

An Adaptive Cooperative Protocol for Multi-Hop Wireless Networks

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Abstract— A Multi-hop relay communication system has gained tremendous attention recently as it reduces capital investment for expansion of coverage area. In this work, an adaptive cooperative decode-and-forward (DF) protocol was developed to enhance the performance of the system. In particular, a ‘best destination relay selection’ approach (BDRS) was proposed to achieve high diversity gain. The approach starts by selecting a destination node with the maximum channel gain first, and then selecting a relay node with the minimum outage probability afterwards. Closed-form expressions for the outage probability, which is a measure of system performance, were derived. Their validity was checked by comparing the calculated results with the simulated results from MATLAB software. Both results were found to be almost identical. Simulated outage probability of the proposed protocol was also found to be many folds lower than those of conventional and modified multi-hop communication protocols. Lastly, an optimum power allocation scheme was applied to further minimize outage probability.

Keyword—Cooperative Communications, Multi-hop, Relay Selection, and Routing Strategy.

I. INTRODUCTION

MULTI-HOP relay communication has become more and more important for the new generation of wireless communication system. It helps expanding service areas, increasing system capacity, and reducing the investment budget for base station expansion. The basic idea of radio relaying [1] is to use a relay node to process base station signal and send them out to another relay or destination node. Multi-hop relaying can expand cell coverage and reduce dead communication spots. Relays can take up some of the traffic load when the full capacity of the base station has been reached.

Radio relaying saves the terminal’s transmitting power, which in turn prolong battery life.

The relay-based architecture, its cooperation diversity, and cooperative multipath technology have already been implemented worldwide. All of the standards for existing and near future mobile communications systems—e.g., The 3rd Generation Partnership Project (3GPP) [2] and broadband wireless network (IEEE 802.16j) [3]—rely on the concept of relaying. A new project, the Wireless World Initiative New Radio (WINNER) project has planned out in detail an implementation of a ubiquitous broadband mobile radio relaying system.

For a small relaying system of one relay and one destination, there is only one possible route from source to destination. However, in a large relaying network (e.g., wireless sensor network), there are many relays between the source and the destination. A key question is which relay node should be selected to forward the information. One of the relay selection techniques is to simply pick the ‘best’ of all available relays for two hops and using that relay to decode and forward the information. In [4], the authors present a selection criterion of $\eta_l = \min[|h_{S,R_l}|^2, |h_{R_l,D}|^2]$ and an alternative ‘smoothed-out’ version of $\eta_l = 2 / \left(\frac{1}{|h_{S,R_l}|^2} + \frac{1}{|h_{R_l,D}|^2} \right)$, where h_{S,R_l} is the

channel impulse response between the source (S) and relay (R_l), $h_{R_l,D}$ is the channel impulse response between relay R_l and destination (D), and $l = 1, 2, \dots, L$. The relay node with the ‘best’ channel that produces the highest η_l is selected to retransmit the signal. This selection criterion helps avoid system bottleneck, but it might not be optimum. Another simple way to find a suitable route is by following the conventional protocol. In this protocol, the system selects the best relay that exhibits the maximum received signal to noise ratio (SNR) for each hop on a hop-by-hop basis. Yet, there is a problem with the last hop since there is no alternative route to the final destination. To solve this problem, the authors of [5] proposed an ad-hoc routing strategy—joint selection for the last two hops. We call this technique ‘modified conventional multi-hop strategy’. This strategy is easy to implement but its performance can still be improved. We describe it in details in system model B.

In [6], the best relay selection based on the technique of minimum outage route (MOR) was proposed. The authors assumed that each relay node can receive information from the

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nodes of two previous hops and combine their signals using a cooperative protocol. This assumption corresponds to a diversity of two transmitting nodes. The performance of such a system is superior to that of the system described in [5]. Nonetheless, the system performance is still not optimum with respect to the outage probability.

In contrast to the dual-hop transmission in [6], the authors in [7] analyzed transmission by multiple relays, where every relay retransmits the signal from the source to the destination. They found that the outage probability was not reduced by much as the number of relays increased. In fact, in some instances, more relays increased the outage probability. On the one hand, increasing the number of relay nodes increases the possibility that a successful relaying can occur, which increases the mutual information between the source and destination. On the other hand, increasing the number of relay nodes increases the probability of outage condition at the relay and destination nodes. This trade-off is a result of the time-division channel allocation scheme that allows proportionally less time for the source to transmit its signal when the number of relay nodes is increasing, i.e., the source is allowed to transmit only a fraction of $1/(m+1)$ of the time, where m is the number of relays. Hence, an optimal number of relay nodes exists, and it could be determined based on the SNR and channel conditions.

Similar to the model in [7], in [8], the authors investigated a model of two-hop transmission with a cooperative protocol and introduced a strategy of selecting the best relay based on the received SNR and channel quality instead of that of using all relays at a reduced power in [7]. They also derived the model's outage probability. Their result showed a better performance than that of [7]. In [7], the multiple relays could not reduce the outage probability significantly, but the best relay selection in [8] was very different—a larger number of relays resulted in a much higher reduction of outage probability.

In [9], for the purpose of further improvement of the system performance realized in [8], the authors applied a cooperative protocol with Alamouti-coding scheme but still used the best relay selection technique proposed in [8] to their system of two-hop transmission with one source, one destination, and two candidate relays. After the best relay was selected from time to time, four time slots were used to transmit two symbols, following the Alamouti-coding scheme; therefore, the system lost some bandwidth efficiency. To compensate, the authors employed Quadrature Phase Shift Keying (QPSK) modulation. They also derived an expression for the system's outage probability. Their simulation results showed that their system performed better than that in [8] by 1.5 dB at an SNR higher than 20 dB.

In [10], the authors considered a linear network model of a multi-hop relay communication system consisting of a source, a destination, and several relays equipped with multiple antennas. They did not focus on the direct link from the source to the destination within the same cluster. Distributed space-time coding was used to maximize diversity gain. In their discussion, the answer to whether to code a multi-hop relay channel in space or time was that it depends on the available resources such as availability of feedback, decoding

complexity, and various requirements of wireless application such as rate, latency, etc.

In this paper, we could not compare our results with those in [10] even though we used a linear network model similar to theirs because their relays were equipped with 2 antennas while ours had only one. Similarly, the cooperative protocol in [6], [7], [8], and [9] could not be compared to ours either because their systems consisted of only two hops while ours consisted of more than two hops, similar to those of [4] and [5]. In reality, multi-hop communication uses many hops and relays in each hop. When a cooperative protocol is applied, there are many candidate relays and candidate destinations in each cluster. There has never been proposed a selection strategy that gives the highest priority to the destination. That was the motivation for this research. Our reason was that the destination of every two hops is the source of the next hop, and we wanted the best source for the next hop, so it was sensible to give the best destination the highest priority. We named our proposed protocol the 'best destination relay selection (BDRS)' approach. We also derived a closed-form expression of the outage probability of our system. To validate it, we compared the calculated results against the simulated ones. We also evaluated our system performance against the modified conventional multi-hop strategy employed in [5]. Finally, we further improved our system performance by employing optimum power allocation for source (S) and relay (R). The results were very interesting. The system tried their best to maintain the S - D link by allocating more power to the source, even when the quality of the transmission link was poor. This finding confirmed that selecting the best destination node first has a tremendous impact on the system's performance.

The rest of this paper is organized as follows: in section II, models of the wireless communication system used in this study is described; in section III, a closed-form outage probability of our system is derived; in section IV, the simulated and calculated results are discussed; in section V, the optimum power allocation scheme and results are discussed; in section VI, the expected real-world implementation issues are considered; and section VII is the conclusion of this paper.

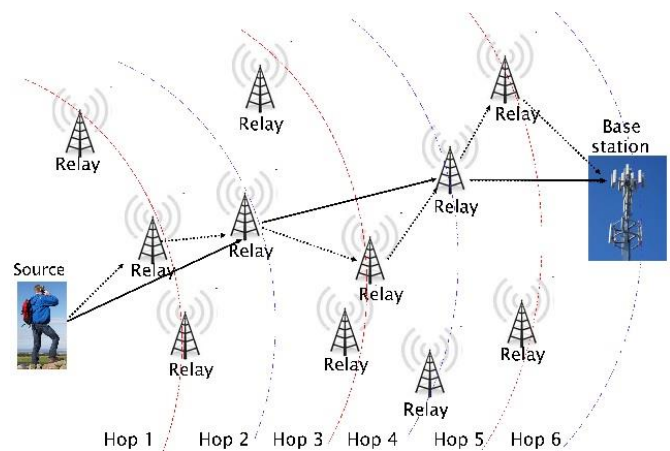


Fig. 1. A multi-hop communication system.

II. SYSTEM MODEL

In a multi-hop communication where a source node communicates with a destination node that is out of its coverage area, relays serve the function of a base station by recovering the signal received from the source node and retransmitting it to the desired destination. Hence, relays can reduce the cost of investment of a multi-hop communication system installation. Figure 1 shows a feasible communication area, a number of hops, and an example of a relay selection strategy. In this paper, our system employs a dual-hop relay transmission, in which a cluster of nodes consists of two hops. All nodes in a cluster can receive the transmitted signal from the source node.

In this section, we describe our system model of the conventional multi-hop relay selection approach and the modified conventional multi-hop relay selection approach.

