noise ratio (SNR) satisfies a predetermined switching threshold instead of best relay. Such a relay that satisfies this threshold will be chosen instead of the best relay. In this study, the authorsuse an upper bound on the end-to-end (e2e) SNR of the selection scheme and derive the probability density function and the cumulative distribution function of this SNR assuming the Rayleigh fading channels. These statistics are then used to derive accurate approximations for both the e2e outage probability and bit error probability, where the direct link in considered. The authours assume that maximal-ratio combining is used at the destination to combine the signals through the relay and the direct link. To obtain more about system insights, the outage performance is studied at high SNR regime, where approximate expressions for the outage probability as well as the diversity order and coding gain are derived and analysed. The Monte-Carlo simulations are provided to illustrate the validity of the analytical results and to show the tightness of the used SNR bound. Results illustrate the effectiveness of the proposed relaying schemes in reducing the required number of channel estimations and hence, reducing the system complexity compared with the opportunistic relaying. Furthermore, results show the gain achieved in the system performance; especially, at low-to-medium SNR values when the SECps selection scheme is used compared with the conventional SEC relaying. Finally, findings show that the system with the SEC and the SECps relaying schemes has the same diversity order of two and the same coding gain.

1 Introduction

In wireless systems, users may not be able to support multiple antennas because of size, complexity and power limitations. The cooperative diversity is a promising technique for such a condition [1, 2]. Among the relaying schemes proposed in these studies are the amplify-and-forward (AF) and the decode-and-forward (DF). In the AF scheme, the relay simply amplifies the source signal before it is forwarded to destination; whereas, in the DF scheme, some signal processing needs to be performed by the relay before the signal being forwarded. Several relaying protocols for multi-relay cooperative systems were proposed in [1], among which are the fixed relaying, the selection relaying and the incremental relaying. In fixed relaying, a set of relays are used to forward the source signal to destination, whereas in selection relaying, a relay or a number of relays are selected to cooperate with the source according to certain selection policies. Finally, in incremental relaying, a relay or a set of relays are selected to forward the source signal only if the direct link channel is under a certain quality.

In the past few years, several relay selection schemes were proposed in the multi-relay cooperative systems. In [3], Bletsas *et al.* proposed the opportunistic relaying where the relay with the strongest end-to-end (e2e) signal-to-noise (SNR) is selected to forward the source signal to destination. This scheme is optimal in the sense that in each transmission period, the relay with the strongest e2e SNR is selected to forward the source message. On the other hand, this scheme suffers from a heavy load of channel estimations where all relay channels are required to be estimated first before the best relay is being selected. Some papers on the performance of relay systems with opportunistic relaying are the one presented in [4, 5]. In these studies, in order for a destination to select the best relay among all other relays, the channels of all relays need to be estimated first.

A partial relay selection scheme for AF relay systems was proposed in [6]. In this scheme, the relay with the best first hop is chosen to forward the source message to destination. The partial relaying schemes are useful for certain practical situations in ad-hoc networks, where only the first hop channels of relays are available to the source. In [7], Ikki *et al.* presented a new relaying scheme, where the relay with the second or even the Nth-best e2e SNR is selected to forward the source signal. This scheme is useful in situations, where the best relay may not be available to cooperate because of some scheduling or load balancing conditions. Some relay selection schemes that are based on certain functions of the two hops SNRs, like the modified harmonic mean, were presented and evaluated in [8]. The switch-and-stay relay selection scheme was recently proposed in [9] for the two-way AF relay systems. The relay out of the two relays with source–relay SNR greater than threshold 1 and destination–relay SNR greater than threshold 2 is asked to relay signals. A relay switching happens when any of the SNRs falls below the corresponding threshold. A threshold-based relaying scheme was presented in [10]. In this scheme, the relays whose first and second hop SNRs larger than certain thresholds are said to be active relays. According to the success or failure of the direct link, a relay or a set of relays are asked to forward the source message until one of the following events happens: a successful decoding happens at the destination, the active relay set becomes empty, or all active relays have reached the retry limit.

A key study that presents new relay selection schemes was presented in [11]. In this paper, the selection criterion is based on the magnitudes of the relays channels and not on the channels SNRs. The authors claimed that these selection schemes are less complicated if compared with the schemes, where the the channels SNRs are required to be estimated in the relay selection process. Three energy-fair decentralised relay selection techniques that take the network topological structure into consideration were presented in [12]. A partial relay selection scheme was proposed in [13]. This protocol is based on the DF relaying scheme, where the relay with a first hop SNR larger than a constant switching threshold is chosen to forward the source signal only if its second hop SNR exceeds the same switching threshold. The authors considered the case of identical relay paths and the switching threshold was assumed to be constant in the analysis. Furthermore, the outage probability and the BEP were numerically evaluated and no closed-form expressions were provided. A study on the performance of some relaying schemes like selection and switched relaying was presented in [14]. The direct link was ignored in the analysis and the switching threshold was assumed to be fixed. Also, only the case of identical relay paths was presented and the performance measures were numerically evaluated without providing any analytical expressions.

Recently, a switch-and-stay partial relay selection was presented in [15] assuming the Rayleigh fading channels. The scheme is only implemented on the first hop channels of the two relays. It works as follows, the first hop channel of the active relay is compared with a certain SNR threshold. If it is larger, then this relay continues forwarding the source signal to destination in the next transmission period. If not, the second idle relay is asked by the source to do the cooperation process in the next transmission time slot. This relaying scheme reduces the complexity of the other relaying schemes that require the channels of both relays to be estimated in each transmission period. On the other hand, a drawback of this scheme is that it does not consider the second hop channels of relays in the selection process. Also, this scheme is limited to practical situation, where two relays are being utilised. In addition, the authors assumed no existence of the direct link between the source and the destination in their analysis. A switch-and-examine-based relaying scheme was proposed in [16]. In this scheme, the SNR of the first hop channel of a relay is examined against a SNR threshold; if it is larger, the relay is selected to forward the source message to destination according to AF relaying. If the SNR is found below the threshold, the process of examining continues till an acceptable relay is found or the last relay is reached. In the last case where the last relay is found unacceptable, no relaying takes place. The main drawback of this scheme is that it is only taking the SNR of the first hop in the selection process. Most recently, a paper on switched relay selection schemes for AF relay systems is presented in [17]. The authors utilised some switched selection schemes for AF relay systems with multiple antennas. The performance measures were numerically computed and no closed-form expressions were provided. Also, the direct link was ignored in the analysis and the switching threshold was assumed to be constant.

As can be seen, most of relay selection schemes in the aforementioned studies suffer from a heavy load of channel estimations. As an example, the best relay selection scheme requires that channels of all relays be estimated each transmission time. On the other hand, in the partial relaying scheme, half this estimation load is required each time. This means more power consumption, low battery life and high system complexity. As known, in most wireless systems like the sensor and ad-hoc networks, once the minimum requirements of the system performance are achieved, no more operations that increase the system complexity need to be done. This shows the significant need for new relay selection schemes with a low implementation complexity and adequate system performance.

Motivated by the above discussion, we propose a low-complexity suboptimal relay selection scheme for channel-state information (CSI)-assisted dual-hop AF relay systems. This scheme is based on the switch-and-examine diversity combining (SEC) and switch-and-examine post-selection (SECps) techniques. The need for channels to be estimated in CSI-based AF relay systems motivated us to consider such a type and not the fixed-gain AF relaying, where fixed relay scales are usually used. The contributions of our paper over the existing studies are summarised in the following points: (i) in contrast to Hwang and Ko [13], the switching threshold is evaluated to minimise the BEP at the output of the maximal-ratio combining (MRC) combiner and thus giving optimum performance; (ii) our proposed analysis is a non-trivial extension of Gharanjik and Mohamed-pour [15], where switch-and-stay was employed using two relays only; (iii) we present a comprehensive study for the outage performance of both relaying schemes at high SNR regime, where the diversity order and coding gain are derived and analysed, (iv) because of its importance, the direct link is considered in all our derivations in contrast to that presented in [15]; and (v) approximate closed-form expressions for both the outage probability and BEP of the generic independent non-identical distributed (i.n.d.) and independent identical distributed (i.i.d.) cases of relay paths are provided in our study in contrast to Hwang and Ko [13], where only the i.i.d. case was considered. In the proposed scheme, only the first checked relay whose e2e SNR exceeds the switching threshold is selected to forward the source signal to destination. Thus, in contrast to the aforementioned relay selection schemes, the channels of only an arbitrary relay are required to be estimated each time of data transmission. In this case, the other relays remain silent and do not need to operate as channel estimators. This results in a notable reduction in the required number of channel estimations and saves the power of these relay and hence, reducing the system complexity. In this paper, we first derive the PDF and the cumulative distribution function (CDF) of the SNR at the output of the selection scheme. Then, we consider the existence of the direct link and derive approximate closed-form expression for the CDF and hence, the outage

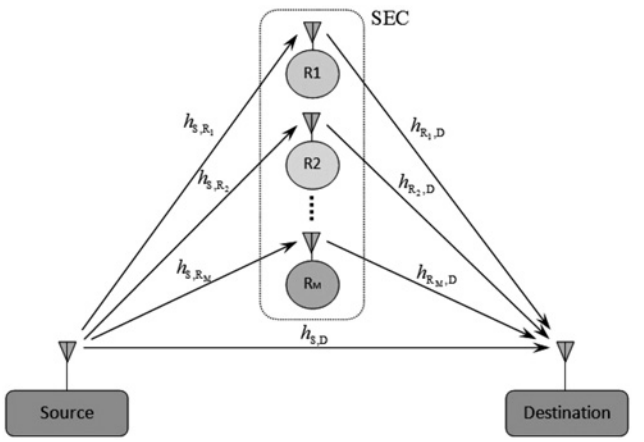

Fig. 1 *Schematic for dual-hop AF relay system with SEC relay selection scheme and MRC at destination*

probability of the e2e SNR at the output of the MRC combiner. Finally, we evaluate approximate closed-form expression for the BEP of the whole system. An upper bound on the SNR of the relay path is used in the analysis. The asymptotic behaviour is derived in the same manner.

