Optimized Relay Selection and Power Allocation by an Exclusive Method in Multi-Relay AF Cooperative Networks

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Received January 19, 2017; revised April 2, 2017; accepted April 24, 2017;
published July 31, 2017

Abstract

In a single-source and multi-relay amplify-forward (AF) cooperative network, the outage probability and the power allocation are two key factors to influence the performance of an entire system. In this paper, an optimized AF relay selection by an exclusive method and near optimal power allocation (NOPA) is proposed for both good outage probability and power efficiency. Given the same power at the source and the relay nodes, a threshold for selecting the relay nodes is deduced and employed to minimize the average outage probability. It mainly excludes the relay nodes with much higher thresholds over the aforementioned threshold and thus the remainders of the relay nodes participate in cooperative forwarding efficiently. So the proposed scheme can improve the utility of the resources in the cooperative multi-relay system, as well as reduce the computational complexity. In addition, based on the proposed scheme, a NOPA is also suggested to approach sub-optimal power efficiency with low complexity. Simulation results show that the proposed scheme obtains about 2.1dB and 5.8dB performance gain at outage probability of 10^{-4}, when compared with the all-relay-forward (6 participated relays) and the single-relay-forward schemes. Furthermore, it obtains the minimum outage probability among all selective relay schemes with the same number of the relays. Meanwhile, it approaches closely to the optimal exhaustive scheme, thus reduce much complexity. Moreover, the proposed NOPA scheme achieves better outage probability than those of the equal power allocation schemes. Therefore, the proposed scheme can obtain good outage probability, low computational complexity and high power efficiency, which makes it pragmatic efficiently in the single-source and multi-relay AF based cooperative networks.

Keywords: amplify-and-forward, exclusive relay selection, relay selection threshold, outage probability, power allocation

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This work was supported by the Zhejiang Provincial National Natural Science Foundation (No. LZ14F010003, LY17F010019), the National Natural Science Foundation of China (No. 61471152, No. 61271214), and the Open Research Fund of National Mobile Communications Research Laboratory Southeast University (No. 2014D02).

https://doi.org/10.3837/tiis.2017.07.012 **ISSN : 1976-7277**

1. Introduction

Recently, with rapid developments in wireless communications, the band spectrum resources have become more and more the bottleneck of the communication systems due to the severe multi-path fading, the open congestion access, and the active jamming, and so on. Then the multiple-input multiple-output (MIMO) technology was proposed to obtain the space diversity by the multi-path effects [1], [2], which were traditionally considered as the destructive interferences and should be eliminated as much as possible. It adopted the multi-path effect as the independent signal component rather than the interference to improve the performance [3]. However, due to the limited physical size of the mobile terminals, as well as the requirement of similar dimensions between independent antenna size and the licensed radio wavelength for efficient radio emmission, multiple antennas were hard to be equipped, especially for the mobile handset transceivers [4]. Thus the MIMO technology was difficult to be deployed easily. Then, a novel cooperative communications have been proposed by the concept of the virtual MIMO [5], [6], where the adjacent mobile terminals can be used to forward messages and play a role of virtual independent antennas to obtain the cooperative space diversity. Therefore, the wireless cooperative networks can obtain the same performance gains as the MIMO ones, which enhance the network coverage and transmission reliability greatly.

