Abstract—In this paper, relay selection is considered to enhance security of a cooperative system with multiple threshold-selection decode-and-forward (DF) relays. Threshold-selection DF relays are the relays in which a predefined signal-to-noise ratio is set for the condition of successful decoding of the source message. We focus on the practical and general scenario where the channels suffer from independent non-identical Rayleigh fading and where the direct links between the source and destination and source and eavesdropper are available. Based on channel state information knowledge, three relay selection strategies, namely traditional, improved traditional, and optimal, are studied. In particular, the secrecy outage probability of all three strategies are obtained in closed-form. It is found that the diversity of secrecy outage probability of all strategies can improve with increasing the number of relays. It is also observed that the secrecy outage probability is limited by either the source to relay or relay to destination channel quality.

I. INTRODUCTION

To secure the broadcast nature of wireless communication against eavesdroppers, physical layer security has gained much prominence [1]. Motivated by recent advances in cooperative communication systems [2], employing the cooperative technique to enhance physical layer security of wireless systems has recently been receiving significant research interest. Compared to multi-relay assisted transmission, relay selection in which a single relay among all possible candidates is selected for relaying a source’s signal has been shown to optimize system resource utilization, such as power and bandwidth, while maintaining the same diversity order.

Relay selection to improve secrecy in cooperative communication system has received considerable attention recently [3]–[13]. The relays considered in these works are conventional amplify-and-forward (AF) or decode-and-forward (DF) relays [2]. In all these works, relay selection is performed depending on the availability of the instantaneous channel state information (ICSI) or statistical channel state information (SCSI) of the links. Based on the knowledge of ICSI or/and SCSI, the following three cases have been considered mostly for the relay selection problem. Case i): when the ICSI of all links are known. In this case, the relay selected is the one which provides maximum secrecy rate. We refer to this as improved traditional selection (ITS). Case ii): when the ICSI of all links are known. In this case, the relay selected is the one which provides maximum secrecy rate. We refer to this as optimal selection (OS). In practise, the ICSI of the various links can be acquired using one of the techniques described in [14] and the references therein.

With the notable exception of [12], [13] and [15], most of the existing work on physical layer security in DF relay cooperative systems has only considered the high signal-to-noise ratio (SNR) regime for the source to relay link. This is not very practical as fading can severely degrade the channel quality of a link in wireless communication systems. In [12], the source to relay link quality is taken into account by considering that the rate at the destination is limited by the minimum of the source to relay and relay to destination rate. In [13], the set of successful relays which recover the source symbol are those for which the source to relay link rate is above a minimum threshold rate. Furthermore, only [13] has considered the existence of direct links from source to destination and source to eavesdropper. However, in this work, all the links are assumed to experience independent and identical Rayleigh fading. Though the identical distribution assumption makes the analysis more tractable, it may not be valid for practical wireless communication applications because, in general, the relays are not closely placed in real environments. Moreover, only the TS scheme is studied in [13] and the relay selection problem is not tackled in [15].

With this motivation in mind, in this paper, we study relay selection to enhance security of a cooperative system with multiple threshold-selection DF relays. In threshold-selection relaying scheme for DF cooperation protocol, the possible candidate relays for selection are those for which the signal-to-noise ratio (SNR) is above a predefined threshold [10]. We consider the more practical scenario where the direct links between the source to destination and source to eavesdropper exist and where the links experience independent but not necessarily identically distributed Rayleigh fading. The main contributions of the paper can be summarized as follows:

1) We study three relay selection strategies, depending on the ICSI and SCSI knowledge to enhance the secrecy outage probability of threshold-selection relaying.
2) We derive the secrecy outage probability in closed-form for the most general case of independent but non-identical
channels.

3) We obtain the secrecy outage assuming direct links from source to destination and source to eavesdropper.

In detailing our contributions, we observe that the studied relay selection strategies can increase the diversity order of secrecy outage probability with increasing the number of relays. Interestingly, we also observe that the secrecy outage probability can not be increased beyond a certain level if either the source to relay or relay to destination channel quality is kept fixed while the other is increased.

The rest of the paper is organized as follows. Section III introduces the system model. Section IV evaluates the secrecy outage probability for the relay selection strategies. Section V discusses the results, and finally, Section VI concludes the paper.