The remainder of this paper is organised as follows. Section 2 presents the system model. The analysis of system performance is conducted in Section 3. Section 4 provides the asymptotic analysis of the considered system. In Section 5, some numerical and simulation results are presented and discussed, and some comparisons with existed selection schemes are conducted. Finally, conclusions are given in Section 6.

2 System model

In the system shown in Fig. 1 with the SEC relaying scheme, a source node (S) communicates with a destination node (D) through the direct link and a relay path. At the guard period of each transmission, a ready-to-send packet and a clear-to-send packet are sent from the source to the destination, respectively. From these signals, an arbitrary relay out of M relays estimates its instantaneous channels. Then, the minimum magnitude of the two hops is compared with a predetermined switching threshold. If this minimum is larger than the switching threshold, then this relay is selected to forward the source signal and a short duration flag packet is sent from this relay to other relays signalling its presence. Otherwise, a flag packet is sent from this relay to the other relays asking it to estimate its channels to be compared then with the switching threshold. This process continues until a relay satisfying the switching threshold is found or reaching the last relay. At this case, the last relay is chosen to forward the source signal. As an enhancement on the SEC-based relaying scheme that we introduced in [18], we propose the SECps selection relaying. This scheme shares all operation steps of the SEC-based relaying and only differs in the last step, where the last relay is reached and found unacceptable. In this case, the SECps scheme will select the best relay among all relays to forward the source message to destination. This results in a notable enhancement in system performance compared with the SEC relaying scheme as will be shown in our results. In calculating the switching threshold, the SNRs of both the first and second hop channels of the selected relay are required at the destination node. These SNR values along with the direct link SNR are then used in calculating the switching threshold in such a way that the e2e BEP is minimised. Flowcharts for the proposed relaying schemes are shown in Fig. 2.

At the destination, MRC is used to combine the signal on the direct path and that through the relay. The channel coefficients between the source and the ith relay $R_i(h_{S,R_i})$, between R_i and $D(h_{R_i,D})$ and between S and D ($h_{S,\ D}$) are assumed to be flat Rayleigh fading gains. In addition, h_{S,R_i}, $h_{R_i,D}$ and $h_{S,D}$ are mutually independent and non-identical. We also assume here, without any loss of generality that the additive white Gaussian noise (AWGN) terms of all links have zero means and equal variance $N_0/2$.

Communications occur in two phases. In phase 1, the source transmits the modulated signal x with unit energy to

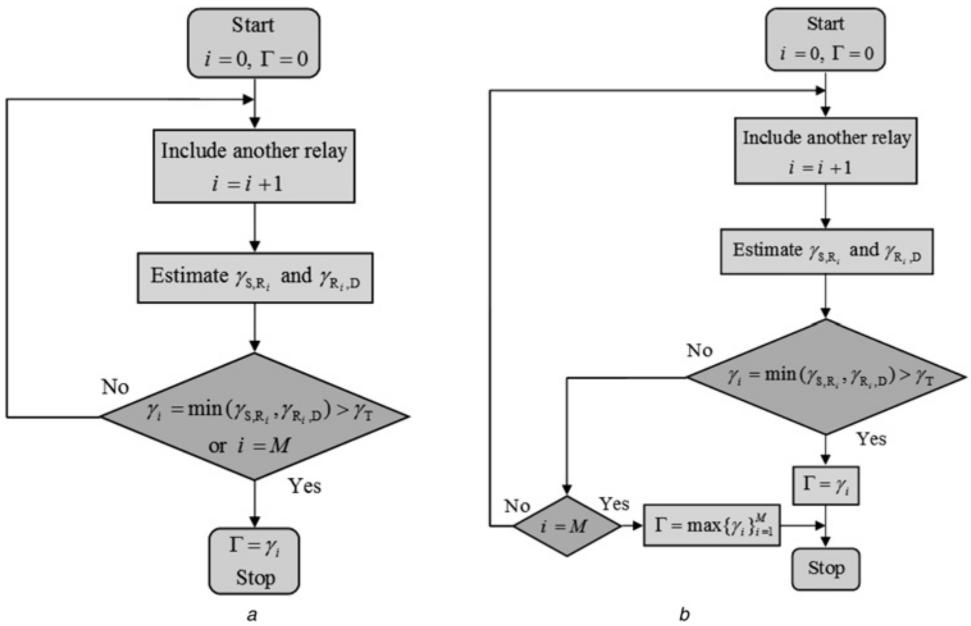

Fig. 2 *Flowcharts for the proposed SEC-based relay selection schemes*

a SEC relaying
b SECps relaying

the destination and the two relays. The received signals at the destination and the ith relay, respectively, are

$$y_{S,D} = h_{S,D}\sqrt{E_s}x + n_{S,D} \tag{1}$$

$$y_{S,R_i} = h_{S,R_i}\sqrt{E_s}x + n_{S,R_i} \tag{2}$$

where E_s is the average received symbol energy, $n_{S,D}$ and n_{S,R_i} are the AWGN between S and D and S and R_i, respectively. The chosen relay by the SEC scheme amplifies the received signal and transmits it to the destination in the second phase of communication. During this phase, the received signal at the destination from the selected relay is

$$y_{R_{sel},D} = Gh_{R_{sel},D}\sqrt{E_s}x + n_{R_{sel},D} \tag{3}$$

where G is the active relay amplifying gain, chosen as $G^2 = E_s/\left(E_s h^2_{S,R_{sel}} + N_0\right)$ [19]. It is widely known that the composite SNR of the relay link can be written as [20]

$$\gamma_{S,R_i,D} = \frac{\gamma_{S,R_i}\gamma_{R_i,D}}{\gamma_{S,R_i} + \gamma_{R_i,D} + 1} \tag{4}$$

where $\gamma_{S,R_i} = h^2_{S,R_i}E_s/N_0$ is the instantaneous SNR of the source signal at R_i and $\gamma_{R_i,D} = h^2_{R_i,D}E_s/N_0$ is the instantaneous SNR of the relay signal (by R_i) at D. By using MRC at the destination node, the total SNR at the combiner output is simply the addition of the two random variables at its inputs as follows

$$\gamma_{tot} = \gamma_{S,D} + \gamma_{SEC} \tag{5}$$

where $\gamma_{S,D} = h^2_{S,D}E_s/N_0$ is the instantaneous SNR between S and D, and γ_{SEC} is the SNR at the output of the SEC selection scheme. To simplify the ensuing derivations, (4) should be expressed in a more mathematically tractable form. A tighter upper bound for $\gamma_{S,R_i,D}$ is given in [21] by

$$\gamma_{S,R_i,D} \le \gamma_i = \min\left(\gamma_{S,R_i}, \gamma_{R_i,D}\right) \tag{6}$$

Assuming the Rayleigh fading channels between source, relays and destination, the distribution of γ_i in (6) is exponential and hence, its PDF can be expressed in terms of the average SNR $\bar{\gamma}_{S,R_i} = \boldsymbol{E}[h^2_{S,R_i}]E_s/N_0$ and $\bar{\gamma}_{R_i,D} = \boldsymbol{E}[h^2_{S,R_i}]E_s/N_0$ (where $\boldsymbol{E}[\cdot]$ is the expectation operator) as

$$f_{\gamma_i}(\gamma) = \frac{1}{\bar{\gamma}_i}\exp\left(-\frac{\gamma}{\bar{\gamma}_i}\right) \tag{7}$$

where $\bar{\gamma}_i = \bar{\gamma}_{S,R_i}\bar{\gamma}_{R_i,D}/\left(\bar{\gamma}_{S,R_i} + \bar{\gamma}_{R_i,D}\right)$.

Our subsequent analysis will be based on the SNR bound given in (6) on the e2e SNR of the selection scheme. This bound has been shown to be quite accurate [21].

3 Performance analysis

In this section, we derive the performance of the proposed relay selection scheme. In the following, we present approximate closed-from expressions for both the e2e outage probability and the BEP.

3.1 SEC-based relay selection

Our results on the outage probability are summarised in Lemma 1 and Corollary 1 as follows.