The widely used cooperative network model was a three-node and two-hop relay model. In this model, the selection of the relays influenced the channel capacity, the throughput, the outage probability, and the symbol error rate (SER) and so on [7]-[10]. Therefore, the selection of one or more relays among all available relays for the cooperation had become one of the key techniques in cooperative networks. There were mainly three cooperative schemes, such as the amplify-and-forward (AF) [7], the decode-and-forward (DF) [8], and the coded cooperation (CC) [9], [10] and so on. Also the distributed space-time code can be incorporated into the cooperative schemes for better performance [11]. Among the above three schemes, the AF scheme just equally amplified the signals and the noises without any signal-to-noise ratio (SNR) improvement. However, it was easily to be implemented and adopted to illustrate the good performance of the proposed relay selection scheme. The spectral efficient protocols of the AF and the DF scheme for half-duplex fading relay channels were investigated in [12], and both protocols obtained a significant performance. For two-way relay channels, there were capacity bound analyses [13] and the practical physical network coding to approach them [14]. And a joint relays/antennas selection and precoding was designed for the two-way MIMO AF relaying systems to attain minimum mean square error (MMSE) criterion and get superior performance in terms of bit error rate (BER) [15]. Also, a relay selection scheme for the two-way multiple AF relay channels were proposed to obtain good transmission by maximizing the worse received SNR of the two end users [16]. In a AF based multi-relay network, traditional cooperative communications would not consider the link status between any two nodes of the source, the relays and the destination. So all potential relay nodes taking part in the AF, *i.e.*, all relay AF (AAF), led to the cost of extra system resources, for just very limited performance improvement. Given the AF protocol, the selection of the single optimal relay node to join the relay AF strategy can cut down the loss of the systematic resource [17]. However, the scheme required the transient channel state information (CSI) of all relay links, which further increased overall computational complexity. And the CSI was dependent on the distance between any two nodes, the situation of the cooperative area, and so on, which were hard to be obtained precisely in dynamic networks [18]. Since the estimation of all CSI of all relay nodes in the system was difficult, a pre-selected single relay amplify-and-forward (SAF) was proposed to forward the information and thus reduce the resource occupations [19], [20]. Also the power allocation accompanied by the relay selection should be optimized to improve the performance [21]. Therefore, the optimal objectives for the power allocation mainly lied in low complexity, maximal throughout, minimal BER, minimal symbol error rate, minimal outage probability, *etc* [22]-[24].

In this paper, by minimizing the average outage probability of the relay transmission system, the relay selection in cooperative networks by an improvement of relay node exclusion can be proposed to improve the aforementioned optimal objectives. In this scheme, a new relay selection threshold is deduced for the exclusion of unnecessary cooperative relay nodes by the statistical information of the channel. So the resources, *e.g.*, the power of the participated relay nodes, the CSI update calculation of the related relay links, *etc.*, can be released for much better power efficiency and thus obtain an efficiently cooperative transmission. Meanwhile, a near optimal power allocation (NOPA) scheme is adopted in each relay node for low complexity. So the scheme can obtain better outage probability, when compared with the traditional equal power allocation (EPA) scheme.

The main contributions of this paper are briefly concluded as follows:

1) By minimizing the average outage probability of the multi-relay cooperative networks, an optimal relay node set for cooperation is selected with a sequence of the candidate relay nodes and an exclusive method, accompanied with computational complexity reduction by proper relay elimination improvement.

2) A new threshold for the optimal relay selection is proposed to eliminate the unnecessary relay nodes and thus improves the utilization rate of the communication resources by the channel statistical information. It is actual a compromise of the AAF and **the** SAF **schemes**;

3) A NOPA scheme is adopted in each participated relay node to approximately optimize the power allocation for low complexity, rather than the huge resource consumed globally optimal exhaustive selection of all relay nodes in the AF scheme.

The remainders of the paper are organized as follows. In Section 2, a cooperative model of a single-source and multi-relay AF scheme is introduced. Base on the aforementioned AF model, an optimized relay selection strategy is proposed in Section 3. It is realized by minimizing the average outage probability and the computational complexity is reduced with proper relay elimination improvement, *i.e.*, an exclusive method, for less relay selection adopted in forwarding. Simultaneously, Section 4 suggests a near optimal power allocation, *i.e.*, the NOPA scheme, with theoretical analyses for the optimized relay selection strategy to improve both of the overall power efficiency and the complexity. After that, numerical simulations and result analyses are presented to verify the proposed relay selection by a outage performance comparison in Section 5. Finally, the summary is drawn in Section 6.

2. System Model of Single-Source and Multi-Relay AF Scheme

2.1 Relay System Model

A typical 2-hop single-source and multi-relay AF cooperative system model is given in **Fig. 1**. It consists of one source node from the several candidate node set $\{S_i, i=1,\ldots,N+1\}$, several relay nodes (R_j) also from the remain candidate node set $\{S_i\}$ other than the selected source node, and a destination node (D). Each channel between any two nodes has independent and identically distributed (*i.i.d.*) channel parameters. Since it is a simple 2-hop relay system, there is no cooperation and thus no channel link between the relays.