Notation: \( \mathbb{P}[\cdot] \) is the probability of occurrence of an event, \( \mathbb{E}_X[\cdot] \) defines the expectation of its argument over the random variable (r.v.) \( X \), \( (x)^{+} \triangleq \max(0,x) \) and \( \max(\cdot) \) denotes the maximum of its argument, \( F_X(\cdot) \) represents the cumulative distribution function (CDF) of the r.v. \( X \), and \( f_X(\cdot) \) is the corresponding probability density function (PDF).

II. SYSTEM MODEL

The system model consists of one source (S), one destination (D), one passive eavesdropper (E), and \( N \) DF relays (\( R_k \), \( k \in \{1,2,\ldots,N\} \)), as shown in Fig. 1. All nodes are equipped with a single antenna. The relays are half-duplex in nature, and hence, complete information transmission takes place in two time slots. S broadcasts its message in the first time slot. We assume that the relays are threshold-selection DF type \[16]; in other words, they correctly decode the received message and retransmits in the second time slot only if their SNR is above a threshold, \( \gamma_{th} \). The SNR threshold, \( \gamma_{th} \), can be properly chosen to achieve the goal of correct decoding. The channels are modeled as independent non-identically distributed flat Rayleigh fading. Both D and E utilize maximal ratio combining (MRC) technique to get the advantage of two copies of same signal from the direct transmission and the relayed transmission. The received SNR, \( \gamma_{xy} \), of any arbitrary \( x-y \) link from node \( x \) to node \( y \) can be expressed as \( \gamma_{xy} = \frac{P_x|h_{xy}|^2}{N_0} \), where \( x \) and \( y \) are from the set \( \{S,R,D,E\} \) for any possible combination of \( x-y \), \( x \neq y \). \( P_x \) is the transmit power from node \( x \) and \( N_0 \) is the noise variance of the additive white Gaussian noise (AWGN) at node \( y \). As \( h_{xy} \) is assumed Rayleigh distributed with average power unity, i.e., \( \mathbb{E}[|h_{xy}|^2] = 1 \), \( \gamma_{xy} \) is exponentially distributed with mean \( 1/\lambda_{xy} = P_x/N_0 \). The CDF of \( \gamma_{xy} \) can be written as \( F_{\gamma_{xy}}(z) = 1 - \exp(-\lambda_{xy}z) \), \( z \geq 0 \).

For simplicity, we further denote the parameters of the \( S-E \) and \( R_k-E \) links which are terminating at \( E \) as \( \lambda_{SE} = \alpha_{se} \) and \( \lambda_{R_kE} = \alpha_{ke} \), respectively. Parameters of the other links which are conveying messages towards \( D \), i.e., \( S-R_k \) or \( R_k-D \), are denoted by \( \lambda_{SR_k} = \beta_{sk} \) and \( \lambda_{R_kD} = \beta_{kd} \), respectively.

![System model with multiple threshold-selection DF relays.](image)

The achievable secrecy rate of the system is

\[
C_S \triangleq \frac{1}{2} \left[ \log_2 \left( \frac{1 + \gamma_M}{1 + \gamma_E} \right) \right]^+, \tag{1}
\]

where \( \gamma_M \) and \( \gamma_E \) are the main channel and eavesdropper channel SNR at \( D \) and \( E \), respectively. The term \( 1/2 \) reflects the fact that two time slots are required for information transfer.

The secrecy outage probability of the system represents the probability that the achievable secrecy rate is less than a target secrecy rate, \( R_s \), and is expressed as

\[
P_o(R_s) = \mathbb{P}[C_S < R_s] = \mathbb{P}[\gamma_M < \rho (1 + \gamma_E) - 1], \tag{2}
\]

where \( \rho = 2^{4R_s} \).