For the sake of simplicity, we depicted an idealized linear network model in Figure 2 with M hops, L relays, and L destinations in each hop [5]. This routing strategy is called an Ad-hoc routing strategy.

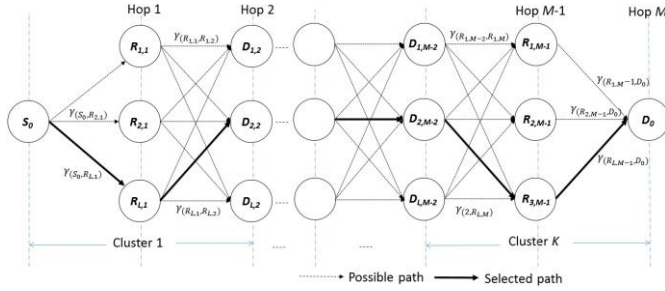


Fig. 2. Idealized linear network model with M hops, L relays, and L destinations for each hop.

In figure 2, it can be seen that there are one source (S), one destination (D), $M - 1$ hops, K clusters, and L linearly distributed nodes. A cluster is defined as a combination of one source, L relays, and L destination nodes for every two consecutive hops, and each node of the linearly distributed nodes functions as either a relay or a destination. The relationship between the index of a cluster (k) and the index of

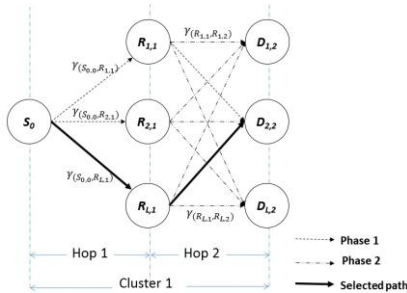


Fig. 3. The first cluster of an idealized linear network model, consisting of 2 consecutive hops, L relays, and L destinations.

a hop (m) is $m = 2k$.

Figure 3 shows an example of a relay selection in the 1st cluster. S_0 is the source node, $R_{l,1}$ represents the relay l of the 1st hop, and $D_{l,2}$ represents the destination node l of the 2nd hop, where $l = 1, 2, \dots, L$ and the distances between hops are equal. The channel impulse response of the system is independently and identically distributed. Each node is

equipped with one antenna employing a Time Division Multiple Access (TDMA) technique without spatial reuse and a decode-and-forward strategy for signal repeating. A selected relay decodes and re-encodes a packet fully before it is forwarded to the next destination. A relay can receive the signal from a neighboring relay only if they are in the same cluster. The solid line is an example of a route that connects nodes that exhibit the highest received SNR of each hop.

A. Conventional Multi-hop Relay Selection Approach

Given a source and a destination, relays are selected to provide the route that is the least error-prone in 2 selection phases [5]. In the first phase (phase 1), for any cluster k where

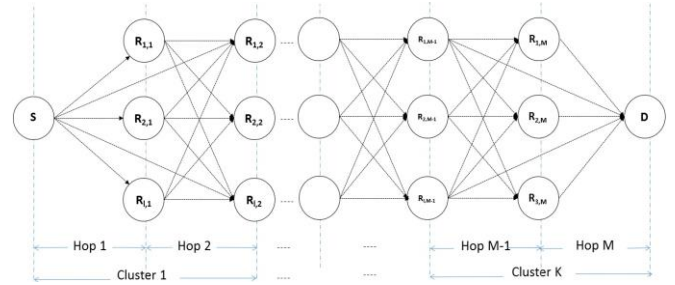


Fig. 4. An idealized linear network model with M hops, L relays, and K clusters, showing direct links in each cluster.

$k = 1, \dots, K - 1$, the relay (R_k^*) that exhibits the highest received SNR from S_0 is selected. R_k^* is found by solving $R_k^* = \arg \max_{R_{l,2k-1}}^{hop} (\gamma_{S,R_{l,2k-1}})$, where

$\gamma_{S,R_{l,2k-1}}$ (which is equal to $P_s |h_{S,R_{l,2k-1}}|^2 / N_0$) represents the received SNR from S to $R_{l,2k-1}$ (where $l = 1, 2, \dots, L$ and $2k-1$ are the indices of relays and the set of relays in the k^{th} cluster, respectively). The received signal at a selected relay R_k^* can be calculated from the following equation,

$$y_{S,R_k^*}^{hop} = \sqrt{P_s} h_{S,R_k^*} x + n_{R_k^*} \quad (1)$$

where P_s is the transmitted power from S to R_k^* , x is transmitted symbols, h_{S,R_k^*} is the channel impulse response of the SR_k^* link, and $n_{R_k^*}$ is the Additive White Gaussian Noise (AWGN) at R_k^* .

In phase 2, R_k^* decodes and re-encodes data then forwards them to a selected destination D_k^* . D_k^* is the node $D_{l,2k}$ that exhibits the highest received SNR from R_k^* . It is determined by solving

$$D_k^* = \arg \max_{D_{l,2k}} (\gamma_{R_k^*,D_{l,2k}}), \quad \text{where}$$

$\gamma_{R_k^*,D_{l,2k}}$ (which is equal to $P_R |h_{R_k^*,D_{l,2k}}|^2 / N_0$) represents the received SNR from R_k^* to $D_{l,2k}$ of hop $2k^{th}$ ($l = 1, 2, \dots, L$ and $2k$ are the indices of relays and the set of relays in the k^{th} cluster, respectively). R_k^* decodes and remodulates data $\tilde{x}$ before forwarding it to D_k^* in the k^{th} cluster. The received signal at a selected destination relay, $y_{R_k^*,D_k^*}^{hop}$, for multi-hop can be calculated from the following equation,

$$y = \sqrt{P_{R_k^*}} h_{R_k^*, D_k^*} \tilde{x} + n_{D_k^*} \quad (2)$$

where $P_{R_k^*}$ is the transmitted power from R_k^* to D_k^* , $\tilde{x}$ are remodulated data to be forwarded, $h_{R_k^*, D_k^*}$ is the channel impulse response between R_k^* and D_k^* , and $n_{D_k^*}$ is the Additive White Gaussian Noise (AWGN) at D_k^* in the k^{th} cluster.

B. Modified Conventional Multi-hop Relay Selection Approach

For the last cluster, there is only one destination available which makes $D_k^* = D_0$. In this approach, the only major difference from the conventional multi-hop relay selection approach is that the last two hops in the K^{th} cluster has to be handled jointly in order to achieve a higher diversity gain. For the hop $2K-1$, instead of determining an R_k^* from the maximum $\gamma_{D_{M-2}^*, R_{l,M-1}^*}$ (which is equal to $|h_{D_{M-2}^*, R_{l,M-1}^*}|^2 / N_0$), we determined it from $\arg \max_{R_{l,M-1}} \left(\min \left(\gamma_{D_{M-2}^*, R_{l,M-1}^*}, \gamma_{R_{l,M-1}^*, D_0} \right) \right)$,

where $\gamma_{D_{M-2}^*, R_{l,M-1}^*}$ (which is equal to $P_s |h_{D_{M-2}^*, R_{l,M-1}^*}|^2 / N_0$) is the received SNR between D_{M-2}^* (of hop $(M-2)^{\text{th}}$) and $R_{l,M-1}^*$, where $l = 1, 2, \dots, L$ and $M-1$ are indices of relays and hops in the K^{th} cluster, respectively, and $\gamma_{R_{l,M-1}^*, D_0}$ (which is equal to $P_R |h_{R_{l,M-1}^*, D_0}|^2 / N_0$) is the received SNR between $R_{l,M-1}^*$ (of hop $(M-1)^{\text{th}}$) and D_0 , where $l = 1, 2, \dots, L$ and $M-1$ are indices of relays and hops in the K^{th} cluster. A summary of this routing strategy is shown in Table 1.

TABLE I
ROUTING STRATEGY FOR MODIFIED CONVENTIONAL MULTI-HOP RELAY SELECTION

Let $l = 1, 2, \dots, L$; $m = 1, 2, \dots, M$; and $k = 1, 2, \dots, K$ be the indices of relays, hops, and clusters in a communication network. Let S denotes the source node; R_k^* denotes the selected relay node in the k^{th} cluster; D_k^* denotes the selected destination node in the k^{th} cluster. A hop index m is always equals to $2k$.

Initialization: $S = S_0$

Recursion:

For $k = 1$ to $K-1$

$$R_k^* = \arg \max_{R_{l,2k-1}} (\gamma_{S_0, R_{l,2k-1}}), l = 1, 2, \dots, L$$

- Decode and remodulate at R_k^*
- Send from R_k^* to D_k^*

$$D_k^* = \arg \max_{D_{l,2k}} (\gamma_{R_k^*, D_{l,2k}}), l = 1, 2, \dots, L$$

- Decode and remodulate at D_k^*

$$S = D_k^*$$

End

$$R_K^* = \arg \max_{R_{l,M-1}} \left(\min \left(\gamma_{D_{M-2}^*, R_{l,M-1}^*}, \gamma_{R_{l,M-1}^*, D_0} \right) \right), l = 1, 2, \dots, L$$

$$D_K^* = D_0$$

Output the optimal route $\{S_0, (R_k^*, D_k^*), D_0\}$, where $k = 1, 2, \dots, K$

The outage probability of this model is expressed in (3), which was derived for the Ad-hoc routing in [5],

$$P_{out,m}^{hop} = [I < th] = \begin{cases} \left(1 - \exp\left(-\frac{\gamma_{th}}{\delta_m^2 \gamma_0}\right)\right)^L, & m = 1, 2, \dots, M-2 \\ 1 - \exp\left(\frac{(\delta_{M-1}^2 \delta_M^2) \gamma_{th}}{(\delta_{M-1}^2 \delta_M^2) \gamma_0}\right)^L, & m = M-1 \end{cases} \quad (3)$$

where δ_m^2 represents the attenuation with distance and shadowing at hop m^{th} , $m = 1, 2, \dots, M$; γ_0 is the SNR averaged over Rayleigh fading, ignoring the path loss and shadowing; γ_{th} represents the given SNR threshold; and L is the number of relay nodes in each hop $l = 1, 2, \dots, L$.