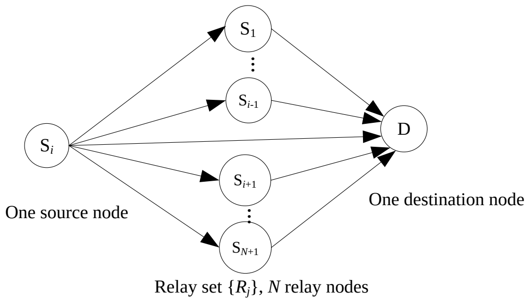
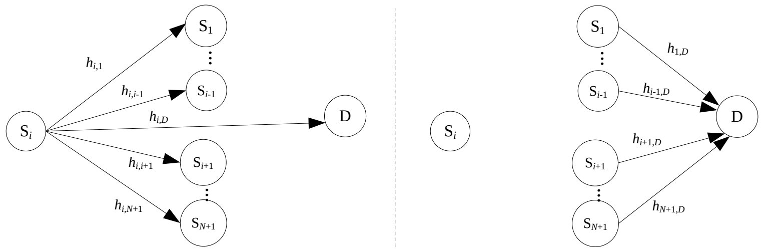


Fig. 1. A typical 2-hop single-source and multiple-relay cooperative network

Suppose that there is an AF based cooperative network of the above cooperative network model, N+1 nodes cooperatively transmit the signals simultaneously, and the node number set is $S=\{1,2,\cdots,N+1\}$. Each node in the number set S is recognized as a source node and it delivers information to all relay node set $\{R_j\}$($R_j \in S, j=1,2,\cdots,N+1, j\neq i$). In this procedure, the transmitted data from each source node is considered as a data sequence. So there are also N+1 data sequence, including N data sequence to the relays and one to the destination. Then, there are N potential relay nodes for each selected source node. In short, any node other than the source node plays a role of relay and takes part in forwarding messages.

The transmission can be divided into two main stages. In the first stage (Stage I), a source node broadcasts the messages to the destination node, as well as all other potential relay nodes. In the second stage (Stage II), the selected relay node forwards the received messages to the destination node. In the whole process, all nodes work in a manner of half duplex. So the access of the relay should meet the requirement of all nodes not transmitting or receiving messages under the same frequency band simultaneously.

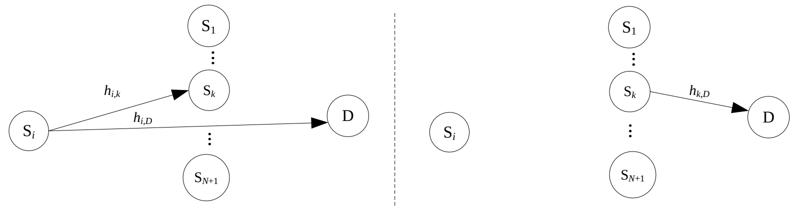
The 2-hop single-source multi-relay cooperative network mainly works in two main manner. One is the AAF scheme and another is the SAF scheme. In the AAF scheme, all relay nodes participate in forwarding the messages from the source node with more complexity. In the SAF scheme, a relay node is selected to forward the messages to reduce the complexity. And the structure of two stages of the two schemes is shown in **Fig. 2**.



Stage I: source node transmitting

Stage II: all N relay nodes forwarding

(a) All-relay amplify-and-forward (AAF) scheme scheme



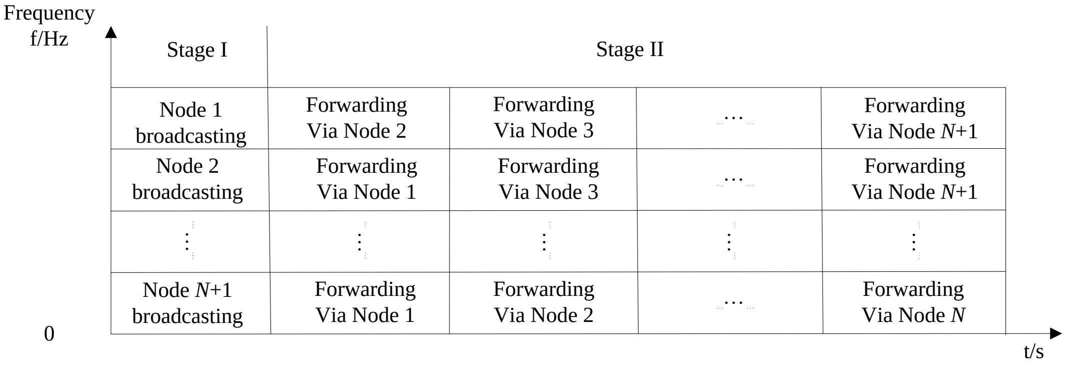
Stage I: source node transmitting

Stage II: single relay node forwarding

(b) Single-relay amplify-and-forward (SAF) scheme scheme

Fig. 2. Two stages of the AAF and the SAF schemes

In **Fig. 2**, the channel coefficient from node i to node j are marked near the channel link and denoted as $h_{i,j}$. And in the more complex AAF scheme, the detailed stages of a typical diagram for all relays taking part in forwarding can be shown in **Fig. 3**.