Lemma 1: the outage probability of the SEC-based relaying scheme for the case of an i.n.d. relay paths $\{\bar{\gamma}_i\}_{i=1}^{M}$ is given in an approximate closed-form expression as

$$\begin{aligned}
P_{out} = {} & \sum_{i=0}^{M-1}\pi_i \prod_{\substack{k=0\\k\neq i}}^{M-1}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_k}\right)\right) \\
& \left[\frac{(1-\exp(-(\gamma_{out})/(\bar{\gamma}_{S,D})))}{(1-(\bar{\gamma}_i)/(\bar{\gamma}_{S,D}))} + \frac{(1-\exp(-(\gamma_{out})/(\bar{\gamma}_i)))}{(1-(\bar{\gamma}_{S,D})/(\bar{\gamma}_i))} - \exp\left(-\frac{\gamma_T}{\bar{\gamma}_i}\right)\right. \\
& \times \frac{\exp((\gamma_T)/(\bar{\gamma}_{S,D}))}{(1-(\bar{\gamma}_i)/(\bar{\gamma}_{S,D}))}\left(\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right) - \exp\left(-\frac{\gamma_{out}}{\bar{\gamma}_{S,D}}\right)\right) + \frac{\exp((\gamma_T)/(\bar{\gamma}_i))}{(1-(\bar{\gamma}_{S,D})/(\bar{\gamma}_i))} \\
& \left(\exp\left(-\frac{\gamma_T}{\bar{\gamma}_i}\right) - \exp\left(-\frac{\gamma_{out}}{\bar{\gamma}_i}\right)\right) + \sum_{j=0}^{M-1}\pi_{((i-j))_M} \\
& \prod_{k=0}^{j-1}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{((i-j+k))_M}}\right)\right) \\
& \left[\exp\left(-\frac{\gamma_T}{\bar{\gamma}_i}\right)\left\{\frac{\exp((\gamma_T)/(\bar{\gamma}_{S,D}))}{(1-(\bar{\gamma}_i)/(\bar{\gamma}_{S,D}))}\right.\right. \\
& \left(1-\exp\left(-\frac{\gamma_{out}}{\bar{\gamma}_{S,D}}\right)\right) + \frac{\exp((\gamma_T)/(\bar{\gamma}_i))}{(1-(\bar{\gamma}_{S,D})/(\bar{\gamma}_i))} \\
& \left.\left.\left.\left(1-\exp\left(-\frac{\gamma_{out}}{\bar{\gamma}_i}\right)\right)\right\}\right]\right]
\end{aligned} \tag{8}$$

Proof: see Appendix 1.

Corollary 1: the outage probability of the SEC-based relaying scheme for the case of i.i.d. relay paths ($\bar{\gamma}_1 = \cdots = \bar{\gamma}_M = \bar{\gamma}_{path}$) is given in an approximate closed-form expression as

$$\begin{aligned}
P_{out} = {} & \frac{1}{(\bar{\gamma}/2 - \bar{\gamma}_{S,D})}\left\{\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}/2}\right)\right)^{M-1}\right. \\
& \left[\bar{\gamma}/2\left(1-\exp\left(-\frac{\gamma_{out}}{\bar{\gamma}/2}\right)\right) - \bar{\gamma}_{S,D}\left(1-\exp\left(-\frac{\gamma_{out}}{\bar{\gamma}_{S,D}}\right)\right)\right] \\
& + \sum_{j=0}^{M-2}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}/2}\right)\right)^j \\
& \left[\bar{\gamma}/2\left\{\exp\left(-\frac{\gamma_T}{\bar{\gamma}/2}\right) - \exp\left(-\frac{\gamma_{out}}{\bar{\gamma}/2}\right)\right\}\right. \\
& - \bar{\gamma}_{S,D}\exp\left(\left(-\frac{1}{\bar{\gamma}/2} + \frac{1}{\bar{\gamma}_{S,D}}\right)\gamma_T\right) \\
& \left.\left.\times\left\{\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right) - \exp\left(-\frac{\gamma_{out}}{\bar{\gamma}_{S,D}}\right)\right\}\right]\right\}
\end{aligned} \tag{9}$$

Proof: the CDF of $\gamma_{\rm SEC}$ for i.i.d. relay paths can be written as [22]

$$F_{\gamma_{\rm SEC}}(\gamma) = \begin{cases} \left[F_\gamma(\gamma_T)\right]^{M-1} F_\gamma(\gamma), & \gamma < \gamma_T \\ \sum_{j=0}^{M-1} \left[F_\gamma(\gamma) - F_\gamma(\gamma_T)\right] \\ \left[F_\gamma(\gamma_T)\right]^j + \left[F_\gamma(\gamma_T)\right]^M, & \gamma \geq \gamma_T \end{cases} \tag{10}$$

Using the CDF in (10) and following the same procedure as in Appendix 1, the outage probability for the case of i.i.d. relay paths can be evaluated in an approximate closed-form expression as in (9), where i.i.d. symmetrical hops, that is $\bar{\gamma}_{S,R_i} = \bar{\gamma}_{R_i,D} = \bar{\gamma}\ \forall i\ i \in \{1,\ldots, M\}$ have been assumed in obtaining this result. □

Our results on the BEP are summarised in Lemma 2 and Corollary 2 as follows.

Lemma 2: the BEP of the SEC-based relaying scheme for the case of i.n.d. relay paths is given in an approximate closed-form expression as (see (11))

where $Q(\cdot)$ is the Gaussian Q-function defined in [22, equation 4.1].

Proof: see Appendix 2. □

Corollary 2: the BEP of the SEC-based relaying scheme for the case of i.i.d. relay paths is given in an approximate closed-form expression as (see (12))

Proof: to derive (12), the moment generating function (MGF) $\mathcal{M}_{\gamma_{\rm SEC}}(s)$ needs to be derived first using $f_{\gamma_{\rm SEC}}(\gamma)$ of the i.i.d. relay paths case. Then, following the same procedure as in Appendix 2, an approximate closed-form expression for the BEP of the i.i.d. relay paths case can be evaluated as in (12), where i.i.d. symmetrical hops, that is $\bar{\gamma}_{S,R_i} = \bar{\gamma}_{R_i,D} = \bar{\gamma}\ \forall i$, $i \in \{1, \ldots, M\}$ have been assumed in obtaining this result. □

3.2 SECps-based relay selection

Our results on the outage probability and the BEP are, respectively, summarised in Corollaries 3 and 4 as follows:

$$\begin{aligned} P_b(E) = {} & \sum_{i=0}^{M-1} \pi_i \prod_{\substack{k=0\\k\neq i}}^{M-1}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_k}\right)\right)\left[\left[\frac{\left(1-\sqrt{\dfrac{\bar{\gamma}_{S,D}}{1+\bar{\gamma}_{S,D}}}\right)}{2\left(1-\dfrac{\bar{\gamma}_i}{\bar{\gamma}_{S,D}}\right)} + \frac{\left(1-\sqrt{\dfrac{\bar{\gamma}_i}{1+\bar{\gamma}_i}}\right)}{2\left(1-\dfrac{\bar{\gamma}_{S,D}}{\bar{\gamma}_i}\right)} - \frac{\exp\left(-\dfrac{\gamma_T}{\bar{\gamma}_i}\right)}{\left(1-\dfrac{\bar{\gamma}_i}{\bar{\gamma}_{S,D}}\right)}\left\{Q\left(\sqrt{2\gamma_T}\right)\right.\right.\right. \\ & \left. - \frac{\exp((\gamma_T)/(\bar{\gamma}_{S,D}))Q\left(\sqrt{2(\gamma_T+(\gamma_T)/(\bar{\gamma}_{S,D}))}\right)}{\sqrt{1+(1/\bar{\gamma}_{S,D})}}\right\} \\ & \left.\left. - \frac{\exp(-(\gamma_T)/(\bar{\gamma}_i))}{(1-(\bar{\gamma}_{S,D})/(\bar{\gamma}_i))}\left\{Q\left(\sqrt{2\gamma_T}\right) - \frac{\exp((\gamma_T)/(\bar{\gamma}_i))Q\left(\sqrt{2(\gamma_T+(\gamma_T)/(\bar{\gamma}_i))}\right)}{\sqrt{1+(1/\bar{\gamma}_i)}}\right\}\right]\right] \\ & + \sum_{i=0}^{M-1}\sum_{j=0}^{M-1} \pi_{((i-j))_M} \prod_{k=0}^{j-1}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{((i-j+k))_M}}\right)\right)\left[\frac{\exp(-(\gamma_T)/(\bar{\gamma}_i))}{(1-(\bar{\gamma}_i)/(\bar{\gamma}_{S,D}))}\left\{Q\left(\sqrt{2\gamma_T}\right) - \frac{\exp((\gamma_T)/(\bar{\gamma}_{S,D}))}{\sqrt{1+(1/\bar{\gamma}_{S,D})}}\right.\right. \\ & \left.\left. \times Q\left(\sqrt{2\left(\gamma_T+\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right)}\right)\right\} + \frac{\exp(-(\gamma_T)/(\bar{\gamma}_i))}{(1-(\bar{\gamma}_{S,D})/(\gamma_i))}\left\{Q\left(\sqrt{2\gamma_T}\right) - \frac{\exp((\gamma_T)/(\bar{\gamma}_i))Q\left(\sqrt{2(\gamma_T+(\gamma_T)/(\bar{\gamma}_i))}\right)}{\sqrt{1+(1/\bar{\gamma}_i)}}\right\}\right] \end{aligned} \tag{11}$$