III. SECRECY OUTAGE OF RELAY SELECTION

Let us assume that \( S \) is a set representing the relays which are able to decode successfully at the first stage. A relay is to be selected from this particular set by a relay selection rule in the second stage. The secrecy outage probability of the system with relay selection, \( P_o(R_s) \), can be mathematically represented as

\[
P_o(R_s) = \sum_{K=0}^{N} \sum_{S=\mathbb{E}_L} \mathbb{P}[S]P_o^S(R_s), \tag{3}
\]

where \( \mathbb{P}[S] \) represents the probability of occurrence of a particular set \( S \) containing \( K \) relays, and \( P_o^S(R_s) \) represents the secrecy outage probability for a given relay selection rule. The second summation in (3) must be performed for \( \binom{N}{K} \) possible combinations. It should be noted that \( \mathbb{P}[S] \) and \( P_o^S(R_s) \) can be evaluated independently, as they are the result of independent events.

Now let us assume that the relays which are unable to exceed \( \gamma_{th} \) constitute the set \( \bar{S} \). \( \mathbb{P}[\bar{S}] \) can be easily evaluated by multiplying the probability of occurrence of \( S \) and \( \bar{S} \). With the probability that a particular relay \( k \) is in \( S \) given by

\[
\mathbb{P}[\gamma_{sk} > \gamma_{th}] = \exp(-\beta_{kd}\gamma_{th}), \tag{4}
\]

\( \mathbb{P}[\bar{S}] \) can be evaluated as

\[
\mathbb{P}[\bar{S}] = \prod_{\forall k \in \bar{S}} \mathbb{P}[\gamma_{sk} > \gamma_{th}] \prod_{\forall j \in \bar{S}} (1 - \exp(-\beta_{sj}\gamma_{th})). \tag{5}
\]

When \( S \) is the empty set, there exists only the direct link to \( D \) and \( E \) from \( S \). In this case, the secrecy outage probability can be obtained from (2) as

\[
P_o^S(R_s) = 1 - \frac{\alpha_{se} \exp(-\beta_{sd}(\rho - 1))}{\rho \beta_{sd} + \alpha_{se}}. \tag{6}
\]
When $S$ contains a single relay, the secrecy outage probability is obtained by using $\gamma_M = \gamma_{sd} + \gamma_{kd}$ and $\gamma_E = \gamma_{se} + \gamma_{ke}$. The $\gamma_M$ and $\gamma_E$ distributions can be readily found for different parameters of the exponential r.v.s as \cite{17}

$$f_X(x) = B_1 e^{-\lambda_1 x} + B_2 e^{-\lambda_2 x}, \quad (7)$$

where $B_1 = \frac{\lambda_2}{\lambda_2 - \lambda_1}$, $B_2 = \frac{\lambda_1}{\lambda_2 - \lambda_1}$. $\lambda_1$ and $\lambda_2$ are the parameters of the two independent exponentially distributed r.v.s, with $\lambda_1 \neq \lambda_2$. Thus, the secrecy outage probability can be obtained from \cite{12} as

$$P_o^S(R_s) = 1 - \frac{\beta_{sd}\alpha_{ke}\alpha_{se}\exp(-\beta_{kd}(\rho - 1))}{(\beta_{sd} - \beta_{rd})(\rho\beta_{sd} + \alpha_{re})(\rho\beta_{kd} + \alpha_{se})}$$

$$- \frac{\beta_{kd}\alpha_{ke}\alpha_{se}\exp(-\beta_{rd}(\rho - 1))}{(\beta_{rd} - \beta_{sd})(\rho\beta_{sd} + \alpha_{re})(\rho\beta_{kd} + \alpha_{se})}. \quad (8)$$

\subsection{A. Traditional Selection (TS)}

The traditional relay selection rule does not take into account the $R_k$-E channel quality for all $k$. This scheme selects the relay which achieves the highest rate through the $R_k$-D link, as successful decoding has already been performed in the first stage. The highest rate is achievable on the link having highest instantaneous SNR.