Stage I	Stage II			
Node 1 broadcasting	Forwarding Via Node 2	Forwarding Via Node 3	…	Forwarding Via Node N+1
Node 2 broadcasting	Forwarding Via Node 1	Forwarding Via Node 3	…	Forwarding Via Node N+1
⋮	⋮	⋮	⋮	⋮
Node N+1 broadcasting	Forwarding Via Node 1	Forwarding Via Node 2	…	Forwarding Via Node N

Fig. 3. Typical access mode for the relay forwarding

In **Fig. 3**, at Stage I, for the AAF scheme, one of the nodes from node 1 to N+1 broadcasts the messages to all relay nodes and the destination node. Then, at the next Stage II, every node other than itself sends or forwards the messages to the destination node via the possible relay. Take a single data sequence (*e.g.* $i(i=1, 2, \ldots, N+1)$) transmission in a cooperative network for example, there are $M(M=0, 1, \ldots, N)$ candidate relay node set and each node transmission need a time slot. But for the SAF scheme, there is only one selected node forwarding the messages.

In stage I, the data sequence i broadcasts the messages to all candidate relay nodes j ($j \in R_M^i$) and the destination node D. The transmitted data sequence i is supposed to be the transmitted data sequence x, with transmission power P_{ii}. The parameters, $h_{i,D}$ and $h_{i,j}$, are the channel coefficients from the source to the destination (D) and all the relay node $\{R_j\}$, respectively. And they belong to the complex Gaussian distribution with zero mean and variance of $\sigma_{i,D}^2$ and $\sigma_{i,j}^2$. So the received signal of $y_{i,D}$ and $y_{i,j}$ at the destination node and the j-th cooperative node, respectively, can be represented as

$$y_{i,D}=\sqrt{P_{ii}}h_{i,D}x+n_{i,D}\ , \tag{1}$$

$$y_{i,j}=\sqrt{P_{ii}}h_{i,j}x+n_{i,j},\ j\in R_M^i\ , \tag{2}$$

where $n_{i,D}$ and $n_{i,j}$ are the AWGN noise and they are belong to the complex Gaussian distribution with zero mean and variance of $N_{i,D}$ and $N_{i,j}$, respectively.

In stage II, each relay node amplifies and forwards the received messages to the destination node at the successive M time slot node by node. And the received message from the j-th relay node at the destination node D can be expressed as

$$y_{j,D}=\beta_j h_{j,D}y_{i,j}+n_{j,D}\ , \tag{3}$$

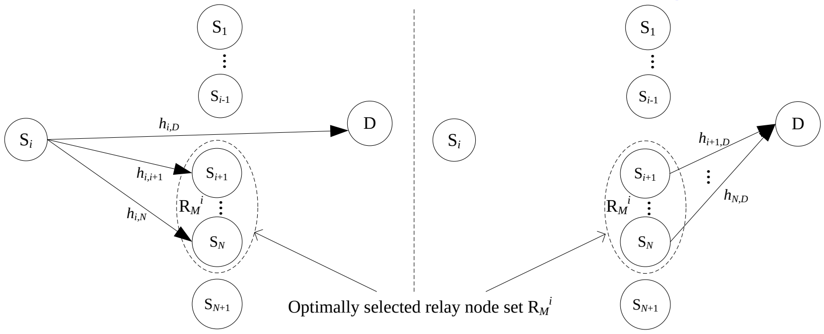
where P_{ij} is the transmitted power of the j-th relay node from the i-th source node. β_j is the amplification factor and it is shown in Equation (4) as follows.

$$\beta_j=\sqrt{P_{ij}}\,/\sqrt{P_{ii}\left|h_{j,D}\right|^2+N_{i,D}}\ . \tag{4}$$

In Equation (4), $h_{j,D}$ is the channel coefficient from the j-th relay node to the destination node and it belongs to the complex Gaussian distribution with zero mean and variance of $\sigma_{j,D}^2$. $n_{j,D}$ is the AWGN of the channel from the candidate relay node to the destination node with Gaussian distribution parameters of zero mean and variance of $N_{j,D}$. In order to simplify the description, we also assume a rational relationship as

$$N_{i,D} = N_{i,j} = N_{j,D} = N_o . \tag{5}$$

According to the above two typical forwarding model, the number of the relay nodes other than 1 or *N* can be selected to compromise the complexity and performance, which can be used in the optimization of the relay selection. And it can be shown in **Fig. 4**.