$$\begin{aligned} P_b(E) = {} & \frac{(1-\exp(-(\gamma_T)/(\bar{\gamma}/2)))^{M-1}}{2}\left[\frac{\left(1-\sqrt{(\bar{\gamma}_{S,D})/(1+\bar{\gamma}_{S,D})}\right)}{(1-(\bar{\gamma}/2)/(\bar{\gamma}_{S,D}))} + \frac{\left(1-\sqrt{(\bar{\gamma}/2)/(1+\bar{\gamma})}\right)}{(1-(\bar{\gamma}_{S,D})/(\bar{\gamma}/2))}\right] \\ & + \exp\left(-\frac{\gamma_T}{\bar{\gamma}/2}\right)\sum_{j=0}^{M-2}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}/2}\right)\right)^j \\ & \times \left\{\frac{1}{(1-(\bar{\gamma}/2)/(\bar{\gamma}_{S,D}))}\left[Q\left(\sqrt{2\gamma_T}\right) - \frac{\exp((\gamma_T)/(\bar{\gamma}_{S,D}))Q\left(\sqrt{2(\gamma_T+(\gamma_T)/(\bar{\gamma}_{S,D}))}\right)}{\sqrt{1+(1/\bar{\gamma}_{S,D})}}\right]\right. \\ & \left. + \frac{1}{(1-(\bar{\gamma}_{S,D})/(\bar{\gamma}/2))} Q\left(\sqrt{2\gamma_T}\right) - \frac{\exp(\gamma_T/\bar{\gamma}/2)Q\left(\sqrt{2(\gamma_T+(\gamma_T)/(\bar{\gamma}/2))}\right)}{\sqrt{1+(1/\bar{\gamma}/2)}}\right]\right\} \end{aligned} \tag{12}$$

doi: 10.1049/iet-com.2012.0659

Corollary 3: the outage probability of the SECps-based relaying scheme for the case of i.i.d. relay paths $\left(\bar{\gamma}_1 = \cdots = \bar{\gamma}_M = \bar{\gamma}_{\text{path}}\right)$ is given in an approximate closed-form expression as

$$
\begin{aligned}
P_{\text{out}} = {} & \frac{\left(1-\left(1-\exp\left(-(\gamma_T)/(\bar{\gamma}/2)\right)\right)^M\right)}{\left(\bar{\gamma}/2-\bar{\gamma}_{S,D}\right)} \\
& \Bigg[\bar{\gamma}/2\exp\left(\frac{\gamma_T}{\bar{\gamma}/2}\right)\left(\exp\left(-\frac{\gamma_T}{\bar{\gamma}/2}\right)-\exp\left(-\frac{\gamma_{\text{out}}}{\bar{\gamma}/2}\right)\right) \\
& -\bar{\gamma}_{S,D}\exp\left(\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right)\times\left(\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right)-\exp\left(-\frac{\gamma_{\text{out}}}{\bar{\gamma}_{S,D}}\right)\right)\Bigg] \\
& +M\sum_{j=0}^{M-1}\binom{M-1}{j}(-1)^j\frac{1}{\left(\bar{\gamma}/2-(j+1)\bar{\gamma}_{S,D}\right)} \\
& \Bigg[\frac{\bar{\gamma}/2}{(j+1)}\times\left(1-\exp\left(-\frac{(j+1)\gamma_{\text{out}}}{\bar{\gamma}/2}\right)\right) \\
& -\bar{\gamma}_{S,D}\left(1-\exp\left(-\frac{\gamma_{\text{out}}}{\bar{\gamma}_{S,D}}\right)\right)-\exp\left(\frac{-(j+1)\gamma_T}{\bar{\gamma}/2}\right) \\
& \Bigg\{\frac{\bar{\gamma}/2\exp\left(\left((j+1)\gamma_T\right)/(\bar{\gamma}/2)\right)}{(j+1)}\times\left(\exp\left(-\frac{(j+1)\gamma_T}{\bar{\gamma}/2}\right)\right. \\
& \left.-\exp\left(-\frac{(j+1)\gamma_{\text{out}}}{\bar{\gamma}/2}\right)\right)-\bar{\gamma}_{S,D}\exp\left(\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right) \\
& \left(\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right)-\exp\left(-\frac{\gamma_{\text{out}}}{\bar{\gamma}_{S,D}}\right)\right)\Bigg\}
\end{aligned}
\tag{13}
$$

Proof: the CDF of γ_{SECps} for i.i.d. relay paths can be written as [22]

$$
F_{\gamma_{\text{SECps}}}(\gamma) = \begin{cases} 1-\sum_{j=0}^{M-1}\left[F_\gamma(\gamma_T)\right]^j\left[1-F_\gamma(\gamma)\right], & \gamma \geq \gamma_T \\ \left[F_\gamma(\gamma)\right]^M, & \gamma < \gamma_T \end{cases}
\tag{14}
$$

Using the CDF in (14) and following the same procedure as in Appendix 1, the outage probability for the SECps-based relaying scheme can be evaluated in an approximate closed-form expression as in (13), where i.i.d. symmetrical hops, that is $\bar{\gamma}_{S,R_i} = \bar{\gamma}_{R_i,D} = \bar{\gamma}\ \forall i,\ i \in \{1,\ldots, M\}$ have been assumed in obtaining this result. □

Corollary 4: the BEP of the SECps-based relaying scheme for the case of i.i.d. relay paths is given in an approximate closed-form expression as (see (15))

Proof: to derive (15), the MGF $\mathcal{M}_{\gamma_{\text{SECps}}}(s)$ needs to be derived first using $f_{\gamma_{\text{SECps}}}(\gamma)$ of the i.i.d. relay paths case. Then, following the same procedure as in Appendix 2, an approximate closed-form expression for the BEP of the i.i.d. relay paths case can be evaluated as in (15), where again i.i.d. symmetrical hops, that is $\bar{\gamma}_{S,R_i} = \bar{\gamma}_{R_i,D} = \bar{\gamma}\ \forall i,\ i \in \{1, \ldots, M\}$ have been assumed in obtaining this result. □

4 Asymptotic analysis

In this section, we derive the outage performance of the proposed relay selection schemes at high SNR regime. At high SNR, the outage probability can be expressed as $P_{\text{out}} \simeq (G_{\text{c}}\text{SNR})^{-G_{\text{d}}}$, where G_{c} denotes the coding gain of the system and G_{d} is the diversity order of the system.

4.1 SEC-based relay selection

At high SNR regime, the exponential CDF and PDF can be, respectively, approximated by $F_\gamma(\gamma) \simeq (\gamma/\gamma)$ and $f_\gamma(\gamma) \simeq (1/\gamma)$. Upon using these statistics and following the same procedure as in Appendix 1, the outage probability for the SEC selection scheme can be obtained at high SNR as

$$
\begin{aligned}
P_{\text{out}} \simeq {} & \frac{1}{2\bar{\gamma}/2\bar{\gamma}_{S,D}}\left\{\left(\frac{\gamma_T}{\bar{\gamma}/2}\right)^{M-1}\left[2\gamma_T\gamma_{\text{out}}-(\gamma_T)^2\right]\right. \\
& \left.+\sum_{j=0}^{M-1}\left(\frac{\gamma_T}{\bar{\gamma}/2}\right)^j\left[(\gamma_{\text{out}})^2+(\gamma_T)^2-2\gamma_T\gamma_{\text{out}}\right]\right\}
\end{aligned}
\tag{16}
$$

$$
\begin{aligned}
P_b(E) = {} & \left[1-\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}/2}\right)\right)^M\right]\Bigg\{\frac{1}{\left(1-(\bar{\gamma}/2)/(\bar{\gamma}_{S,D})\right)}\left(Q\left(\sqrt{2\gamma_T}\right)-\frac{\exp\left((\gamma_T)/(\bar{\gamma}_{S,D})\right)Q\left(\sqrt{2\left(\gamma_T+(\gamma_T)/(\bar{\gamma}_{S,D})\right)}\right)}{\sqrt{1+(1/\bar{\gamma}_{S,D})}}\right) \\
& +\frac{1}{\left(1-(\bar{\gamma}_{S,D}/\bar{\gamma}/2)\right)}\left(Q\left(\sqrt{2\gamma_T}\right)-\frac{\exp(\gamma_T/\bar{\gamma}/2)Q\left(\sqrt{2\left(\gamma_T+(\gamma_T/\bar{\gamma}/2)\right)}\right)}{\sqrt{1+(1/\bar{\gamma}/2)}}\right)\Bigg\}+M\sum_{j=0}^{M-1}\binom{M-1}{j}(-1)^j \\
& \times\Bigg[\frac{\left(1-\sqrt{(\bar{\gamma}_{S,D})/(1+\bar{\gamma}_{S,D})}\right)}{2\left(j+1-(\bar{\gamma}/2)/(\bar{\gamma}_{S,D})\right)}+\frac{\left(1-\sqrt{(\bar{\gamma}/2)/\left((j+1+\bar{\gamma}/2)\right)}\right)}{2(j+1)\left(1-(j+1)(\bar{\gamma}_{S,D})/(\bar{\gamma}/2)\right)}-\exp\left(\frac{-(j+1)\gamma_T}{\bar{\gamma}/2}\right) \\
& \times\Bigg\{\frac{1}{\left(j+1-(\bar{\gamma}/2)/(\bar{\gamma}_{S,D})\right)}\left(Q\left(\sqrt{2\gamma_T}\right)-\frac{\exp\left((\gamma_T)/(\bar{\gamma}_{S,D})\right)Q\left(\sqrt{2\left(\gamma_T+(\gamma_T)/(\bar{\gamma}_{S,D})\right)}\right)}{\sqrt{1+(1/\bar{\gamma}_{S,D})}}\right) \\
& +\frac{1}{(j+1)\left(1-(j+1)(\bar{\gamma}_{S,D})/(\bar{\gamma}/2)\right)}\left(Q\left(\sqrt{2\gamma_T}\right)-\frac{\exp\left(((j+1)\gamma_T)/(\bar{\gamma}/2)\right)Q\left(\sqrt{2\left(\gamma_T+((j+1)\gamma_T)/(\bar{\gamma}/2)\right)}\right)}{\sqrt{1+\left((j+1)/\bar{\gamma}/2\right)}}\right)\Bigg\}\Bigg]
\end{aligned}
\tag{15}
$$