The secrecy outage probability of the traditional rule corresponding to $S$ can be evaluated using the law of total probability as

$$P_o^S(R_s) = \sum_{\forall k \in S} \mathbb{P} \left[ \text{Relay} = R_k \right] \mathbb{P} \left[ C_S^k < R_s \right]$$

$$= \sum_{\forall k \in S} \mathbb{P} \left[ \gamma_{kd} > \gamma_{kd} \right] \mathbb{P} \left[ \frac{1 + \gamma_{kd} + \gamma_{sd}}{1 + \gamma_{ke} + \gamma_{se}} \leq \rho \right]$$

$$= \sum_{\forall k \in S} \mathbb{P} \left[ \gamma_{kd} < \gamma_{kd} \leq (\rho - 1) + \rho (\gamma_{ke} + \gamma_{se}) - \gamma_{sd} \right], \quad (9)$$

where $C_S^k$ is the secrecy outage probability for the $k$th relay in $S$, $\gamma_{kd} = \max\{\gamma_{i}\}$, where $\forall i \in S$ and $i \neq k$, is the maximum SNR between all relays which are not selected from $S$ by the relay selection rule. The distribution $f_{\gamma_{kd}}(y)$ is expressed as \cite{12}

$$f_{\gamma_{kd}}(y) = -\sum_{m=1}^{K-1} (-1)^m \sum_{m_i \neq m} \beta_m e^{-y/\beta_m}, \quad (10)$$

where \sum_{m}^t is defined as

$$\sum_{m}^t = \sum_{i_1=1 \atop i_1 \neq k}^{K-(m-1)} \sum_{i_2=i_1+1 \atop i_2 \neq k}^{K-(m-2)} \cdots \sum_{i_m=1 \atop i_m \neq k}^{K-m+1} \sum_{i_{m+1}=i_m+1 \atop i_{m+1} \neq k}^{K-m}.$$

$$\quad \sum_{m}^t \beta_m = \beta_{kd} \sum_{m}^t \beta_m.$$

and $\beta_m = \sum_{i_1=1 \atop i_1 \neq k}^{K-(m-1)} \beta_{i_1}$. To further evaluate the probability in \cite{9}, let us assume a new r.v, $X = \gamma_{ke} + \gamma_{se}$. As all r.v.s in \cite{9} are independent, the solution can be written in integral form as

$$P_o^S(R_s) = \sum_{\forall k \in S} (I_1 + I_2), \quad (12)$$

where

$$I_1 = \int_{\rho-1}^{\rho} \int_{z-(\rho-1)}^{\infty} \int_{0}^{\lambda} f_{\gamma_{kd}}(t) f_{\gamma_{kd}^{-1}}(y) f_X(x)$$

$$\times f_{\gamma_{sd}}(z) dtdydz,$$

$$I_2 = \int_{\rho-1}^{\rho} \int_{0}^{\infty} \int_{0}^{\lambda} f_{\gamma_{kd}}(t) f_{\gamma_{kd}^{-1}}(y) f_X(x)$$

$$\times f_{\gamma_{se}}(z) dtdydz,$$

and $\lambda = \rho - 1 + \rho x - z$.

In deriving \cite{12}, $x$, $y$, and $z$ represent the realizations of $X$, $\gamma_{kd}$, and $\gamma_{sd}$, respectively. The distribution $f_{\gamma_{kd}}(y)$ is given in \cite{10}, while the distribution of the r.v $X$ is given in \cite{7}. The integration limits are due to following reasons: i) $\gamma_{kd}$ should be always less than $\lambda$; hence, $y$ takes values from zero to $\lambda$, ii) none of the r.v.s can take negative values, and hence, when $\gamma_{sd}$ exceeds $(\rho - 1)$, $X$ is higher than $(z - (\rho - 1))/\rho$ in \cite{13}, iii) when $\gamma_{sd}$ is below $(\rho - 1)$, $X$ has positive values; hence, the corresponding integral is from zero to infinity in \cite{14}. Final expressions of $I_1$ and $I_2$ are given in \cite{20} and \cite{21}, respectively.