Stage I: source node transmitting Stage II: selected *M* relay nodes forwarding

Fig. 4. Two stages of the proposed relay selection scheme

In **Fig. 4**, the procedure of the source node transmitting and the relay node forwarding at Stage I and II can be the sub-set R_M^i of those of the AAF scheme shown in **Fig. 4**. The optimized selection of the sub-set of the relay node set will be investigated in the next section. And the relay node number may be inconstant under different channel environment.

3. Optimized Relay Selection by an Exclusive Method

For a specific data sequence *i*, one cooperative transmission in an amplify-and-forward (AF) multi-relay network requires *M*+1 time slot, when *M* potential relay nodes take part in the cooperation. In addition, the destination node uses the maximum ratio combination (MRC) to combine the received signals. So the instantaneous mutual information, which can be used to evaluate the channel capacity, is shown in Equation (6) similar to that in [17]

$$I_i = \frac{1}{M+1}\log_2[1+P_{ii}\left|h_{i,D_i}\right|^2\gamma + \sum_{j\in R_M^i} f(P_{ii}\left|h_{i,j}\right|^2\gamma, P_{ij}\left|h_{j,D_i}\right|^2\gamma)], \tag{6}$$

where γ is the signal-to–noise ratio (SNR) of the system and it is expressed as $\gamma = 1/N_0$, where N_0 is the power spectrum density (PSD) of the channel noise. The function *f*(*x*,*y*) is defined as $xy/(x+y+1)$.

When the target rate of the destination node is *R* bit/s, and the instantaneous mutual information is less than it, the outage occurs. The outage probability of the data sequence *i* is presented as

$$\begin{aligned} &P_{out}^{(i)} = P_{out}(I_i < R) = \\ &\Pr\left(P_{ii}\left|h_{i,D_i}\right|^2\gamma + \sum_{j\in R_M^i} f\left(P_{ii}\left|h_{i,j}\right|^2\gamma, P_{ij}\left|h_{j,D_i}\right|^2\gamma\right) < 2^{(M+1)R} - 1\right) \end{aligned} \tag{7}$$

Similar to the deduction in [9], the above Equation (7) under high SNR can be simplified and denoted as

$$P_{out}^{(i)}(M)=P_{out}^{(i)}=W(M)\frac{1}{P_{ii}\sigma_{i,D}^{2}\gamma^{M+1}}\prod\nolimits_{j\in R_M^i}\left(\frac{1}{P_{ii}\sigma_{i,j}^{2}}+\frac{1}{P_{ij}\sigma_{j,D}^{2}}\right) \tag{8}$$

where there is $W(M)=(2^{(M+1)R}-1)^{M+1}/(M+1)!$ and R is the target rate. $\sigma_{i,D}^2$, $\sigma_{i,j}^2$, and $\sigma_{j,D}^2$ are the variance of the channel coefficients, from source node *i* to destination node *D*, source node *i* to relay node *j*, and relay node *j* to destination node *D*, respectively.

When the total power from all type of data sequence is constrained, a mathematical technique can be employed to select the proper relay set and minimize the average outage probability. And the mathematical function can be modeled and shown as follows

$$\min P_{out}=\frac{1}{M}\sum\nolimits_{i=1}^{M}P_{out}^{i}\ , \tag{9}$$

$$\sum\nolimits_{j\in R_M^i}P_{ij}\le P_t, i=1,2,\cdots,N+1\ , \tag{10}$$

where P_t is the total power available, P_{ij} is the power from the *i*-th source node to the *j*-th relay node. P_{out} and $P_{out}{}^{i}$ are the overall and the *i*-th outage probability, respectively. So the optimal solution is equivalent to the optimization problem of the individual data sequence, which reduces as much outage probability as possible, as well as the complexity.