This expression can be further simplified due to the fact that it is still dominant when $j|=0$. In addition, upon evaluating the last result in the MAPLE software, we have noted that the first part of the expression has a negligible effect on the performance, especially, when we go further in increasing SNR. Therefore, the result in (16) can be simplified as

$$P_{\text{out}} \simeq \frac{1}{\bar{\gamma}\bar{\gamma}_{S,D}}\left[\left(\gamma_{\text{out}}\right)^2+\left(\gamma_T\right)^2-2\gamma_T\gamma_{\text{out}}\right] \tag{17}$$

By noting that $\bar{\gamma}=\bar{\gamma}_{S,D}=\text{SNR}$, the result in (17) can be rewritten as

$$P_{\text{out}} \simeq \left(\left(\left[\left(\gamma_{\text{out}}\right)^2+\left(\gamma_T\right)^2-2\gamma_T\gamma_{\text{out}}\right]\right)^2\text{SNR}\right)^{-2} \tag{18}$$

As can be noted from the last result, the coding gain of the system is$([(\gamma_{\text{out}})^2+(\gamma_T)^2-2\gamma_T\gamma_{\text{out}}]/2)^2$, whereas the diversity order is 2. This is clear in the numerical examples where all the curves of different M asymptotically converge to the same behaviour and result in a diversity order of 2 (the relay path| + direct link). Also, it is proved in the numerical examples that the system performance is affected by several parameters as γ_T and γ_{out}, which are only affecting the coding gain of the system. It is expected from results to have the maximum gain in system performance because of increasing M to happen at values of SNR that are comparable with γ_T. As in this case, the switching rate will increase and the probability to have better relays also increases. At the same time, as the asymptotic analysis is done at high SNR values and with constant γ_T and γ_{out}, it is expected the whole time to have most of the relays to be acceptable and thus, the first checked relay is being selected in both selection schemes. This means all curves of different M asymptotically converge to the same behaviour and thus, the same diversity order and coding gain are achieved for the different curves. Also, this explains why the system with the SEC and SECps selection schemes achieves the same diversity order and coding gain.

4.2 SECps-based relay selection

Upon substituting the approximate expressions of the exponential statistics in (14) and following the same procedure as in Appendix 1, the outage probability for the SECps selection scheme can be obtained at high SNR as

$$\begin{aligned} P_{\text{out}} \simeq \frac{1}{2\bar{\gamma}/2\bar{\gamma}_{S,D}}\Bigg\{&2M!\left(\frac{1}{\bar{\gamma}/2}\right)^{M-1}\Bigg[\frac{(\gamma_{\text{out}})^{M+1}}{M!(M+1)} \\ &-\sum_{k=0}^{M-1}\frac{(\gamma_T)^k}{(M-k)!k!}\sum_{i=0}^{M-k}\binom{M-k}{i}\frac{(-\gamma_T)^{M-k-i}}{(i+1)} \\ &\times\left[\left(\gamma_{\text{out}}\right)^{i+1}-\left(\gamma_T\right)^{i+1}\right]\Bigg] \\ &+\sum_{j=0}^{M-1}\left(\frac{\gamma_T}{\bar{\gamma}/2}\right)^j\left[\left(\gamma_{\text{out}}\right)^2+(\gamma_T)^2-2\gamma_T\gamma_{\text{out}}\right]\Bigg\} \end{aligned} \tag{19}$$

This expression can be further simplified due to the fact that it is still dominant when $k=0$, $i=0$ and $j=0$. In addition, upon evaluating the last result in the MAPLE mathematical software, we have noted that the first part of the expression has a negligible effect on the performance, especially, when we go further in increasing the value of the SNR. Therefore the result in (19) can be simplified as

$$P_{\text{out}} \simeq \frac{1}{\bar{\gamma}\bar{\gamma}_{S,D}}\left[\left(\gamma_{\text{out}}\right)^2+(\gamma_T)^2-2\gamma_T\gamma_{\text{out}}\right] \tag{20}$$

As can be seen, the asymptotic outage probability in (20), which corresponds to the SECps selection scheme is exactly the same as that in (17) for the SEC scheme. Hence, it can be easily concluded that both selection schemes have the same coding gain and the same diversity order as derived before in the subsection or SEC relaying. This is clear from the numerical examples, where the SECps selection scheme behaves similar to the SEC scheme, especially, at high SNR values. This is expected at high SNR values, most of the relays will be acceptable the whole time and hence, the first checked relay will be suitable and thus selected in both schemes. Again, as the asymptotic analysis is conducted at high SNR values, this explains why the system with the two selection schemes achieves the same diversity order and coding gain.

5 Numerical results

In this section, we illustrate the validity of the achieved analytical expressions and the tightness of the used bound via a comparison with the Monte-Carlo simulations. We also provide some numerical examples to prove the effectiveness of the proposed relay selection scheme in reducing the system complexity and to show the effect of some system parameters like the number of relays, the switching threshold, the outage threshold and the relays location on the system performance.

Fig. 3 portrays the system outage probability for the SEC and SECps relaying schemes for different values of outage threshold γ_{out}. It is clear from this figure that as γ_{out} increases, the system performance is more degraded, as expected. Also, the enhancement achieved in system performance when the SECps is used is obvious in this figure compared with the SEC relaying scheme. This gain is more notable in the range, where the value of γ_T is comparable with the average SNR. For the case where γ_T is

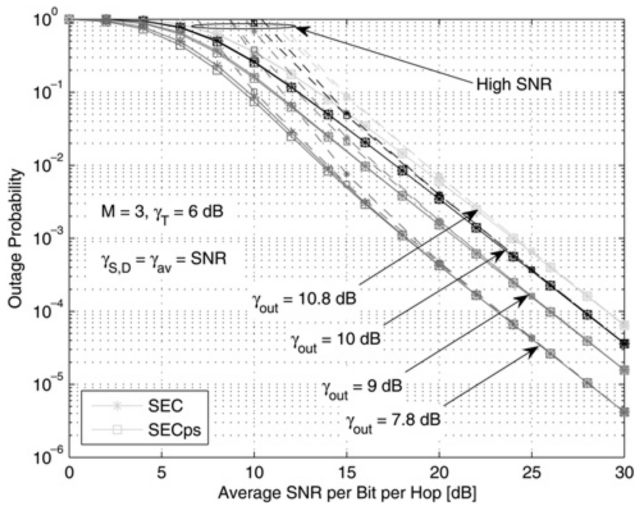

Fig. 3 *Outage probability against average SNR for AF relay system with SEC and SECps relaying schemes and MRC at destination for different values of outage threshold γ_{out}*

IET Commun., 2013, Vol. 7, Iss. 9, pp. 848–859
doi: 10.1049/iet-com.2012.0659

much larger than the average SNR, the probability that all relays are unacceptable is high and thus, the two selection schemes almost behave the same. As SNR increases and becomes close to γ_T, more relays become acceptable and hence, the SECps scheme behaves better than the SEC scheme. In the region where γ_T is much smaller than the average SNR, the probability that all the relays will be acceptable is very high and thus, the two schemes give the same behaviour. In addition, the perfect match between the analytical results and the asymptotic curves is obvious in this figure for both the SEC and the SECps selection schemes. Finally, this figure shows that increasing γ_{out} degrades the system performance of both schemes via affecting the coding gain, whereas the diversity order remains constant at 2.

Fig. 4 studies the effect of number of relays M on the outage performance. We can see that at the medium values of SNR, as M increases the better the achieved behaviour. Also, one can note that as M continues increasing in this region, the gain in the system performance becomes smaller. More importantly, it is obvious in this figure that at both low and high SNR values, all curves asymptotically converge to the same behaviour and no gain is achieved in system performance with adding more relays. This is expected since when the switching threshold γ_T takes values much smaller or larger than the average SNR, the system asymptotically converges to the case of two relays and hence, adding more relays will not help in enhancing the system performance. Finally, it is clear from this figure that the curves asymptotically behave similar, especially, at high SNR values and this leads to the same diversity order. In other words, this figure shows that M has no effect on the diversity order of the system which remains constant at 2 in all cases of this figure.

Fig. 5 illustrates the outage performance for different values of SNR. As expected, as the value of SNR increases and hence, enhancing the direct link and relay paths channels, the better the achieved performance. In addition, the gain achieved in the system performance when the SECps scheme is used is clear in this figure compared with the case where the SEC is used. This gain is more notable for the case, where SNR value is comparable with γ_T. As the value of SNR becomes much larger than γ_T, the gain in the system behaviour becomes smaller.