C. The proposed best destination relay selection (BDRS)

In this paper, we propose a BDRS strategy for improving the performance of a multi-hop relay communication system and reducing the system complexity. This strategy employs a cooperative protocol—directly transmitted signal from the source and signal from a selected relay in each cluster are combined at a destination node—together with an efficient node selection rule. In this section, the preliminary information of the strategy is presented first followed by the routing strategy

Figure 4 shows a picture of the idealized linear network model investigated in this study. It has one source (S), one destination (D), and $M-1$ hops where each hop has L nodes that can function as a relay or a destination node in each cluster. A cluster can be viewed as a combination of one source, L relays, and L destination nodes in every two consecutive hops. The relationship between the index of cluster (k) and index of hop (m) is $m = 2k$. A direct link is a link between S - D , and an indirect link is a link via a cooperative relay S - R - D . The following are the characteristics of our model: the variance of additive white Gaussian noise (AWGN) is $N_0/2$ per complex dimension; the channel impulse response in this system is Rayleigh slow fading; the channel quality is checked periodically to enable adaptive feature; all channel links are statistically independent to each other; and a Time Division Multiple Access (TDMA) technique was applied in signal transmission. Specifically, TDMA was applied in each phase of the two transmission phases of the cooperative protocol as follows: in phase 1, S broadcasts a signal to $R_{l,m}$ and $D_{l,m}$ within a cluster; and in phase 2, $R_{l,m}$ detects the signal from S and remodulates it before transmitting the remodulated signal to $D_{l,m}$. $D_{l,m}$ of a previous cluster is the source ($S_{l,m}$) of the next cluster. The destination node ($D_{l,m}$) combines the signals from

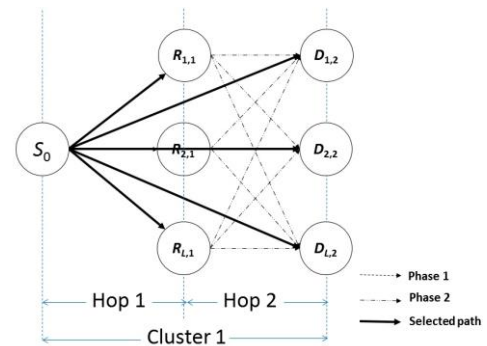


Fig. 5. The idealized linear network model with M hops and L relays in the 1st cluster for analyzing BDRS routing strategy.

S and $R_{l,m}$ using a maximum ratio combining (MRC) technique [11].

As for the BDRS routing strategy, we describe it by showing an analysis of only the first cluster, depicted in Figure 4. Other clusters can be analyzed in exactly the same way, up to the K -th cluster. The last cluster (the K th cluster) has only one final destination node; therefore, our protocol does not apply, and instead, selection of the best relay is performed according to the method in [7]. We considered only the case of $L = 3$ and $M = 2$ for our analysis, but it can be generalized to the cases of $l = 1, 2, \dots, L$ and $M = 2$.

Figure 5 shows a BDRS implementation in the first cluster of our modified conventional multi-hop communication model (illustrated in Figure 1). The model's cooperative protocol has an advantage of evenly broadcasting a signal from a source to all nodes in a cluster, including the selected destination node of the cluster. The proposed BDRS strategy, which is implemented in 2 phases, can be described as follows. The first node that transmits a signal is defined as $S = S_0$, and the destination node that receives a signal is $D = D_k$. Any number of k clusters, where $k = 1, \dots, K-1$, can be between the 2 nodes. In phase 1, a destination relay that exhibits the maximum received SNR is selected (D_k^*). D_k^* is found by calculating $\arg \max_{D_{l,2k}} (\gamma_{S,D_{l,2k}})$, where $l = 1, 2, \dots, L$ and $k = 1, 2, \dots, K-1$, and

$\gamma_{S,D_{l,2k}}$ (calculated from $P_S |h_{S,D_{l,2k}}|^2 / N_0$) represents the SNR from S to $D_{l,2k}$, where $l = 1, 2, \dots, L$. The expression for the received signal is

$$y_{S,D_k^*}^{coop} = \sqrt{P_S} h_{S,D_k^*} x + n_{SD_k^*}, \quad (4)$$

where P_S is the transmitted power from S to D , x represents modulated transmitted symbols, h_{S,D_k^*} is the channel impulse response from S to D , and $n_{SD_k^*}$ is AWGN from S to D .

In phase 2, a relay R_k^* is selected that exhibits the minimum outage probability (P_{out}), where $R_k^* = \arg \min_{R_{l,2k-1}} (P_{out})$ and P_{out} is as expressed in (19). R_k^* receives a broadcast signal from the source, detects $\tilde{x}$ by using a Maximum-Likelihood (ML) technique, and decodes and re-encodes the $\tilde{x}$ before transmitting it to the next destination node D_k^* . The optimal route is then the best one in the set of a-node-to-another-node routes $\{\mathbf{R}\} = \{S_0, (R_k^*, D_k^*), (R_k^*, D_0)\}$, and $k = 1, 2, \dots, K$. The received signal from R_k^* to D_k^* can be expressed as follows,

$$y_{R_k^*,D_k^*}^{coop} = \sqrt{P_{R_k^*}} h_{R_k^*,D_k^*} \tilde{x} + n_{R_k^*,D_k^*}, \quad (5)$$

where $P_{R_k^*}$ is the transmitted power from R_k^* to D_k^* , $\tilde{x}$ represents the decoded transmitted symbols, $h_{R_k^*,D_k^*}$ represents the channel impulse response from the selected R_k^* to D_k^* in cluster k^{th} , $n_{R_k^*,D_k^*}$ represents the Additive White Gaussian Noise (AWGN) from the selected R_k^* to D_k^* .

The destination relay (D_k^*) combines the received signals from S and R_k^* using a cooperative maximum ratio combining

(C-MRC) technique presented in [12]. Note that, at high $\gamma_{SR_k^*}$, the node that detects the signal places full confidence on the arriving signals from the relay. At low $\gamma_{SR_k^*}$, its confidence is weighted according to the ratio of both hops, which are the SR_k^* and $R_k^*D_k^*$ routes. The received symbols were detected by using the maximum likelihood (ML) technique. Then, the destination relay (D_k^*) functions as the source ($S_{l,2k-2}$) for the next consecutive cluster. The received signal is detected and re-encoded before the re-encoded signal is transmitted to a relay in the next cluster. The received signal can be calculated from the following expression,

$$y_{C-MRC}^{coop} = \left(\frac{\sqrt{P_S} h_{SD_k^*} y_{SD_k^*}}{n_{D_k^*}} \right) + \left(\frac{\min(\gamma_{SR_k^*}, \gamma_{R_k^*D_k^*})}{\gamma_{R_k^*D_k^*}} \right) \left(\frac{\sqrt{P_{R_k^*}} h_{R_k^*D_k^*} y_{R_k^*D_k^*}}{n_{D_k^*}} \right). \quad (6)$$

For the last cluster, a cooperative relay R_K^* is selected such that it exhibits the minimum outage probability ($R_K^* = \arg \min_{R_{l,2K-1}} (P_{out})$). Our proposed protocol is summarized in Table 2 as follows.

TABLE II
ROUTING STRATEGY FOR THE PROPOSED BDRS

Let $l = 1, 2, \dots, L$ be the index of relay nodes; $m = 1, 2, \dots, M$ be the index of communication hops; and $k = 1, 2, \dots, K$ be the index of clusters in a communication network. Let S denotes the source node; R_k^* denotes the selected relay node in the k^{th} cluster; and D_k^* denote the selected destination node in the k^{th} cluster; and note that a hop index $m = 2k$.