\subsection{B. Improved Traditional Selection (ITS)}

Traditional relay selection can be improved by using the statistical channel knowledge of the $R_k$-E link, $\alpha_{ke}$, in \cite{9} to obtain $P_o^S(R_s)$, as follows

$$P_o^S(R_s) = \sum_{\forall k \in S} \mathbb{P} \left[ \gamma_{kd} > \left( \frac{\gamma_{kd}}{1/\alpha_{ke}} \right)^{-1} \right] \mathbb{P} \left[ 1 + \gamma_{kd} + \gamma_{sd} \leq \rho \right]$$

$$= \sum_{\forall k \in S} \mathbb{P} \left[ \gamma_{kd} > \left( \frac{\gamma_{kd}}{1/\alpha_{ke}} \right)^{-1} \right] \mathbb{P} \left[ 1 + \gamma_{ke} + \gamma_{se} \leq \rho \right]$$

$$= \sum_{\forall k \in S} (I_3 + I_4), \quad (15)$$

where

$$\gamma_M = \left( \frac{\gamma_{kd}}{1/\alpha_{ke}} \right)^{-1} = \max_{\forall k \in S \atop \forall i \neq k} \left\{ \gamma_{i} \right\} = \max_{\forall i \neq k} \left\{ \gamma_{i} \right\}, \quad (16)$$

and $I_3$ and $I_4$ are expressed in \cite{22} and \cite{23}, respectively. The PDF of $\gamma_M$ can be easily obtained as in \cite{10}, with $\beta_m = \sum_{i=1}^t \beta_{i}$. $I_3$ and $I_4$ can be integrated to $I_4 = -\sum_{m=1}^{K-1} (-1)^m \sum_{m_i \neq m} (P_{11} + P_{12} - P_{13})$ and $I_4 = -\sum_{m=1}^{K-1} (-1)^m \sum_{m_i \neq m} (P_{21} + P_{22} - P_{23})$, respectively, where $P_{11}, P_{12}, P_{13}, P_{21}, P_{22}, P_{23}$ are given in \cite{24} to \cite{29}.
It is worth mentioning that (24) to (29) are valid for \((\alpha_k/\beta_{kd} + \beta_{kd}) \neq \beta_{sd}\) and \(\beta_{kd} \neq \beta_{sd}\). When either \((\alpha_k/\beta_{m} + \beta_{kd}) = \beta_{sd}\) or \(\beta_{kd} = \beta_{sd}\), the analytical expressions can be similarly found after slight modifications.

C. Optimal Selection (OS)

Optimal selection takes into account both main channel and \(E\) channels quality. The relay is selected for which the secrecy rate is maximum, and

\[
P^\text{O}_o(R_k) = \mathbb{P}\left[ \max_{\forall k \in S} \left( \frac{1 + \gamma_{kd} + \gamma_{sd}}{1 + \gamma_{ke} + \gamma_{se}} \right) \leq \rho \right].
\]

The above probability can be evaluated first for given \(\gamma_{ke}\) and \(\gamma_{sd}\), and then by averaging over them. In this case, (17) can be written as a product of individual probabilities

\[
P^\text{O}_o(R_k) = \mathbb{E}_{\gamma_{se}} \mathbb{E}_{\gamma_{sd}} \prod_{\forall k \in S} \mathbb{P}\left[ \frac{1 + \gamma_{kd} + \gamma_{sd}}{1 + \gamma_{ke} + \gamma_{se}} \leq \rho | \gamma_{se}, \gamma_{sd} \right]
\]

\[
= \mathbb{E}_{\gamma_{se}} \mathbb{E}_{\gamma_{sd}} \prod_{\forall k \in S} \mathbb{P}\left[ \gamma_{kd} \leq (\rho - 1) + \rho (\gamma_{ke} + \gamma_{se}) \right]
\]

\[-\gamma_{sd} | \gamma_{se}, \gamma_{sd} ] = I_5 + I_6,
\]

where \(I_5 \) and \(I_6\) are expressed in (30) and (32), respectively, with \(\lambda = ((\rho - 1) + \rho (x + y) - z)\), and \(x, y, z\) are realizations of the r.v.s \(\gamma_{ke}, \gamma_{se}\), and \(\gamma_{sd}\) respectively. The solution of \(I_5\) and \(I_6\) are provided in (31) and (33), respectively, with \(\sum_m\) defined as \(12\)

\[
\sum_m = \sum_{i_1=1}^{K-1} \sum_{i_2=i_1+1}^{K-2} \cdots \sum_{i_m-1=i_m-2+1}^{K-1} \sum_{i_m}^{K-1}.
\]

We also define \(\beta'_m = \sum_{l=1}^{k} \beta_{kd}' A_k' = \prod_{l=1}^{k} A_{it}\), and \(A_{k} = \alpha_{ke} \exp(-\beta_{kd} (\rho - 1))\).