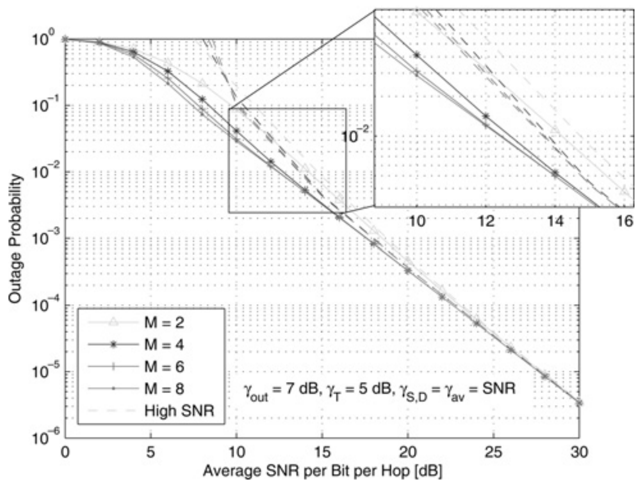

Fig. 4 *Outage probability against average SNR for AF relay system with SEC relaying scheme and MRC at destination for different numbers of relays M*

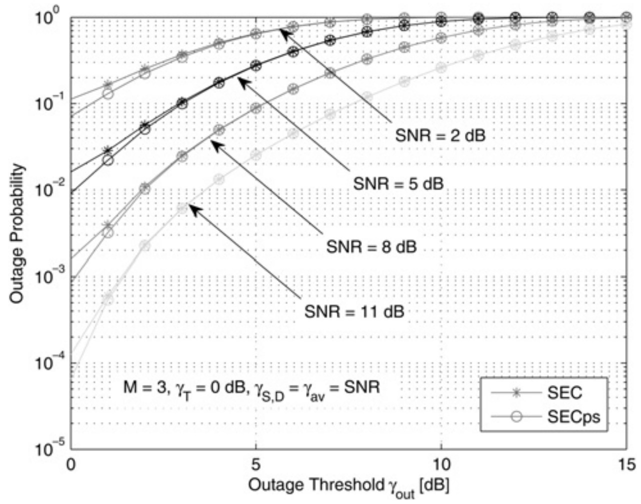

Fig. 5 *Outage probability against outage threshold for AF relay system with SEC and SECps relaying schemes and MRC at destination for different values of SNR*

Fig. 6 studies the system performance for various relay selection schemes; SEC, SECps and best relay selection. In this figure, the switching threshold was assumed to fixed $\gamma_T = 6$ dB and $\bar{\gamma}_{S,D} = \bar{\gamma} = \text{SNR}$. It is clear to note from this figure that the SECps has nearly the same performance as the best relay selection for the low-SNR region. When SNR increases, the error performance of the SECps scheme degrades and eventually becomes the same as that of SEC. This is expected since when γ_T is large in comparison with the average SNR, no relay will be acceptable and the SECps selection scheme will always select the best relay, just as in the best relay selection scheme; whereas, when γ_T is small compared with SNR, the SECps selection scheme works more like the conventional SEC scheme.

Fig. 7 shows the average BEP performance for the proposed system for no diversity, SEC and SEC + MRC cases with an optimal switching threshold $\gamma_{T\text{-opt}}$ being used. It can be noted from this figure that the derived upper bound of the total SNR (lower bound of BEP) is tight enough, especially, at medium and high SNR values. For example, the exact average BEP (simulation) for the SEC +

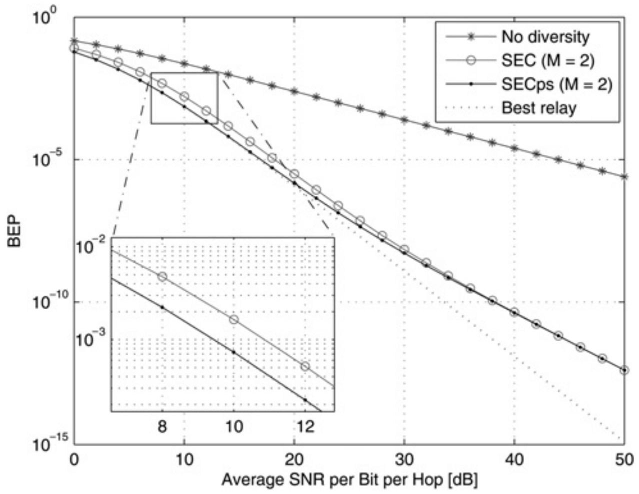

Fig. 6 *Average BEP against average SNR for AF relay system with SEC relaying scheme and MRC at destination in comparison with SECps relaying scheme and MRC at destination, and best relay selection scheme and MRC at destination for* $\bar{\gamma}_{S,D} = \bar{\gamma} = \text{SNR}$

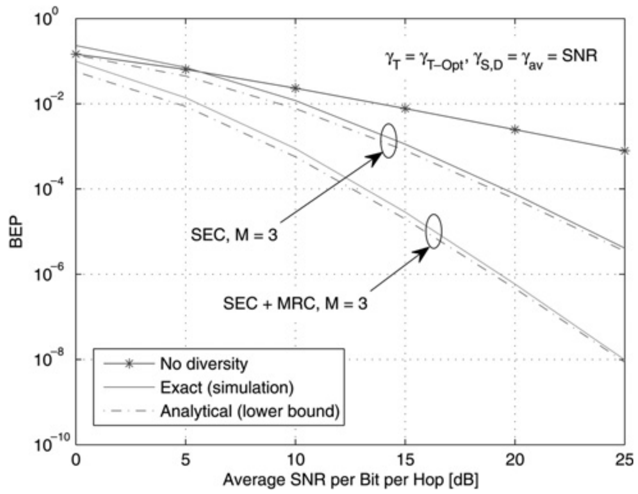

Fig. 7 *Average BEP against average SNR for AF relay system with SEC relaying scheme and MRC at destination for cases of no relaying, SEC relaying only and SEC relaying with MRC at destination*

MRC case at SNR = 15 dB equals $1 \times 10^{-4.7}$, whereas the analytical average BEP is $1 \times 10^{-4.8}$. This trend is valid for both the SEC and the SEC + MRC cases. This bound on the SNR is also used in the case of SECps relaying scheme. The gain that the SEC and the SEC + MRC cases add to the system performance compared with the no diversity case is obvious in this figure. In addition, the enhancement of the direct link adds to the system behaviour via the SEC + MRC case compared with the case of no direct link through the SEC alone is also clear in this figure.

Fig. 8 studies the effect of number of relays M on the average BEP performance of the SEC and SECps relay selection schemes. As we can see, increasing M leads to a significant gain in system performance for both schemes, especially, in the region where the average SNR value is comparable with γ_T. Also, the enhancement of the SECps scheme adds to system performance compared with the SEC scheme is clear in this figure. Finally, the achievement in system performance because of the relay cooperative diversity is obvious in this figure when compared with the no diversity case.

Fig. 9 studies the effect of the switching threshold γ_T and the number of relays M on the average BEP performance of the proposed relaying schemes. For the case of SEC relaying scheme, increasing M leads to a significant gain in system performance, especially, in the medium SNR region. On the other hand, as γ_T becomes much smaller or much larger than the average SNR, the BEP improvement decreases, as all curves asymptotically converge to the case of two relays. This is due to the fact that, if the average SNR is very small compared with γ_T, all the relays will be unacceptable most of the time. On the other hand, if the average SNR is very high when compared to γ_T, all the relays will be acceptable and one relay will be used most of the time. Thus, in both cases, the additional relays will not lead to any gain in system behaviour. On the other hand, the SECps relaying scheme gives the same performance as the SEC scheme in the region, where γ_T is much smaller than the average SNR, as expected; whereas, in the region where γ_T is much larger than the average SNR, the SECps gives better performance compared with the SEC scheme. This is because in the SECps scheme, when the last relay is reached and found unacceptable, the scheme selects the best relay among all relays in contrast to the SEC scheme which in this case sticks to that last relay. This explains the gap in system performance between the two schemes in this region of γ_T.

Fig. 10 illustrates the effect of switching threshold γ_T on the average BEP performance of the proposed system. It is clear from this figure that the best performance is achieved when the optimum switching threshold $\gamma_{T\text{–opt}}$ is used, as expected.

Fig. 11 demonstrates the impact of number of relays M on the BEP performance of the SEC relaying scheme. As expected, as M increases, the better the achieved performance, especially, in the region where the average SNR values are comparable with γ_T. The figure also shows that this behaviour extends to the case of i.n.d. relay hops.

Fig. 12 demonstrates the effectiveness of the proposed selection schemes compared with some popular schemes. As an example, for the case of four relays, the number of active relays in the best and partial relay selection schemes is four all the time. Whereas, it is smaller in the case of the SEC proposed scheme and depends on γ_T. In the worst case, it reaches three. For channel estimations, in the case of the best and partial relay selection schemes, 4 and 8

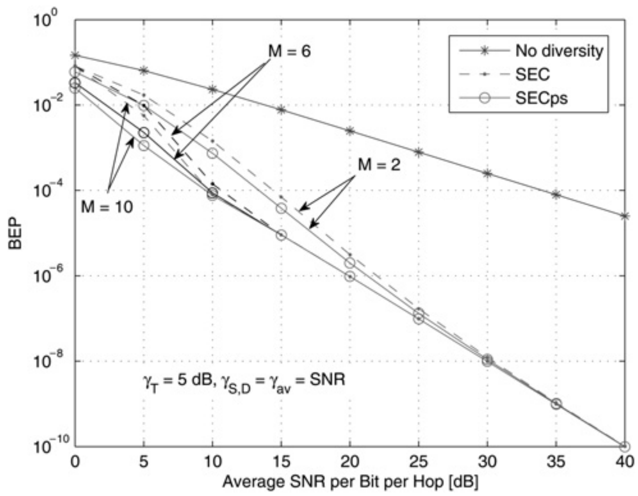

Fig. 8 *Average BEP against average SNR for AF relay system with SEC and SECps relaying schemes and MRC at destination for different numbers of relays M*