Initialization: $S = S_0$

Recursion:

For $k = 1$ to $K-1$

$$D_k^* = \arg \max_{D_{l,2k}} (\gamma_{S,D_{l,2k}}), \quad l = 1, 2, \dots, L$$

$$R_k^* = \arg \min_{R_{l,2k-1}} (P_{out}) \quad (P_{out} \text{ expression is in (19)})$$

- Decode at R_k^* and remodulate

- Send from R_k^* to D_k^*

- Combine signals by using C-MRC represented

by (6)

- Decode at R_k^* and remodulate at D_k^*

$$S = D_k^*$$

End

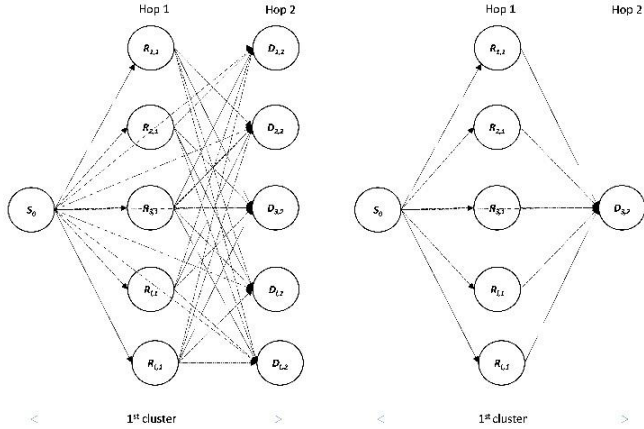
$$D_K^* = D_0$$

$$R_K^* = \arg \min_{R_{l,M-1}} (P_{out}) \quad (P_{out} \text{ is expressed in (19)})$$

Output the optimal route $\{S_0, (R_k^*, D_k^*), (R_{M-1}^*, D_0)\}$, $k = 1, 2, \dots, K$

In order to implement a cooperative protocol in a multi-hop relay system, we have to find two optimum nodes, i.e., one is the cooperative relay node and the other one is the destination node. We found that the proposed BDRS can reduce the computational complexity by searching only L times compared to the heuristic strategy that searches all nodes, as illustrated in Figure 6 (a) and (b). In the latter strategy, the source has to

search for the best relay node and the best destination node from all nodes in order to minimize the outage probability. In contrast, the proposed BDRS reduces the system complexity from an exponential function of L^m to a linear function of L , where L is the number of relays in each hop and m is the number of hops. In Figure 6, $m = 2$; the cluster consists of two hops. The proposed BDRS can reduce the complexity of clusters $k=1$ to $k = K-1$. The complexity of the last cluster ($k = K$) is, however, the same because there is only one final destination.



(a) Heuristic Searching Strategy. (b) The proposed BDRS searching strategy.

Fig. 6. Comparison of complexity for two different searching strategies.

III. PERFORMANCE ANALYSIS

In this section, we derive a closed-form expression of the outage probability for our BDRS protocol. The number of hops (M) was set to be 2, the number of cooperative relays (L) to be 1, and the number of destination relays (L) to be 3. We call this configuration 1R3D. We picked 1R3D as the best configuration to show the derivation of our protocol because a configuration of 3 Ds shows sufficiently the complexity of the derivation in a manageable length. Furthermore, any configuration with a higher number of Ds can be derived by using the same principle. We only consider the outage probability of a system with one relay for the reason that the best relay of a system with more relays can be selected in the same way by applying this expression to each relay, one-by-one, and choosing the relay with the minimum outage probability among all of the relays.

Our derivation starts by, first, finding the mutual information between S and $R_{l,2k-1}$, as shown below,

$$I_{SR_{l,2k-1}} = \frac{1}{2} \log_2 (1 + \gamma_{SR_{l,2k-1}}), \quad l = 1, 2, \dots, L \text{ and } k = 1, 2, \dots, K \quad (7)$$

where $\gamma_{SR_{l,2k-1}} = P_S |h_{SR_{l,2k-1}}|^2 / N_0$ is the instantaneous SNR between S and $R_{l,2k-1}$ and $h_{SR_{l,2k-1}}$ is the channel impulse response between S and $R_{l,2k-1}$. If $I_{SR_{l,2k-1}}$ is higher than a given threshold (th) specified by the system designer according to the type of application, the relay $R_{l,2k-1}$ decodes and retransmits the signal to a selected destination relay (D_k^*). The reason why we have a factor of $1/2$ in (7) is because we use two time slots (or orthogonal channels) for data transmission. The

mutual information between S and D for the proposed BDRS protocol can be written as

$$I_{DF} = \frac{1}{2} \log_2 \left(1 + \max_{l=1, \dots, L} (\gamma_{SD_{l,2k}}) + \gamma_{R_{l,2k-1}D_k^*} \right), \quad l = 1, 2, \dots, L \text{ and } k = 1, 2, \dots, K \quad (8)$$

where $\gamma_{SD_{l,2k}} = P_S |h_{SD_{l,2k}}|^2 / N_0$ is the instantaneous SNR between S and $D_{l,2k}$ at hop $m = 2k$ and $\gamma_{R_{l,2k-1}D_k^*} = P_R |h_{R_{l,2k-1}D_k^*}|^2 / N_0$ is the instantaneous SNR between $R_{l,2k-1}$ and D_k^* at the cluster k^{th} . In fact, the mutual information in (8) can be determined by the BDRS selection principle that selects the destination node with the maximum received SNR first then uses the node to retransmit the signal. Based on the principle of C-MRC signal combining [12], the total received SNR (SNR_{total}) is the summation of the received SNR from both the direct and indirect links, i.e., $SNR_{\text{total}} = \max_{l=1, 2, 3} (\gamma_{SD_{l,2}}) + \gamma_{R_{l,2k-1}D_k^*}$. From a general principle together with the expression for mutual information in (8), a general form of the outage probability can be expressed as follows,

$$P_{\text{out}} = \Pr(I_{DF} \leq th) = \Pr \left(\max_{l=1, \dots, L} (\gamma_{SD_{l,2k}}) + \gamma_{R_{l,2k-1}D_k^*} \leq 2^{2th} - 1 \right) \quad (9)$$

where $l = 1, 2, \dots, L$ and $k = 1, 2, \dots, K$.

For the purpose of making the derivation clear and easy to understand, only the first cluster of our model is considered. We present the derivation of the outage probability (P_{out}) in steps as follows: 1) determine the distribution of the total received SNR (SNR_{total}) by using a moment generating function (MGF). Since MGF of SNR_{total} is equal to the product of MGF of $\max_{l=1, \dots, L} (\gamma_{SD_{l,2k}})$ and MGF of $\gamma_{R_{l,2k-1}D_k^*}$, we have to determine each MGF separately and derive the probability density function (PDF) by applying an inverse Laplace transform to the MGF of SNR_{total} ; 2) determine P_{out} by calculating a cumulative distribution function (CDF) with respect to the outage threshold (th) which can be found directly by integrating its PDF from the previous step.

In order to simplify the analysis in step 1, we introduce a new random variable Z which is a sum of two random variables, $Z = \chi + \gamma_{R_{1,1}D_2^*}$ where $\chi = \max_{l \in \{1, 2, 3\}} (\gamma_{SD_{l,2}})$. Now, the outage probability can be written as $P_{\text{out}} = \Pr(Z \leq 2^{2th} - 1)$. Therefore, the CDF of the received signal can be obtained directly from the PDF of Z evaluated at $2^{2th} - 1$ since the two random variables χ and $\gamma_{R_{1,1}D_2^*}$ are statistically independent, and the PDF of Z is just the convolution of the PDFs of χ and $\gamma_{R_{1,1}D_2^*}$ (its calculation method reported in [13]). The PDF of χ can be found from the CDF of χ as follows,

$$F_{\chi}(x) = \Pr \left(\max_{l \in \{1, 2, 3\}} (\gamma_{SD_{l,2}}) \leq x \right) = \prod_{l=1}^3 \Pr(\gamma_{SD_{l,2}} \leq x) = \prod_{l=1}^3 F_{\gamma_{SD_{l,2}}}(x) \quad (10)$$

$$f_{\chi}(x) = \sum_{l=1}^3 \exp\left(-\frac{x}{\gamma_{SD_{1,2}}}\right) - \left(\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}} \right) \frac{\exp\left(-\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} x\right)}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} - \left(\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}} \right) \frac{\exp\left(-\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} x\right)}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} - \left(\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}} \right) \frac{\exp\left(-\frac{\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} x\right)}{\gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} + \left(\gamma_{SD_{1,2}} (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) + \gamma_{SD_{2,2}} \gamma_{SD_{3,2}} \right) \frac{\exp\left(-\frac{\gamma_{SD_{2,2}} \gamma_{SD_{3,2}} + \gamma_{SD_{1,2}} \gamma_{SD_{3,2}} \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} x\right)}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \quad (11)$$

$$M(f_{\chi}(x)) = \sum_{l=1}^3 \exp\left(-\frac{1}{\gamma_{SD_{1,2}}} - s\right) - \left(\frac{\left(\frac{1}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) (\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}})}{\left(\left(\frac{1}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) (\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}) \right) - s} \right) - \left(\frac{\left(\frac{1}{\gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}})}{\left(\left(\frac{1}{\gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) \right) - s} \right) - \left(\frac{\left(\frac{1}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} \right) (\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}})}{\left(\left(\frac{1}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} \right) (\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}) \right) - s} \right) - \left(\frac{\left(\frac{\gamma_{SD_{1,2}} (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) + \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right)}{\left(\left(\frac{\gamma_{SD_{1,2}} (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) + \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) - s \right)} \right). \quad (12)$$

$$f_{\gamma_{R_{1,1}D_2^*}}(x) = f_{\gamma_{R_{1,1}D_2^*}|R_{1,1} \text{ is off}}(x) \Pr(R \text{ is off}) + f_{\gamma_{R_{1,1}D_2^*}|R_{1,1} \text{ is on}}(x) \Pr(R \text{ is on}) \quad (13)$$

$$A = \Pr(I \leq th) = \Pr(\gamma_{SR_{1,1}} \leq 2^{2th} - 1) = 1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,1}}}\right) \quad (14)$$

$$f_{\gamma_{R_{1,1}D_2^*}|R_{1,1} \text{ is on}}(x) = \frac{1}{\bar{\gamma}_{R_{1,1}D_2^*}} \exp\left(-\frac{x}{\bar{\gamma}_{R_{1,1}D_2^*}}\right), \quad x \geq 0 \quad (15)$$