IV. NUMERICAL AND SIMULATION RESULTS

This section describes numerical and simulation results. Unless otherwise mentioned, \(1/\beta_{sd} = 3\) dB, \(1/\alpha_{se} = 2\) dB, \(\gamma_{th} = 3\) dB, \(N = 4\), and \(R = 1\) bits per channel use (bpcu).

In Fig. 2, the secrecy outage probabilities of the selection schemes TS, ITS and OS are plotted versus average SNR, \(1/\beta\), for different rate requirements, \(R_k = 1\), 2 bpcu. Non-identical link parameters are considered, with \(1/\beta_{kd} = 0.2/\beta, 0.6/\beta, 0.4/\beta, 0.8/\beta, 1/\beta_{kd} = 0.8/\beta, 0.4/\beta, 0.6/\beta, 0.2/\beta\), whereas \(1/\alpha_{ke} = 0, 3, 6, 9\) dB, respectively, for \(k = 1, \cdots, 4\). As expected, OS works the best, followed by ITS, and TS is the worst. Additionally, it is worth noting that as \(R_k\) increases, the secrecy outage probability deteriorates.

Fig. 3 depicts the secrecy outage probabilities of the selection schemes TS, ITS and OS for two different \(\gamma_{th}\) values, i.e., \(\gamma_{th} = 0, 15\) dB. It is assumed that the \(S-R_k\) and \(R_k-D\) link qualities are identical, i.e., \(1/\beta_{kd} = 1/\beta_{kd} = 0.5/\beta\), while the \(R_k-E\) link qualities are non-identical, i.e., \(1/\alpha_{ke} = 0, 3, 6, 9\) dB for \(k = 1, \cdots, 4\). The secrecy outage probability deteriorates with the increase in \(\gamma_{th}\). Higher values of \(\gamma_{th}\) reduces the number of relays available for selection, hence the observation.

In Fig. 4 the secrecy outage probabilities of the selection schemes TS, ITS and OS are plotted versus the average SNR for increasing number of relays from \(N = 1\) to \(N = 4\). Identical link qualities are assumed as \(1/\beta_{kd} = 1/\beta_{kd} = 0.5/\beta\) and \(1/\alpha_{ke} = 3\) dB for all \(k\), respectively. It is clear that the performance improves as the number of relays increase. The slope of the curves also increases with increasing the number of relays, which means that the diversity order of the secrecy outage probability improves with \(N\). An important observation is that the improvement obtained by increasing the number of relays following the laws of diminishing return. Furthermore, as the \(R_k-E\) link qualities are identical for all \(k\), the ITS selection scheme can not provide better performance than the TS selection scheme and merges with TS. It is worth noting that the performances of the TS and ITS schemes do not merge in Fig. 2 and Fig. 3 respectively.

Fig. 5 shows the secrecy outage probabilities of the selection schemes TS, ITS and OS when the links \(S-R_k\) and \(R_k-D\) are unbalanced. Two cases are considered, as follows: Case
outage probability. Furthermore, it can be observed that when 
the secrecy outage probability saturates to a particular value 
depending on the values of $1/\beta_{sk}$ or $1/\beta_{kd}$. This indicates that 
either link $S-R_k$ or $R_k-D$, for all $k$, can limit the secrecy 
outage probability. Furthermore, it can be observed that when 
$1/\beta_{sk} = 10$ dB, the performance of the relay selection 
schemes saturates to the same value, while the performance 
saturates to different values when $1/\beta_{kd} = 20$ dB. When the $S-R_k$ link quality improves, the number of relays that 
exceed $\gamma_{sh}$ increases. As the relay selection schemes can take 
increased advantage when there are more relays to choose from, performance saturates to different values in Case 1 
depending on the selection scheme.

It should be noted that, in all figures, simulation results are in agreement with numerical results. This validates our analysis in Section III.