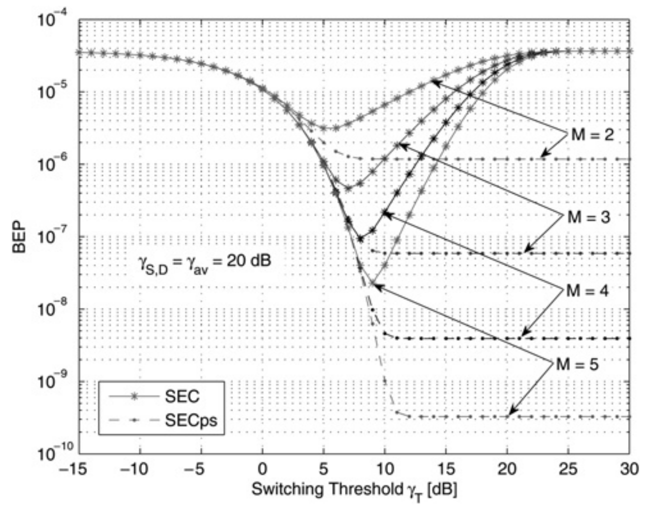

Fig. 9 *Average BEP against switching threshold for AF relay system with SEC and SECps relaying schemes and MRC at destination for different numbers of relays M*

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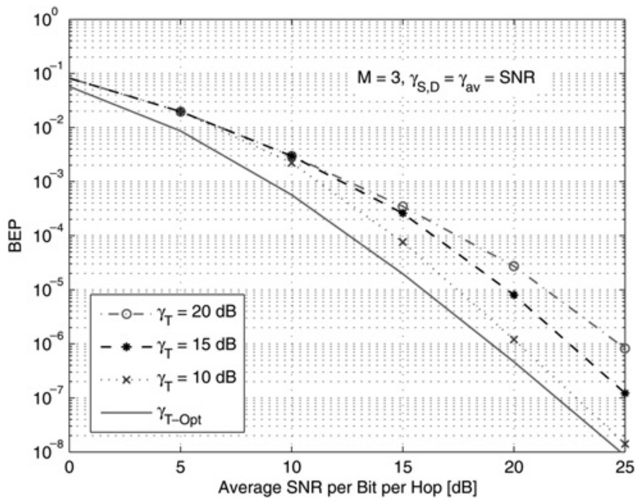

Fig. 10 *Average BEP against average SNR for AF relay system with SEC relaying scheme and MRC at destination for different values of switching threshold γ_T*

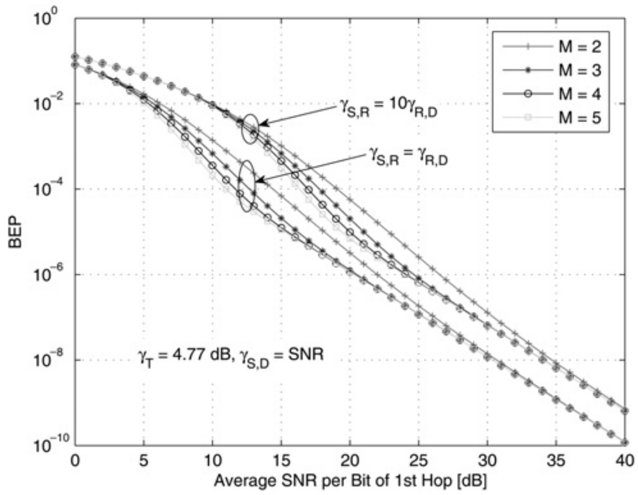

Fig. 11 *Average BEP against average SNR for AF relay system with SEC relaying scheme and MRC at destination for i.n.d. hops and different numbers of relays M*

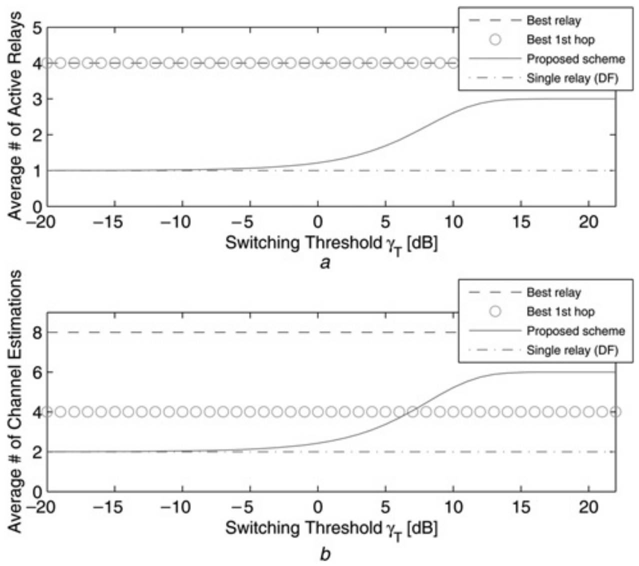

Fig. 12 *Complexity-performance tradeoff of the proposed SEC relaying scheme for AF relay system with BPSK, M = 4 and* $\bar{\gamma} = 7$dB

a Average number of active relays
b Average number of channel estimations

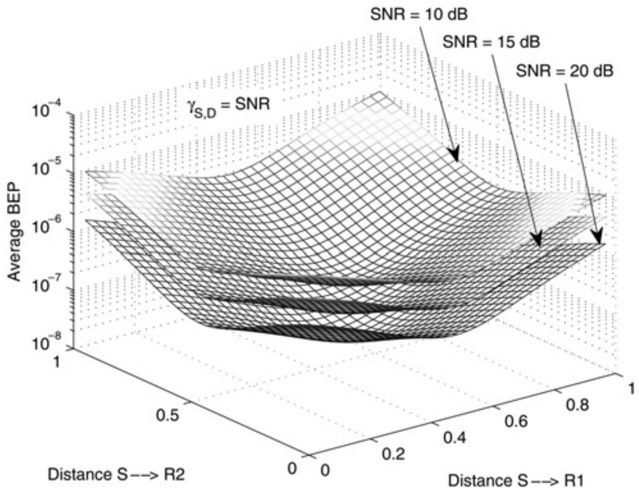

Fig. 13 *Average BEP against* $D_{S\rightarrow R_1}$ and $D_{S\rightarrow R_2}$ *for AF relay system with SEC relaying scheme for different values of SNR*

channels are required to be estimated, respectively. Whereas, it is lower in the proposed SEC protocol which reaches 6 at the worst case. This shows the significant reduction in system complexity the proposed schemes achieve.

Fig. 13 shows a three-dimensional portray for the average BEP against the distances from the source to relays for the case of two relays. This is equivalent to the case where the relays have i.n.d. hops. The curve studies the effect of the relays position on the average BEP performance for different values of SNR. It is clear that in order to have the best performance for this AF relay system, the two relays must be located in the midway between the source and the destination. In addition, it can be seen that as SNR increases, the system performance is more enhanced.

6 Conclusion

In this paper, we proposed a low-complexity SEC-based relay selection scheme for AF relay systems. This scheme is based on the well known SEC and SECps techniques. Using an upper bound on the SNR of the relay paths, the probability density and the CDFs of the SNR at output of the SEC combiner were first derived. Then, the e2e outage probability and BEP were derived for i.n.d. and i.i.d. relay channels. The Monte-Carlo simulations proved the accuracy of the analytical results and the tightness of the used bound, especially, at medium-to-high SNR values. Asymptotic high SNR results showed that the system with the SEC and SECps relaying schemes has the same diversity order of two and the same coding gain which is affected by the switching and outage thresholds. Furthermore, findings illustrated the effectiveness of the proposed relay selection schemes in reducing the system complexity compared with the existing relay selection schemes. Also, results showed that the gain achieved in system performance because of increasing the number of relays happens in the range of SNR values that are comparable with the switching threshold. Finally, findings illustrated the gain achieved in system performance by the SECps relaying scheme over the conventional SEC relaying, especially, at low-to-medium SNR values.

7 Acknowledgment

This work is supported by King Fahd University of Petroleum and Minerals (KFUPM) under grant number FT121002. The authors would like to thank Prof. M.-S. Alouini of King Abdullah University of Science and Technology for his helpful suggestions and encouragement.

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9 Appendix

9.1 Appendix 1 Proof of Lemma 1

In this Appendix, we evaluate the outage probability for the case of i.n.d. relay paths of the proposed system. For i.n.d. relay channels, the CDF of γ_{SEC} in (5) can be written as [22]

$$F_{\gamma_{\text{SEC}}}(\gamma) = \begin{cases} \sum_{i=0}^{M-1} \pi_i F_{\gamma_i}(\gamma) \prod_{k=0 k\neq i}^{M-1} F_{\gamma_k}(\gamma_T), & \gamma < \gamma_T \\ \sum_{i=0}^{M-1} \Big(\pi_i \prod_{k=1}^{M} F_{\gamma_k}(\gamma_T) \\ + \sum_{j=0}^{M-1} \pi_{((i-j))_M} [F_{\gamma_i}(\gamma) - F_{\gamma_i}(\gamma_T)] \\ \times \prod_{k=0}^{j-1} F_{\gamma_{((i-j+k))_M}}(\gamma_T) \Big), & \gamma \geq \gamma_T \end{cases} \tag{21}$$

where M is the number of relays and γ_T is a predetermined switching threshold, π_i, $i = 0, \ldots, M| - |1$ are the stationary distribution of a M-state Markov chain as given in [22] and it is the probability that the ith relay is chosen, and $((i-j))_M$ denotes i–j modulo M. For the Rayleigh fading channels, the CDF and the PDF of the ith relay path are, respectively, given by

$$F_{\gamma_i(\gamma)} = 1 - \exp\left(-\frac{\gamma}{\bar{\gamma}_i}\right) \quad \text{and} \quad f_{\gamma_i(\gamma)} = \frac{1}{\bar{\gamma}_i}\exp\left(-\frac{\gamma}{\bar{\gamma}_i}\right)$$

where $\bar{\gamma}_i$ is as defined before.