$$f_{\gamma_{R_{1,1}D_2^*}}(x) = A\delta(x) + (1 - A) \frac{1}{\bar{\gamma}_{R_{1,1}D_2^*}} \exp\left(-\frac{x}{\bar{\gamma}_{R_{1,1}D_2^*}}\right), \quad x \geq 0. \quad (16)$$

$$M(f_{\gamma_{R_{1,1}D_2^*}}(x)) = A\delta(x) + (1 - A) \left(\frac{\bar{\gamma}_{R_{1,1}D_2^*}}{\bar{\gamma}_{R_{1,1}D_2^*} - s} \right) \quad (17)$$

$$\begin{aligned}
 F_Z(x) = & A \sum_{l=1}^3 \left(1 - \exp \left(-\frac{x}{\gamma_{SD_{l,2}}} \right) \right) + \sum_{l=1}^3 \left\{ \frac{\exp \left(-\frac{x}{\gamma_{SR_{l,1}}} \right)}{\frac{1}{\gamma_{SD_{l,2}}} - \frac{1}{\gamma_{R_{l,1}D_{l,2}}}} \left[\frac{1}{\gamma_{SD_{l,2}}} \left(1 - \exp \left(-\frac{x}{\gamma_{R_{l,1}D_{l,2}}} \right) \right) - \frac{1}{\gamma_{R_{l,1}D_{l,2}}} \left(1 - \exp \left(-\frac{x}{\gamma_{SD_{l,2}}} \right) \right) \right] \right\} \\
 & - A \left(1 - \exp \left(-x \frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) \right) - \frac{\exp \left(-\frac{x}{\gamma_{SR_{1,1}}} \right)}{\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}}} \left[\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) \left(1 - \exp \left(-\frac{x}{\gamma_{R_{1,1}D_{2,2}^*}} \right) \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}} \left(1 - \exp \left(-x \frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) \right) \right] \\
 & - A \left(1 - \exp \left(-x \frac{\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} \right) \right) - \frac{\exp \left(-\frac{x}{\gamma_{SR_{1,1}}} \right)}{\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}}} \left[\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} \right) \left(1 - \exp \left(-\frac{x}{\gamma_{R_{1,1}D_{2,2}^*}} \right) \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}} \left(1 - \exp \left(-x \frac{\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} \right) \right) \right] \\
 & + A \left(1 - \exp \left(-x \frac{\gamma_{SD_{1,2}} (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) + (\gamma_{SD_{2,2}} \gamma_{SD_{3,2}})}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) \right) - \frac{\exp \left(-\frac{x}{\gamma_{SR_{1,1}}} \right)}{\left(\frac{\gamma_{SD_{1,2}} (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) + (\gamma_{SD_{2,2}} \gamma_{SD_{3,2}})}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}}} \\
 & \times \left[\left(\frac{\gamma_{SD_{1,2}} (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) + (\gamma_{SD_{2,2}} \gamma_{SD_{3,2}})}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) \left(1 - \exp \left(-\frac{x}{\gamma_{R_{1,1}D_{2,2}^*}} \right) \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}} \left(1 - \exp \left(-x \frac{\gamma_{SD_{1,2}} (\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}) + (\gamma_{SD_{2,2}} \gamma_{SD_{3,2}})}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) \right) \right] \quad (18)
 \end{aligned}$$

$$\begin{aligned}
 P_{out}^{coop} = & \left[1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SR_{1,1}}} \right) \right] \sum_{l=1}^3 \left[1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SD_{l,2}}} \right) \right] \\
 & + \sum_{l=1}^3 \left\{ \frac{\exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SR_{l,1}}} \right)}{\left(\frac{1}{\gamma_{R_{l,1}D_{l,2}}} - \frac{1}{\gamma_{R_{l,1}D_{l,2}^*}} \right)} \left[\frac{1}{\gamma_{SD_{l,2}}} \left(1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{R_{l,1}D_{l,2}^*}} \right) \right) - \frac{1}{\gamma_{R_{l,1}D_{l,2}^*}} \left(1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SD_{l,2}}} \right) \right) \right] \right\} \\
 & - \left[\left(1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SR_{1,1}}} \right) \right) \left(1 - \exp \left(-\frac{(2^{2th} - 1)(\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}})}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) \right) \right] \\
 & - \left[\left(1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SR_{1,1}}} \right) \right) \left(1 - \exp \left(-\frac{(2^{2th} - 1)(\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}})}{\gamma_{SD_{1,2}} \gamma_{SD_{3,2}}} \right) \right) \right] \\
 & - \left[\left(1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SR_{1,1}}} \right) \right) \left(1 - \exp \left(-\frac{(2^{2th} - 1)(\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}})}{\gamma_{SD_{2,2}} \gamma_{SD_{3,2}}} \right) \right) \right] \\
 & - \frac{\exp \left(-\frac{(2^{2th} - 1)}{\gamma_{SR_{1,1}}} \right)}{\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}}} \left[\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) \left(1 - \exp \left(-\frac{(2^{2th} - 1)}{\gamma_{R_{1,1}D_{2,2}^*}} \right) \right) - \frac{1}{\gamma_{R_{1,1}D_{2,2}^*}} \left(1 - \exp \left(-(2^{2th} - 1) \frac{\gamma_{SD_{1,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{1,2}} \gamma_{SD_{2,2}}} \right) \right) \right]
 \end{aligned}$$

$$\begin{aligned}
 & - \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{1,1}}}\right)}{\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}}\gamma_{SD_{3,2}}}\right) - \frac{1}{\gamma_{R_{1,1}D_2^*}}} \left[\left(\frac{\gamma_{SD_{1,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{1,2}}\gamma_{SD_{3,2}}} \right) \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{1,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{1,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{SD_{1,2}}\gamma_{SD_{3,2}}}\right) \right) \right] \\
 & - \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{1,1}}}\right)}{\left(\frac{\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{2,2}}\gamma_{SD_{3,2}}}\right) - \frac{1}{\gamma_{R_{1,1}D_2^*}}} \left[\left(\frac{\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{2,2}}\gamma_{SD_{3,2}}} \right) \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{1,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{1,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{SD_{2,2}}\gamma_{SD_{3,2}}}\right) \right) \right] \\
 & + \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{1,1}}}\right)}{\sum_{l=1}^3 \frac{1}{\gamma_{SD_{l,2}}} - \frac{1}{\gamma_{R_{1,1}D_2^*}}} \left[\sum_{l=1}^3 \frac{1}{\gamma_{SD_{l,2}}} \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{1,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{1,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\sum_{l=1}^3 \frac{1}{\gamma_{SD_{l,2}}}}\right) \right) \right]. \quad (19)
 \end{aligned}$$

where $F_{\gamma_{SD_{l,2}}}(x)$ is the CDF of $\gamma_{SD_{l,2}}$ and $F_{\gamma_{SD_{l,2}}}(x) = 1 - \exp\left(-\frac{x}{\gamma_{SD_{l,2}}}\right)$. By using the expression for the CDF of $\gamma_{SD_{l,2}}$ the expression for the PDF of χ can be found by taking the derivative of (10) with respect to x , and after some manipulations, $f_{\chi}(x)$ can be written as (11). To determine the MGF of $\gamma_{R_{2k-1}D_{l,2}^*}$, we obtain it from the PDF of $\gamma_{R_{1,1}D_2^*}$, expressed in (12).

The operation of the relay can be explained as follows. When I is equal or less than th , the received SNR at the destination sent by $R_{1,1}$ is 0 since there is no signal retransmission from $R_{1,1}$. Therefore, the conditional PDF $f_{\gamma_{R_{1,1}D_2^*}|R \text{ is off}}(x)$ can be expressed as $f_{\gamma_{R_{1,1}D_2^*}|R \text{ is off}}(x) = \delta(x)$ (i.e., when the mutual information of SR is less than th , $I \leq I_{th}$). We define an outage probability for when $R_{1,1}$ is off as A , expressed in (14) where $\bar{\gamma}_{SR_{1,1}} = \mathbf{E}\left(\frac{P_S|h_{SR_{1,1}}|^2}{N_0}\right)$ stands for the average SNR between S and $R_{1,1}$ and $\mathbf{E}(\cdot)$ is a statistical expectation operator. When $I > I_{th}$, the outage probability that $R_{1,1}$ is on is $(1 - A)$ and the conditional PDF $f_{\gamma_{R_{1,1}D_2^*}|R_{1,1} \text{ is on}}(x)$ can be written as (15)

where $\bar{\gamma}_{R_{1,1}D_2^*} = \mathbf{E}\left(\frac{P_R|h_{R_{1,1}D_2^*}|^2}{N_0}\right)$ stands for the average SNR

between $R_{1,1}$ and D_2^* . Therefore, the PDF of $\gamma_{R_{1,1}D_2^*}$ can be written as shown in (16). The MGF of $f_{\gamma_{R_{1,1}D_2^*}}(x)$ can be obtained by transforming (16) from time domain to frequency domain, expressed in (17). Multiplying (12) with (17) and then inverse Laplace transforming the multiplication product to time domain, we obtain expression (18) for the CDF of Z .