V. CONCLUSION

Three relay selection schemes, namely traditional, improved 
traditional, and optimal are proposed to enhance the secrecy 
outage probability using threshold-selection DF relays. The 
secrecy outage probability is derived in closed-form assuming the most practical scenario of independent but non-identical fading channels and including direct links from the source to destination and eavesdropper. It is found that by increasing the number of relays, the diversity gain of the secrecy outage probability can be increased. On the other hand, higher SNR threshold at the relays can decrease the secrecy performance. It is observed that the improved traditional relay selection can outperform the traditional relay selection only if the eavesdropper links are non-identical. It is also noticed that the secrecy outage probability is limited by either the source to relay or the relay to destination link quality.

REFERENCES

[1] A. D. Wyner, “The Wire-Tap Channel,” Bell System Technical Journal, vol. 54, no. 8, pp. 1355–1387, Oct. 1975.
[2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior,” IEEE Trans. Inf. Theory, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.
[3] I. Krikidis, “Opportunistic Relay Selection for Cooperative Networks with Secrecy Constraints,” IET Commun., vol. 4, no. 15, pp. 1787–1791, Oct. 2010.
[4] I. Krikidis, J. Thompson, and S. McLaughlin, “Relay Selection for Secure Cooperative Networks with Jamming,” IEEE Trans. Wireless Commun., vol. 8, no. 10, pp. 5003–5011, Oct. 2009.
[5] Y. Zou, X. Wang, and W. Shen, “Optimal Relay Selection for Physical-Layer Security in Cooperative Wireless Networks,” IEEE J. Sel. Areas Commun., vol. 31, no. 10, pp. 2099–2111, Oct. 2013.
[6] E. R. Alotaibi and K. A. Hamdi, “Relay Selection for Multi-Destination in Cooperative Networks with Secrecy Constraints,” in Proc. IEEE Vehicular Technology Conference, Sep. 2014, pp. 1–5.
[7] V. N. Q. Bao, N. Linh-Trung, and M. Debbah, “Relay Selection Schemes for Dual-Hop Networks under Security Constraints with Multiple Eavesdroppers,” IEEE Trans. Wireless Commun., vol. 12, no. 12, pp. 6076–6085, Dec. 2013.
[8] L. Wang, K. J. Kim, T. Q. Duong, M. Elkashlan, and H. Poor, “Security Enhancement of Cooperative Single Carrier Systems,” IEEE Trans. Inf. Forensics and Security, vol. 10, no. 1, pp. 90–103, Jan. 2015.
[9] L. Fan, X. Lei, T. Q. Duong, M. Elkashlan, and G. K. Karagiannidis, “Secure Multiuser Communications in Multiple Amplify-and-Forward Relay Networks,” IEEE Trans. Commun., vol. 62, no. 9, pp. 3299–3310, Sep. 2014.
[10] A. Jindal, C. Kundu, and R. Bose, “Secrecy Outage of Dual-hop Amplify-and-Forward System and its Application to Relay Selection,” in Proc. IEEE Vehicular Technology Conference, May 2014, pp. 1–5.
[11] ——, “Secrecy Outage of Dual-hop AF Relay System With Relay Selection Without Eavesdropper’s CSI,” IEEE Commun. Lett., vol. 18, no. 10, pp. 1759–1762, Oct. 2014.
[12] C. Kundu, S. Ghose, and R. Bose, “Secrecy Outage of Dual-hop Regenerative Multi-Relay System with Relay Selection,” IEEE Trans. Wireless Commun., vol. 14, no. 8, pp. 4614–4625, Aug. 2015.
[13] F. S. Al-Qahtani, C. Zhong, and H. Alnuweiri, “Opportunistic Relay Selection for Secrecy Enhancement in Cooperative Networks,” IEEE Trans. Commun., vol. 63, no. 5, pp. 1756–1770, May 2015.
[14] A. Bliztosas, A. Khisti, D. P. Reed, and A. Lippman, “A simple Cooperative diversity method based on network path selection,” IEEE J. Sel. Areas Commun., vol. 24, no. 3, pp. 659–672, Mar. 2006.
[15] S. Ghose, C. Kundu, and R. Bose, “Secrecy Performance of Dual-hop DF Relay System with Diversity Combining at the Eavesdropper,” IET Communications, Feb. 2016. [Online]. Available: http://dx.doi.org/10.1049/iet-com.2015.0906
[16] W. Smitrongpoom, F. Himsoon, W. Sin, and K. Liu, “Optimum Threshold-Selection Relaying for Decode-and-Forward Cooperation Protocol,” in Proc. IEEE Wireless Communications and Networking Conference, Apr. 2006, pp. 1015–1020.
[17] M. Akkouchi, “On the Convolution of Exponential Distributions,” J. Chungcheong Math. Soc., vol. 21, no. 4, pp. 501–510, Dec. 2008.
\[ I_1 = \sum_{m=1}^{N-1} (-1)^m \sum_{m'} B_1 b_{m} \exp(-\beta_{sd}(\rho - 1)) \left[ \frac{\beta_{m}'}{\alpha_{sc}/\rho + \beta_{sd}} + \frac{\beta_{sd}}{(\beta_{m}' + \beta_{kd})} \right] \left[ \frac{\beta_{m}}{\alpha_{sc}/(\rho(\beta_{m}' + \beta_{kd}) + \alpha_{sc})} + \frac{1}{\rho\beta_{kd} + \alpha_{sc}} \right] \]