Differentiating (21) with respect to γ and upon taking the Laplace transform using $\int_0^\infty f_{\gamma_{\text{SEC}}}(\gamma)\exp(s\gamma)\,\mathrm{d}\gamma$, and after some algebraic manipulations, the MGF of γ_{SEC} can be obtained. As the MRC is used at the destination, the MGF of the total SNR at the MRC output is simply their multiplication $\mathcal{M}_{\gamma_{\text{tot}}}(s) = \mathcal{M}_{\gamma_{S,D}}(s)\mathcal{M}_{\gamma_{\text{SEC}}}(s)$.

Upon substituting the MGF of both the direct links $(1 - \bar{\gamma}_{S,D}s)^{-1}$ and $\mathcal{M}_{\gamma_{\text{SEC}}}(s)$ in $\mathcal{M}_{\gamma_{\text{tot}}}(s)$, and after using partial fraction operation and taking the inverse Laplace transform, the PDF of γ_{tot} can be obtained as

$$f_{\gamma_{\text{tot}}}(\gamma) = \sum_{i=0}^{M-1} \pi_i \prod_{\substack{k=0\\k\neq i}}^{M-1} \left(1 - \exp\left(-\frac{\gamma_T}{\bar{\gamma}_k}\right)\right)$$
$$\left[\frac{\exp(-(\gamma/\bar{\gamma}_{S,D}))}{\bar{\gamma}_{S,D}(1 - (\bar{\gamma}_i)/(\bar{\gamma}_{S,D}))} + \frac{\exp(-(\gamma/\bar{\gamma}_i))}{\bar{\gamma}_i(1 - (\bar{\gamma}_{S,D})/(\bar{\gamma}_i))}\right.$$
$$- \exp\left(-\frac{\gamma_T}{\bar{\gamma}_i}\right) \times \left\{\frac{\exp(-(1/\bar{\gamma}_{S,D})(\gamma - \gamma_T))}{\bar{\gamma}_{S,D}(1 - (\bar{\gamma}_i)/(\bar{\gamma}_{S,D}))}\right.$$
$$\left.\left. + \frac{\exp(-(1/\bar{\gamma}_i)(\gamma - \gamma_T))}{\bar{\gamma}_i(1 - (\bar{\gamma}_{S,D})/(\bar{\gamma}_i))}\right\} U(\gamma - \gamma_T)\right] + \sum_{i=0}^{M-1}\sum_{j=0}^{M-1} \pi_{((i-j))_M}$$

doi: 10.1049/iet-com.2012.0659

$$\times \prod_{k=0}^{j-1}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{((i-j+k))_M}}\right)\right)\left[\exp\left(-\frac{\gamma_T}{\bar{\gamma}_i}\right)\right.$$
$$\left.\left\{\frac{\exp\left(-(1/\bar{\gamma}_{S,D})(\gamma-\gamma_T)\right)}{\bar{\gamma}_{S,D}\left(1-(\bar{\gamma}_i/\bar{\gamma}_{S,D})\right)}+\frac{\exp\left(-(1/\bar{\gamma}_i)(\gamma-\gamma_T)\right)}{\bar{\gamma}_i\left(1-(\bar{\gamma}_{S,D}/\bar{\gamma}_i)\right)}\right\}\right] \tag{22}$$

where $U(\cdot)$ is the unit step function. The CDF of γ_{tot} can be evaluated by integrating (22) with respect to γ using $\int_{-\infty}^{\gamma} f_{\gamma_{\text{tot}}}(\lambda)\,\mathrm{d}\lambda$, and after some algebraic manipulations, the outage probability for the case of i.n.d. relay paths can be evaluated in an approximate closed-form expression as in (8).

9.2 Appendix 2. Proof of Lemma 2

In this Appendix, we evaluate the BEP for the case of i.n.d. relay paths of the proposed system. The average BEP for BPSK signals in terms of the MGF is given by Simon and Alouini [22]

$$P_b(E)=\frac{1}{\pi}\int_0^{\pi/2} M_{\gamma_{\text{tot}}}\left(-\frac{1}{\sin^2\phi}\right)\mathrm{d}\phi \tag{23}$$

Upon substituting (22) in (23), we obtain

$$P_b(E)=\sum_{i=0}^{M-1}\pi_i\prod_{\substack{k=0\\k\neq i}}^{M-1}\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_k}\right)\right)$$
$$\left[\frac{1}{\left(1-(\bar{\gamma}_i/\bar{\gamma}_{S,D})\right)}\underbrace{\frac{1}{\pi}\int_0^{\pi/2}\frac{\sin^2\phi}{\sin^2\phi+\bar{\gamma}_{S,D}}\mathrm{d}\phi}_{I_1}\right.$$
$$+\frac{1}{\left(1-(\bar{\gamma}_{S,D}/\bar{\gamma}_i)\right)}$$
$$\times\underbrace{\frac{1}{\pi}\int_0^{\pi/2}\frac{\sin^2\phi}{\sin^2\phi+\bar{\gamma}_i}d\phi}_{I_2}-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_i}\right)$$
$$\times\left\{\frac{1}{\left(1-(\bar{\gamma}_i/\bar{\gamma}_{S,D})\right)}\underbrace{\frac{1}{\pi}\int_0^{\pi/2}\frac{\sin^2\phi\exp\left(-\frac{\gamma_T}{\sin^2\phi}\right)}{\sin^2\phi+\bar{\gamma}_{S,D}}\mathrm{d}\phi}_{I_3}\right.$$
$$+\frac{1}{\left(1-(\bar{\gamma}_{S,D}/\bar{\gamma}_i)\right)}$$
$$\left.\left.\times\underbrace{\frac{1}{\pi}\int_0^{\pi/2}\frac{\sin^2\phi\exp\left(-\left(\gamma_T/(\sin^2\phi)\right)\right)}{\sin^2\phi+\bar{\gamma}_i}\mathrm{d}\phi}_{I_4}\right\}\right]$$
$$+\sum_{i=0}^{M-1}\sum_{j=0}^{M-1}\pi_{((i-j))_M}\prod_{k=0}^{j-1}$$
$$\left(1-\exp\left(-\frac{\gamma_T}{\bar{\gamma}_{((i-j+k))_M}}\right)\right)\left[\exp\left(-\frac{\gamma_T}{\bar{\gamma}_i}\right)\right.$$
$$\times\left\{\left[\frac{1}{\left(1-(\bar{\gamma}_i)/(\bar{\gamma}_{S,D})\right)}\right.\right.$$
$$\underbrace{\frac{1}{\pi}\int_0^{\pi/2}\frac{\sin^2\phi\exp\left(-(\gamma_T)/(\sin^2\phi)\right)}{\sin^2\phi+\bar{\gamma}_{S,D}}\mathrm{d}\phi}_{I_3}$$
$$+\frac{1}{\left(1-(\bar{\gamma}_{S,D})/(\bar{\gamma}_i)\right)}$$
$$\left.\left.\underbrace{\frac{1}{\pi}\int_0^{\pi/2}\frac{\sin^2\phi\exp\left(-(\gamma_T)/(\sin^2\phi)\right)}{\sin^2\phi+\bar{\gamma}_i}\mathrm{d}\phi}_{I_4}\right]\right\} \tag{24}$$

With the help of [22, equation (5A.9)], the integrals I_1 and I_2 can be obtained.

In evaluating the integral I_3, upon adding and subtracting $\bar{\gamma}_{S,D}$ to and from its numerator, we obtain

$$I_3=\frac{1}{\pi}\int_0^{\pi/2}\exp\left(-\frac{\gamma_T}{\sin^2\phi}\right)\mathrm{d}\phi-\frac{1}{\pi}\int_0^{\pi/2}\frac{\bar{\gamma}_{S,D}\exp\left(-(\gamma_T)/(\sin^2\phi)\right)}{\sin^2\phi+\bar{\gamma}_{S,D}}\mathrm{d}\phi \tag{25}$$

where the first part in (25) is the well known Gaussian Q-function given by $Q\left(\sqrt{2\gamma_T}\right)$.

After applying the change of variables

$$w=\sqrt{\frac{\gamma_T}{\sin^2\phi}-\gamma_T}=\sqrt{\gamma_T}\cot\phi$$

and after some algebraic manipulations, the integral I_3 can be obtained as

$$I_3=Q\left(\sqrt{2\gamma_T}\right)-\frac{1}{\sqrt{1+(1/\bar{\gamma}_{S,D})}}\times\exp\left(\frac{\gamma_T}{\bar{\gamma}_{S,D}}\right)Q\left(\sqrt{2\gamma_T+\frac{2\gamma_T}{\bar{\gamma}_{S,D}}}\right) \tag{26}$$

The integral I_4 can be evaluated by following the same steps as in the case of I_3. It can be obtained as

$$I_4=Q\left(\sqrt{2\gamma_T}\right)-\frac{1}{\sqrt{1+(1/\bar{\gamma}_i)}}\exp\left(\frac{\gamma_T}{\bar{\gamma}_i}\right)Q\left(\sqrt{2\gamma_T+\frac{2\gamma_T}{\bar{\gamma}_i}}\right) \tag{27}$$

Finally, upon substituting the results of I_1, I_2, (26) and (27) in (24), and after few simple manipulations, the BEP for the case of i.n.d. relay paths can be evaluated in an approximate closed-form expression as in (11).