Lastly, in order to find P_{out} in step 2, we integrate directly the CDF expression in (18) with respect to the given threshold (th). Hence, in general, P_{out} can be expressed as $P_{out} = \Pr(Z \leq 2^{2th} - 1) = F_Z(2^{2th} - 1)$. For the 1R3D configuration, P_{out} of a cluster becomes (19). The derivation of (19) is shown in the Appendix.

For comparison, we also derive the outage probability for 1R1D and 1R2D systems in the same manner. In principle, our derivation procedure can be applied to a system of any numbers of relays and destinations.

The outage probability for the 1R1D configuration is as follows,

$$P_{out}^{coop} = \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,1}}}\right) \right] \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SD_{1,2}}}\right) \right] + \frac{\exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,1}}}\right)}{\left(\frac{1}{\bar{\gamma}_{SD_{1,2}}} - \frac{1}{\bar{\gamma}_{RD_{1,2}}}\right)} \left[\frac{1}{\bar{\gamma}_{SD_{1,2}}} \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{R_{1,1}D_{1,2}}}\right) - \frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}} \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SD_{1,2}}}\right) \right] \quad (20)$$

The outage probabilities for the 1R2D is as follows,

$$\begin{aligned}
 P_{out}^{coop} = & \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,1}}}\right) \right] \sum_{l=1}^2 \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SD_{l,2}}}\right) \right] + \sum_{l=1}^2 \frac{\exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,1}}}\right)}{\left(\frac{1}{\bar{\gamma}_{SD_{l,2}}} - \frac{1}{\bar{\gamma}_{R_{1,1}D_2^*}}\right)} \left[\frac{1}{\bar{\gamma}_{SD_{l,2}}} \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{R_{1,1}D_2^*}}\right) - \frac{1}{\bar{\gamma}_{R_{1,1}D_2^*}} \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SD_{l,2}}}\right) \right] \\
 & - \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,1}}}\right) \right] \left[1 - \exp\left(-\left(2^{2th}-1\right) \sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SD_{l,2}}}\right)\right) \right] \\
 & - \frac{\exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,1}}}\right)}{\sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SD_{l,2}}}\right) - \frac{1}{\bar{\gamma}_{R_{1,1}D_2^*}}} \left[\sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SD_{l,2}}}\right) \left(1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{R_{1,1}D_2^*}}\right)\right) - \frac{1}{\bar{\gamma}_{R_{1,1}D_2^*}} \exp\left(-\frac{(2^{2th}-1) \sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SD_{l,2}}}\right)}{\bar{\gamma}_{SD_{2,2}}}\right) \right] \quad (21)
 \end{aligned}$$

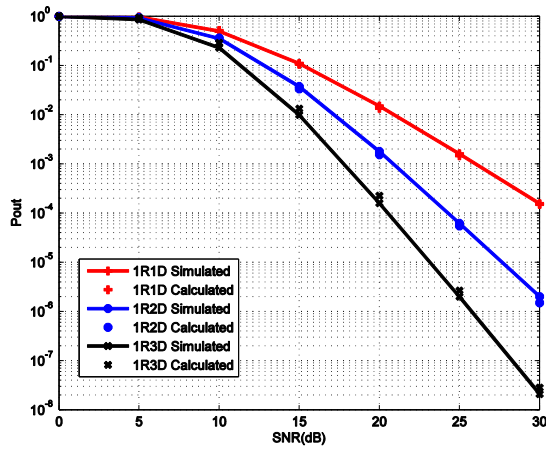


Fig. 7. Simulated and calculated performances of BDRS (first cluster, fixed source, 1 relay node, and 1-3 destination nodes).

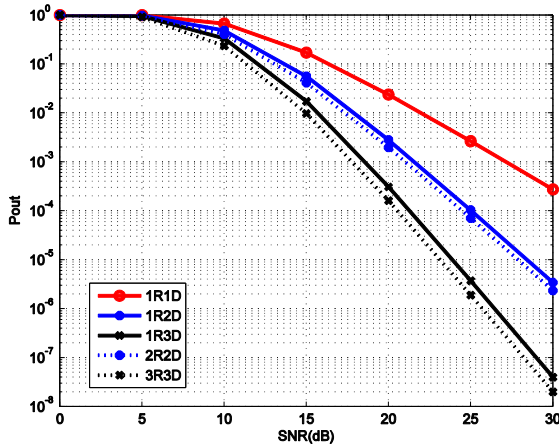


Fig. 8. Simulated performance of BDRS with various numbers of relay and destination nodes (first cluster, fixed source, 1-3 relays, and 1-3 destinations).

IV. SIMULATION RESULTS

Based on computer simulation with MATLAB software, the performance of the BDRS system was determined and compared with that from the closed-form expression (19). Simulation settings were as follows: binary phase shift keying

(BPSK) modulation was used with a total transmitted power of 1 Watt; noise variance was N_0 ; and bandwidth efficiency was 1 bit/s/Hz. In addition, Jake's model [14] was employed for simulating Rayleigh fading channels with normalized Doppler shift of 5,000 Hz, and all channel link variances in the system were assumed to be dependent on the distance between nodes in an idealized linear system.

Figure 7 shows the simulated and calculated performances of the first cluster of 3 different configurations of a system: 1R2D, 1R2D, and 1R3D. It can be seen that the performances were very close. Note that the BDRS protocol reduced the system complexity from L^2 to L , compared to that of searching for the best case of all cases in the same cluster in a non-augmented cooperative protocol.

Figure 8 depicts the performances 4 configurations of a system: 1R1D, 1R2D, 1R3D, 2R2D, and 3R3D. The performance curves show that when the number of destination nodes was fixed, more relays resulted in more coding gain. Moreover, the curves in this figure and in Figure 7 indicate that the diversity gain was dependent on the number of destination nodes, and the coding gain was dependent on the number of cooperative relay nodes.

Figure 9 shows the simulated performances of the proposed BDRS strategy versus the modified conventional multi-hop strategy for 3 clusters, as an extension for the cases of only 1 cluster above. The result shows that the proposed strategy outperformed the modified conventional multi-hop communication strategy dramatically—the SNR differences for 1R1D, 2R2D, 3R3D, 4R4D, and 5R5D configurations were 5, 9, 12, 13 and 13 dB, respectively, at P_{out} of 10^{-2} . In addition, at a high SNR regime, as the number of destination relays increased, the proposed protocol achieved more diversity gain.

Figure 10 shows simulated performances for 3 clusters as the source was fixed or moving. When the source moved, channel variances were changed from the distance variation. BDRS will adaptively search for the new best destination, and then the new best relay with minimum outage probability. The software was set to simulate the source moving randomly up and down vertically in every 10,000 bits transmission. It can be seen that

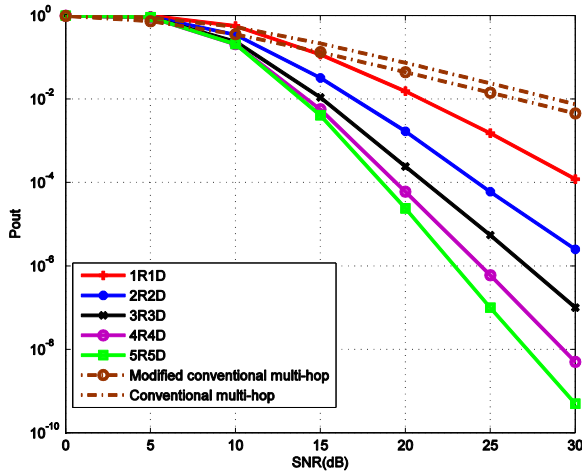


Fig. 9 Simulated performances for three clusters of the proposed BDRS, conventional multi-hop, and modified conventional multi-hop.

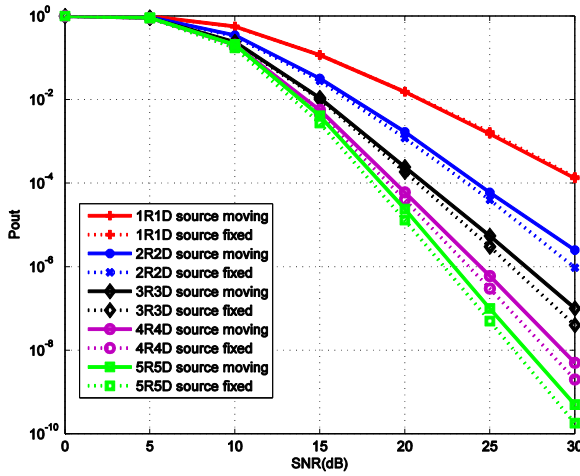


Fig.10 Simulated performances for 3 clusters with the source fixed or moving.

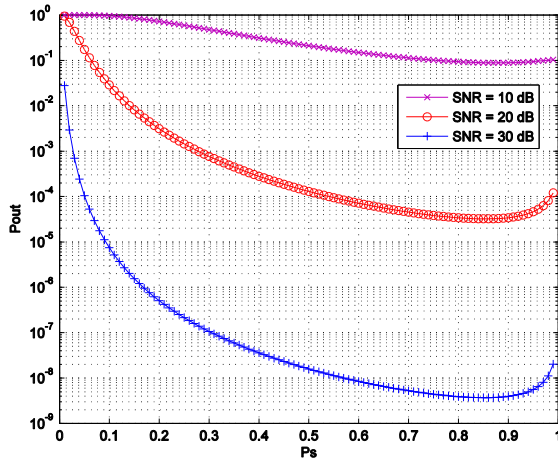


Fig. 11. P_{out} of BDRS (1R3D) with fixed SNR at various source transmitting powers at SNR =10, 20, and 30 dB.

moving source deteriorate the performances marginally, but would not be as much as that of a non-adaptive protocol.