For the *i*-th data sequence, the source node and the relay nodes are supposed to be allocated with equal power P_0. Then, there are *M* relay candidates from the relay node set R_M^i with total *M*-relay outage probability $P_{out}^{(i)}(M)$ and every node is allocated with power $P_1=P_0$. After that, a new relay specific node set R_M^i is defined as the original relay node set R_M^i accompanied by an exclusive method, *e.g.*, excluding the specific relay node *k*, and so on. So the outage probability is turned out to be $P_{out}^{(i)}(M-1)$ under the same allocated power $P_2=P_0$ for each relay node. In order to minimize the overall outage probability of the entire relay system, the outage probability should be reduced after the relay node exclusion. Then there should be a relationship as

$$P_{out}^{(i)}(M)\,/\,P_{out}^{(i)}(M-1)\ge 1. \tag{11}$$

For the relay node *k*, substituting the Equation (8) into the left part of Equation (11) with some simplification, there is

$$\frac{P_{out}^{(i)}(M)}{P_{out}^{(i)}(M-1)}=\frac{W(M)}{W(M-1)}\left(\frac{P_2}{P_1}\right)^{M}\frac{1}{\gamma P_1}\left(\frac{1}{\sigma_{i,k}^{2}}+\frac{1}{\sigma_{k,D}^{2}}\right). \tag{12}$$

where γ is the systematic SNR, and $\sigma_{i,k}^2$ and $\sigma_{k,D}^2$ are the variance of the channel coefficients, from source node *i* to relay node *k*, and relay node *k* to destination node *D*, respectively.

Due to the relationship of the same power allocation as $P_1=P_2=P_0$, Equation (11) and Equation (12) can be combined together as

$$\frac{W(M)}{W(M-1)}\frac{1}{\gamma P_0}\left(\frac{1}{\sigma_{i,k}^{2}}+\frac{1}{\sigma_{k,D}^{2}}\right)\ge 1. \tag{13}$$

Subsequently, replacing $W(M)$ with the detailed expression of $(2^{(M+1)R}-1)^{M+1}/(M+1)!$ from the explanation of Equation (8) with some simplification, Equation (13) is turned into

$$\frac{1}{\sigma_{i,k}^{2}}+\frac{1}{\sigma_{k,D}^{2}}\ge\frac{\gamma P_0(M+1)(2^{MR}-1)^{M}}{(2^{(M+1)R}-1)^{M+1}}. \tag{14}$$

For the ease of analysis, we define three new notations as the equivalent channel gain (ECG) about the relay node *k* (V_k), the relay selection threshold (T_r) and the SNR threshold of the relay system (γ_r), respectively. And they are expressed as follows.

$$V_k = 1/\sigma_{i,k}^2 + 1/\sigma_{k,D}^2 , \tag{15}$$

$$T_r = \frac{\gamma_r P_0 (M+1)(2^{MR}-1)^M}{(2^{(M+1)R}-1)^{M+1}} , \tag{16}$$

$$\gamma_r = V_k \frac{(2^{(M+1)R}-1)^{M+1}}{P_0 (M+1)(2^{MR}-1)^M} . \tag{17}$$

where γ_r is the specific SNR γ with respect to the relay selection threshold (T_r).

If the relay node *k* satisfies the following condition, it will be excluded from the relay set.

$$V_k \geq T_r \tag{18}$$

Finally, from the above deduction, a relay node for the cooperative forwarding are mainly decided by the equivalent channel gain of it. In addition, it also dependents on the selection threshold of the relay node itself, target transmission rate and the potential number of all the relay nodes available. The selection threshold of the relay node increases, accompanied by the raise of the SNR threshold γ_r. Therefore, large γ_r leads to large selection threshold of the relay node, and thus more relay nodes can't be excluded from the proposed method. So more relay nodes are retained to participate in the cooperative forwarding and transmission, which degenerates to the original all-relay forwarding algorithm. Based on the above analysis, the proposed relay selection can be concluded in **Table 1** as follows.

Table 1. The proposed relay selection with an exclusive method.

Main Steps	Algorithm procedures
Step 1) Initialization	Supposing that all potential relay node can participate in the cooperative forwarding, there is *M*=*N*. Then the relay set is $R_M^i = \{1, 2, ..., N\}$. In addition, the initial relay selection threshold $T_r = T_r^{(0)}$ is calculated by Equation (16).
Step 2) Calculation of the max ECG $V_{\max}(k)$ with the index *k* in all ECGs of the relay nodes	The equivalent channel gain (ECG) V_j of each potential relay node *j* is computed by Equation (15). Then the ECG sequence $\{V_j\}$ of all relay nodes is obtained and the max ECG $V_{\max}(t)$ is got as $V_{\max}(k) = \max_{k, j \in R_M^i}(\{V_j\})$ with the index *k*.
Step 3) Update of the relay selection threshold (T_r) and the relay node set R_M^i	If $V_{\max}(t)$ is larger or equal than T_r, the relay node *k* is excluded from the relay node set R_M^i. Otherwise, go to **Step 5)**.
Step 4) Update of the iteration step	The element number of the relay node set R_M^i is decreased by 1 as $M = M - 1$ and new T_r is calculated by Equation (16) with the decreased *M*. If $M = 1$, goto **Step 5)**. Otherwise, go to **Step 3)**.
Step 5) End of the Algorithm	The algorithm is completed and the residual relay node set R_M^i is the optimal relay selection node set for cooperation.