\[ I_2 = \sum_{m=1}^{N-1} (-1)^m \sum_{m'} B_2 b_{sd} \exp(-\beta_{sd}(\rho - 1)) \left[ \frac{\beta_{m}'}{\alpha_{ke}/\rho + \beta_{sd}} + \frac{\beta_{sd}}{(\beta_{m}' + \beta_{kd})} \right] \left[ \frac{\beta_{m}}{\alpha_{ke}/(\rho(\beta_{m}' + \beta_{kd}) + \alpha_{ke})} + \frac{1}{\rho\beta_{kd} + \alpha_{ke}} \right] . \]

\[ I_3 = \int_{-1}^{\infty} \int_{y/\alpha_{ke}}^{\infty} \int_{0}^{\lambda} f_{\gamma_{kd}}(t) f_{\gamma_{zd}}(y) f_{T_{zd}}(z) dt dy dz . \]

\[ I_4 = \int_{-1}^{\infty} \int_{0}^{\lambda} f_{\gamma_{kd}}(t) f_{\gamma_{zd}}(y) f_{T_{zd}}(z) dt dy dz . \]

\[ P_{11} = \frac{\beta_{sd}\alpha_{ke} b_{m}'}{\alpha_{ke}(\alpha_{sc}/\rho + \beta_{sd}) + \beta_{m}'} + \frac{B_1}{\alpha_{ke}/(\rho(\beta_{m}' + \beta_{kd}) + \alpha_{sc})} . \]

\[ P_{12} = \frac{\beta_{sd}\alpha_{ke} b_{m}'}{\alpha_{ke}(\alpha_{sc}/\rho + \beta_{sd}) + \beta_{m}'} + \frac{B_1}{\alpha_{ke}/(\rho(\beta_{m}' + \beta_{kd}) + \alpha_{sc})} . \]

\[ P_{21} = \frac{B_1}{\alpha_{ke}/(\rho(\beta_{m}' + \beta_{kd}) + \alpha_{sc})} . \]

\[ P_{22} = \frac{B_1}{\alpha_{ke}/(\rho(\beta_{m}' + \beta_{kd}) + \alpha_{sc})} . \]

\[ P_{23} = \frac{B_1}{\alpha_{ke}/(\rho(\beta_{m}' + \beta_{kd}) + \alpha_{sc})} . \]

\[ I_5 = \int_{0}^{\infty} \int_{y/\alpha_{sc}}^{\infty} \left[ K_{y/\alpha_{sc}} \int_{0}^{\lambda} f_{\gamma_{kd}}(t) f_{T_{zd}}(x) dt dx \right] f_{\gamma_{zd}}(z) f_{T_{zd}}(y) dz dy . \]

\[ I_6 = \int_{0}^{\infty} \int_{y/\alpha_{sc}}^{\infty} \left[ K_{y/\alpha_{sc}} \int_{0}^{\lambda} f_{\gamma_{kd}}(t) f_{T_{zd}}(x) dt dx \right] f_{\gamma_{zd}}(z) f_{T_{zd}}(y) dz dy . \]