V. PERFORMANCE IMPROVEMENT

This section discusses the general concept of power allocation, implementation issue, and the results. In principle, C-MRC alone cannot guarantee maximum total SNR at the destination, but by varying power allocation according to channel quality, system performance should be improved. The objective of power allocation is to selectively allocate certain transmitted power to source (P_S) and relay (P_R) such that the total transmitted power (P_T) is fixed, in order to minimize P_{out} . We can write the power allocation condition as follows,

$$P_T = \lambda P_S + (1 - \lambda) P_R \quad \text{at } 0 < \lambda < 1, \quad (22)$$

where λ is the power allocation factor between P_S and P_R .

In this study, the optimum power allocation was determined by replacing P_R with $(1 - \lambda)P_S$ and P_S with λP_S in the expression for outage probability (19) and then heuristically varying λ from 0 to 1 until the minimum outage probability was found. Graphs of P_{out} as a function of λ at SNR = 10dB, 20dB, and 30dB were plotted in Figure 11. To find the minimum outage probability ($\min(P_{out})$) from the curves, normally we take a derivative of (19) with respect to P_S and set it equal to zero then algebraically solve the equation. However, this expression is very difficult to solve in closed-form, so we determined the minimum outage probability by finding the zero-crossing as follows,

$$\frac{dP_{out}^{coop}(\lambda)}{d\lambda} = 0 \quad (23)$$

In detail, Figure 12 shows the optimum power allocation in the first cluster of 1R3D configuration. The crossing point at x-axis is the source power that yields the minimum outage probability. This figure shows how much power of a total of 1 Watt should be allocated between the source and the relay when the channel quality of each link changes at a fixed SNR = 20 dB. The results indicate that more power—0.83, 0.93, and 0.81 Watt—should be allocated to the source when the qualities of the SD link, SR link, and RD link, respectively, were set to be poor one at a time. The rest of the power (P_R) should be allocated to the cooperative relay.

In Figure 13, the effects of channel variances (δ^2) on power allocation are shown in plots of P_{out} as a function of λ at SNR = 10 dB (Figure 11a), SNR = 20 dB (Figure 11b), and SNR = 30 dB (Figure 11c) where $(\delta_{SD}^2 = 0.1, \delta_{SR}^2 = 1, \delta_{RD}^2 = 1)$, $(\delta_{SD}^2 = 1, \delta_{SR}^2 = 0.1, \delta_{RD}^2 = 1)$, and $(\delta_{SD}^2 = 1, \delta_{SR}^2 = 1, \delta_{RD}^2 = 0.1)$ for each SNR case. The results show that the optimum power allocation was always with λ more than 0.5 in all cases.

VI. IMPLEMENTATION ISSUES

In this section, we discuss the following: cases when central control is available and when control is unavailable, error detection, channel estimation when source is moving, collision problem, and an issue regarding odd hops.

Following the BDRS strategy, the best destination for each cluster is selected first based on received SNR, or equivalently, measured channel gain. Selection can be implemented in either a centralized or distributed way. If a central controller is available (such as the cases of base station in a cellular network or an access point in a mesh network), it can collect all channel state information (CSI) and then assign a transmission. In the case where a central controller is not available, BDRS strategy can also be implemented in a distributed way by using a distributed relay selection algorithm proposed in [15] where each relay sets a timer based on its measured channel gain. The larger the channel gain is, the shorter the receiving time is. In this way, the timer of the destination with the best channel, i.e., the best destination selected, expires first. That destination then sends a flag signal. All other destinations, while waiting for their timer to count down to zero, are in listening mode. As soon as they hear the flag signal, they back off. This method requires that every destination can hear all the others. For error

detection, cyclic redundancy check (CRC), commonly used in wireless communication systems, is applied to the selected node. For estimation of channel impulse response when the source is moving, a short-term statistical technique reported in [16] that levels out short-term changes can be employed. To deal with possible hidden-node collisions, each relay can randomly stop transmitting then wait and see if other relays are re-transmitting. Finally, it may seem that the proposed BDRS is limited to systems consisting of even hops, however, that is not the case. When a system consists of odd hops, the BDRS strategy works by selecting the best relay at hop $M-1$, from the neighboring nodes in the same hop, which will then cooperate with the source to retransmit the signal to the final destination.

VII. CONCLUSION

In this paper, we propose an adaptive cooperative protocol for multi-hop wireless network with a 'best destination relay selection' (BDRS) routing protocol. The proposed routing protocol was designed to achieve an optimal route while reducing system complexity. To assess the performance of the proposed protocol, its operations in a system with different numbers of hops and clusters were simulated and their results were compared to those of the conventional multi-hop and modified conventional multi-hop protocols. It was found that our proposed protocol outperformed those protocols by several folds—it achieved a 15 dB and 14 dB received SNR improvement gains, respectively, at an outage probability of less than 10^{-2} . Moreover, we found that the simulated results agreed closely with the calculated results from the exact, closed-form mathematical expression of the outage probability of our proposed protocol. Lastly, we used an optimum power allocation scheme to further improve the system performance and found that its operation supported our reasoning that the direct source to destination link is the most important link.

APPENDIX

A. Derivation for the 1R1D configuration

Let u be the CDF of the received SNR of a direct link and v is the CDF of the received SNR of an indirect link as follows,

$$u = 1 - e^{-\frac{x}{\bar{\gamma}_{SD1,2}}}, \quad (25)$$

$$v = A\delta(x) + (1 - A) \left(1 - e^{-\frac{x}{\bar{\gamma}_{R1,1D1,2}}} \right). \quad (26)$$

The PDF of u and v can be determined by differentiating their CDFs,

$$f(u) = \frac{d}{dx} \left(1 - e^{-\frac{x}{\bar{\gamma}_{SD1,2}}} \right) = \frac{e^{-\frac{x}{\bar{\gamma}_{SD1,2}}}}{\bar{\gamma}_{SD1,2}}, \quad (27)$$

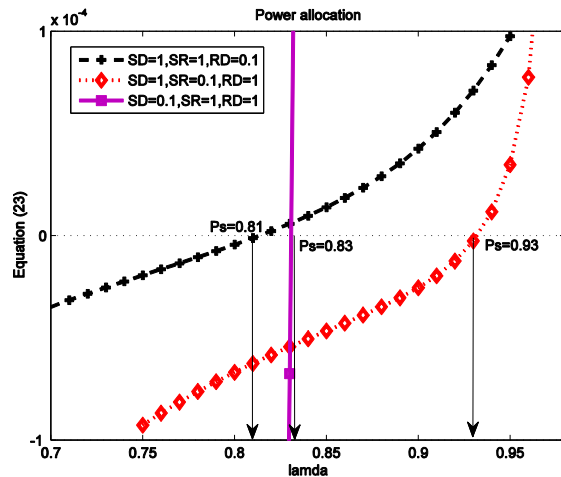


Fig. 12. Optimum power for the first cluster, found by searching for zero crossing of (23)

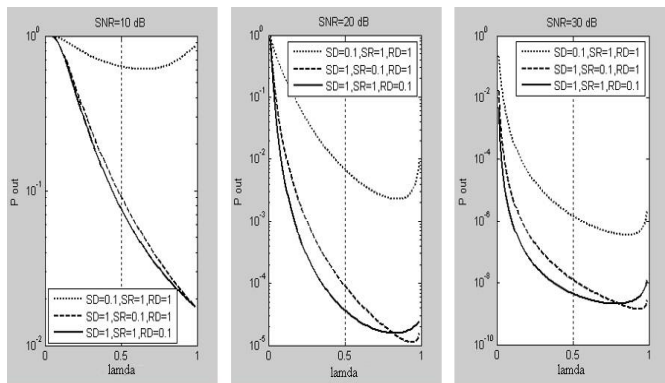


Fig. 13. P_{out} of BDRS (1R3D) at various transmitting powers, SNRs, and channel variances.

$$f(v) = \frac{d}{dx} \left(A\delta(x) + (1-A) \frac{e^{-\frac{x}{\bar{\gamma}_{R_{1,1}D_{1,2}}}}}{\bar{\gamma}_{R_{1,1}D_{1,2}}} \right) = A\delta(x) + (1-A) \frac{e^{-\frac{x}{\bar{\gamma}_{R_{1,1}D_{1,2}}}}}{\bar{\gamma}_{R_{1,1}D_{1,2}}}. \quad (28)$$

Transforming u and v to the frequency domain by using the moment generating function (M), expressed as

$$M(u) = \frac{\frac{1}{\bar{\gamma}_{SD_{1,2}}}}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - s}, \quad (29)$$

$$M(v) = A + (1-A) \left(\frac{\frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}}}{\frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}} - s} \right). \quad (30)$$

The PDF of the total received SNR can be found by multiplying $M(u)$ with $M(v)$, expressed as

$$f_Z(x) = M(u) \times M(v) = A \left(\frac{\frac{1}{\bar{\gamma}_{SD_{1,2}}}}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - s} \right) + (1-A) \left(\frac{\frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}}}{\frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}} - s} \right) \left(\frac{\frac{1}{\bar{\gamma}_{SD_{1,2}}}}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - s} \right). \quad (31)$$