Because the above steps in the proposed relay selection just utilize the information about the ECG and the relay number and so on, the relay selection threshold can be determined at the beginning and updated in the iteration, which reduces much system resource occupation, such as the bandwidth spectrum, CSI calculation, power consuming, and so on. The excluded relay nodes are just idle and need not any resource in the process. So the occupied resource of the excluded relay nodes, *e.g.*, the channel bandwidth occupation, power consuming, *etc.*, can be released and re-allocated to other relay nodes with maximum ECG for low average outage probability of the whole system and thus high system resource utility can be achieved.

The proposed algorithm mainly excludes the relay nodes with larger ECG than the threshold one by one and the remainders of the relay node set are united as an optimized relay node set to participate in the cooperative forwarding. However, intuitively, the exhaustive method can also be used to find such a set at a first glance. In other words, all potential relay nodes in the system are enumerated to form the relay node set. So there are 2^{M-1} such sets. Then, the average outage probability of the relay sets under the equal power allocation is calculated. And the optimal relay node set with minimum average system outage probability can be found by global searching and comparison. The exhaustive method has obvious deficiency of highest computational complexity. However, the proposed scheme is a relative low complex method to find the optimal relay node set. It only needs calculate the ECG and re-order them with the relay node index. Therefore, the proposed relay selection scheme obtains similar performance but with lower complexity, which makes it more pragmatic in practice.

4. Near Optimal Power Allocation for the Above Relay Selection

The optimized relay system set by the above relay selection method is mainly under the constraint of equal power allocation. But the power allocation can be further optimized for better outage probability performance by a near optimal power allocation (NOPA) method. And the proposed power allocation can be described as follows.

For a single data sequence i, there are M relay nodes, *i.e.* the relay node set R_M^i , to be selected after the above exclusive method. So an optimized power allocation scheme for assigning the power for both the source node and all the relay nodes can be considered to minimize the overall outage probability under the constraint of M selected relay nodes mentioned above. Then, by minimizing the outage probability of the system $P_{out}^{(i)}$ in Equation (8), the optimization function can be modeled as

$$\begin{aligned} P_{out}^{i} &= \min\left\{ W(M)\frac{1}{P_{ii}\sigma_{i,D}^{2}\gamma^{M+1}}\prod\nolimits_{j\in R_M^i}\left(\frac{1}{P_{ii}\sigma_{i,j}^{2}}+\frac{1}{P_{ij}\sigma_{j,D}^{2}}\right)\right\} . \\ s.t.\quad & P_{ii}+\sum\nolimits_{j\in R_M^i} P_{ij}\le P_t \end{aligned} \tag{19}$$

Suppose that there is $\alpha_j=\sigma_{i,j}^2/\sigma_{j,D}^2\cdot\left(j\in R_M^i\right)$, Equation (19) can be deduced and expressed as

$$\begin{aligned} P_{out}^{i} &= \min\left\{ W(M)\frac{1}{P_{ii}\sigma_{i,D}^{2}\gamma^{M+1}}\prod\nolimits_{j\in R_M^i}\frac{1}{\sigma_{i,j}^{2}}\left(\frac{1}{P_{ii}}+\frac{\alpha_j}{P_{ij}}\right)\right\} . \\ s.t.\quad & P_{ii}+\sum\nolimits_{j\in R_M^i} P_{ij}\le P_t \end{aligned} \tag{20}$$

In Equation (20), by excluding some unknow but constant variables, the optimization function can be further simplified as

$$\begin{aligned} P_{out}^{i} &= \min \quad 1/P_{ii}\cdot\prod\nolimits_{j\in R_M^i}\left(1/P_{ii}+\alpha_j/P_{ij}\right) . \\ s.t.\quad & P_{ii}+\sum\nolimits_{j\in R_M^i} P_{ij}\le P_t \end{aligned} \tag{21}$$

Then, we use a Lagrange multiplier method to solve Equation (21) and the Lagrange function is constructed as

$$F\left(P_{ii},P_{ij},\lambda\right)=\frac{1}{P_{ii}}\prod\nolimits_{j\in R_M^i}\left(\frac{1}{P_{ii}}+\frac{\alpha_j}{P_{ij}}\right)+\lambda\left(P_{ii}+\sum\nolimits_{j\in R_M^i}P_{ij}-P_t\right). \tag{22}$$