Using partial fraction expansion to expand the multiplication product term, we obtain

$$f_Z(x) = M(u) \times M(v) = A \left(\frac{\frac{1}{\bar{\gamma}_{SD_{1,2}}}}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - s} \right) + \frac{1-A}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - \frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}}} \left[\left(\frac{\frac{1}{\bar{\gamma}_{SD_{1,2}}}}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - s} \right) - \left(\frac{\frac{1}{\bar{\gamma}_{SD_{1,2}}}}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - s} \right) \right]. \quad (32)$$

Determining the CDF by transforming it to the time domain by applying an inverse Laplace transform to $F_Z(x)$, we get

$$F_Z(x) = A \left(\frac{e^{-\frac{x}{\bar{\gamma}_{SD_{1,2}}}}}{\bar{\gamma}_{SD_{1,2}}} \right) + \frac{1-A}{\frac{1}{\bar{\gamma}_{SD_{1,2}}} - \frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}}} \left[\left(\frac{e^{-\frac{x}{\bar{\gamma}_{R_{1,1}D_{1,2}}}}}{(\bar{\gamma}_{SD_{1,2}})(\bar{\gamma}_{R_{1,1}D_{1,2}})} \right) - \left(\frac{e^{-\frac{x}{\bar{\gamma}_{SD_{1,2}}}}}{(\bar{\gamma}_{SD_{1,2}})(\bar{\gamma}_{R_{1,1}D_{1,2}})} \right) \right]. \quad (33)$$

Then, we can calculate the outage probability (P_{out}^{coop}) by integrating $F_Z(x)$ with respect to the given threshold (th),

$$P_{out}^{coop} = \left[1 - \exp \left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,i}}} \right) \right] \left[1 - \exp \left(-\frac{2^{2th}-1}{\bar{\gamma}_{SD_{1,2}}} \right) \right] + \frac{\exp \left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR_{1,i}}} \right)}{\left(\frac{1}{\bar{\gamma}_{SD_{1,2}}} - \frac{1}{\bar{\gamma}_{RD_{1,2}}} \right)} \left[\frac{1}{\bar{\gamma}_{SD_{1,2}}} \exp \left(-\frac{2^{2th}-1}{\bar{\gamma}_{R_{1,1}D_{1,2}}} \right) - \frac{1}{\bar{\gamma}_{R_{1,1}D_{1,2}}} \exp \left(-\frac{2^{2th}-1}{\bar{\gamma}_{SD_{1,2}}} \right) \right]. \quad (34)$$

B. Derivation for the 1R2D configuration

The CDF of the received SNR of a direct link (u) and the CDF of the received SNR of an indirect link (v) in the case of 1R2D are as follows,

$$u = \left(1 - e^{-\frac{x}{\bar{\gamma}_{SD1,2}}}\right) \left(1 - e^{-\frac{x}{\bar{\gamma}_{SD2,2}}}\right), \quad (35)$$

$$v = A\delta(x) + (1 - A) \left(1 - e^{-\frac{x}{\bar{\gamma}_{R1,1D_2^*}}}\right). \quad (36)$$

Using the same method in the derivation of the 1R1D configuration, we get the following expression for the outage probability,

$$\begin{aligned} P_{out}^{coop} = & \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR1,1}}\right)\right] \sum_{l=1}^2 \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SDl,2}}\right)\right] + \sum_{l=1}^2 \frac{\exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR1,1}}\right)}{\left(\frac{1}{\bar{\gamma}_{SDl,2}} - \frac{1}{\bar{\gamma}_{R1,1D_2^*}}\right)} \left[\frac{1}{\bar{\gamma}_{SDl,2}} \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{R1,1D_2^*}}\right) - \frac{1}{\bar{\gamma}_{R1,1D_2^*}} \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SDl,2}}\right)\right] \\ & - \left[1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR1,1}}\right)\right] \left[1 - \exp\left(-\left(2^{2th}-1\right) \sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SDl,2}}\right)\right)\right] \\ & - \frac{\exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{SR1,1}}\right)}{\sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SDl,2}}\right) - \frac{1}{\bar{\gamma}_{R1,1D_2^*}}} \left[\sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SDl,2}}\right) \left(1 - \exp\left(-\frac{2^{2th}-1}{\bar{\gamma}_{R1,1D_2^*}}\right)\right) - \frac{1}{\bar{\gamma}_{R1,1D_2^*}} \exp\left(-\frac{(2^{2th}-1) \sum_{l=1}^2 \left(\frac{1}{\bar{\gamma}_{SDl,2}}\right)}{\bar{\gamma}_{SD2,2}}\right)\right]. \end{aligned} \quad (37)$$

C. Derivation for the 1R3D configuration

The CDF of the received SNR of a direct link (u) and the CDF of the received SNR of an indirect link (v) in the case of 1R3D are as follows,

$$u = \left(1 - e^{-\frac{x}{\bar{\gamma}_{SD1,2}}}\right) \left(1 - e^{-\frac{x}{\bar{\gamma}_{SD2,2}}}\right) \left(1 - e^{-\frac{x}{\bar{\gamma}_{SD3,2}}}\right), \quad (38)$$

$$v = A\delta(x) + (1 - A) \left(1 - e^{-\frac{x}{\bar{\gamma}_{R1,1D_2^*}}}\right). \quad (39)$$

Using the same method in the derivation of the 1R1D configuration, we get the following expression for the outage probability,

$$P_{out}^{coop} = \left[1 - \exp\left(-\frac{(2^{2th}-1)}{\bar{\gamma}_{SR1,1}}\right)\right] \sum_{l=1}^3 \left[1 - \exp\left(-\frac{(2^{2th}-1)}{\bar{\gamma}_{SDl,2}}\right)\right]$$

$$\begin{aligned}
 & + \sum_{l=1}^3 \left\{ \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right)}{\left(\frac{1}{\gamma_{R_{l,1}D_{1,2}}} - \frac{1}{\gamma_{R_{l,1}D_2^*}}\right)} \left[\frac{1}{\gamma_{SD_{l,2}}} \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{l,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{l,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{SD_{l,2}}}\right) \right) \right] \right\} \\
 & - \left[\left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right) \right) \left(1 - \exp\left(-\frac{(2^{2th}-1)(\gamma_{SD_{l,2}} + \gamma_{SD_{2,2}})}{\gamma_{SD_{l,2}}\gamma_{SD_{2,2}}}\right) \right) \right] \\
 & - \left[\left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right) \right) \left(1 - \exp\left(-\frac{(2^{2th}-1)(\gamma_{SD_{l,2}} + \gamma_{SD_{3,2}})}{\gamma_{SD_{l,2}}\gamma_{SD_{3,2}}}\right) \right) \right] \\
 & - \left[\left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right) \right) \left(1 - \exp\left(-\frac{(2^{2th}-1)(\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}})}{\gamma_{SD_{2,2}}\gamma_{SD_{3,2}}}\right) \right) \right] \\
 & - \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right)}{\left(\frac{\gamma_{SD_{l,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{l,2}}\gamma_{SD_{2,2}}} - \frac{1}{\gamma_{R_{l,1}D_2^*}}\right)} \left[\left(\frac{\gamma_{SD_{l,2}} + \gamma_{SD_{2,2}}}{\gamma_{SD_{l,2}}\gamma_{SD_{2,2}}}\right) \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{l,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{l,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1)(\gamma_{SD_{l,2}} + \gamma_{SD_{2,2}})}{\gamma_{SD_{l,2}}\gamma_{SD_{2,2}}}\right) \right) \right] \\
 & - \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right)}{\left(\frac{\gamma_{SD_{l,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{l,2}}\gamma_{SD_{3,2}}} - \frac{1}{\gamma_{R_{l,1}D_2^*}}\right)} \left[\left(\frac{\gamma_{SD_{l,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{l,2}}\gamma_{SD_{3,2}}}\right) \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{l,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{l,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1)(\gamma_{SD_{l,2}} + \gamma_{SD_{3,2}})}{\gamma_{SD_{l,2}}\gamma_{SD_{3,2}}}\right) \right) \right] \\
 & - \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right)}{\left(\frac{\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{2,2}}\gamma_{SD_{3,2}}} - \frac{1}{\gamma_{R_{l,1}D_2^*}}\right)} \left[\left(\frac{\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}}}{\gamma_{SD_{2,2}}\gamma_{SD_{3,2}}}\right) \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{l,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{l,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1)(\gamma_{SD_{2,2}} + \gamma_{SD_{3,2}})}{\gamma_{SD_{2,2}}\gamma_{SD_{3,2}}}\right) \right) \right] \\
 & + \sum_{l=1}^3 \frac{\exp\left(-\frac{(2^{2th}-1)}{\gamma_{SR_{l,1}}}\right)}{\gamma_{SD_{l,2}} - \frac{1}{\gamma_{R_{l,1}D_2^*}}} \left[\sum_{l=1}^3 \frac{1}{\gamma_{SD_{l,2}}} \left(1 - \exp\left(-\frac{(2^{2th}-1)}{\gamma_{R_{l,1}D_2^*}}\right) \right) - \frac{1}{\gamma_{R_{l,1}D_2^*}} \left(1 - \exp\left(-\frac{(2^{2th}-1) \sum_{l=1}^3 \frac{1}{\gamma_{SD_{l,2}}}}{\gamma_{SD_{l,2}}}\right) \right) \right]. \tag{40}
 \end{aligned}$$

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