Firstly, taking partial derivation of Equation (22) with respect to P_{ii}, P_{ij} ($j\in R_M^i$) and λ, and then making them equal to zero, we can get

$$-\frac{1}{P_{ii}^2}\prod\nolimits_{j\in R_M^i}\left(\frac{1}{P_{ii}}+\frac{\alpha_j}{P_{ij}}\right)+\sum\nolimits_{k\in R_M^i}\frac{1}{P_{ii}}\left[\prod\nolimits_{j\in R_M^i,j\neq k}\left(\frac{1}{P_{ii}}+\frac{\alpha_j}{P_{ij}}\right)\right]\left(-\frac{1}{P_{ii}^2}\right)+\lambda=0, \tag{23}$$

$$\frac{1}{P_{ii}}\left[\prod\nolimits_{k\in R_M^i,k\neq j}\left(\frac{1}{P_{ii}}+\frac{\alpha_k}{P_{ik}}\right)\right]\left(-\frac{\alpha_j}{P_{ij}^2}\right)+\lambda=0,\quad j\in R_M^i, \tag{24}$$

$$P_{ii}+\sum\nolimits_{j\in R_M^i}P_{ij}-P_t=0. \tag{25}$$

Then, solving the joint Equation group, *i.e.*, Equation (23)~(25), there is

$$P_{ij}^2+\alpha_jP_{ii}P_{ij}-\alpha_jP_{ii}P_t\big/(M+1)=0. \tag{26}$$

So P_{ij} can be represented by P_{ii} as

$$P_{ij}=\left[-\alpha_jP_{ii}+\sqrt{\alpha_j^2P_{ii}^2+4\alpha_jP_{ii}P_t/(M+1)}\right]/2,\quad j\in R_M^i, \tag{27}$$

which determines the relationship of P_{ij} and P_{ii}.

Suppose that there are $P_{ii}=\eta_0P_t$ and $P_{ij}=\eta_jP_t, j\in R_M^i$, then there are $\eta_0>0$ and $0\leq\eta_j\leq1, j\in R_M^i$. η_0 is the power allocation factor of the source node, and η_j is the power allocation factor of the *j*-th relay node. According to the constraint condition of Equation (20), *i.e.*, $P_{ii}+\sum_{j\in R_M^i}P_{ij}\leq P_t$, with the extereme condition of equality, there is

$$P_{ii}+\sum\nolimits_{j\in R_M^i}P_{ij}=P_t. \tag{28}$$

By the similar subordinate optimized power allocation factor technique for a single data stream deduced in [9], *i.e.*, the factor of all relay nodes being the same under the equal power allocation (EPA) scheme, there is

$$\eta_j=(1-\eta_0)\big/M,\ j\in R_M^i. \tag{29}$$

Substituting the result of the proposed power allocation scheme as Equation (27) into Equation (28), there is

$$P_{ii}+\sum\nolimits_{j\in R_M^i}\left[-\alpha_jP_{ii}+\sqrt{\alpha_j^2P_{ii}^2+4\alpha_jP_{ii}P_t/(M+1)}\right]/2=P_t. \tag{30}$$

And Equation (30) can be reorganized as

$$\sum\nolimits_{j\in R_M^i}\sqrt{\alpha_j^2P_{ii}^2+4\alpha_jP_{ii}P_t/(M+1)}=\sum\nolimits_{j\in R_M^i}\alpha_jP_{ii}+2(P_t-P_{ii}). \tag{31}$$

Divided by P_t at both sides of Equation (31), and using the definition of $\eta_0=P_{ii}/P_t$, there is

$$\sum\nolimits_{j\in R_M^i}\sqrt{\alpha_j^2\eta_0^2+4\alpha_j\eta_0/(M+1)}=\eta_0\sum\nolimits_{j\in R_M^i}\alpha_j+2(1-\eta_0). \tag{32}$$

Then, we defined $\bar{\alpha}$ as the average of all $\alpha_j=\sigma_{i,j}^2/\sigma_{j,D}^2$, $\left(j\in R_M^i\right)$ and it is expressed as

$$\bar{\alpha}=1/M\cdot\sum\nolimits_{j\in R_M^i}\alpha_j=1/M\cdot\sum\nolimits_{j\in R_M^i}\sigma_{i,j}^2/\sigma_{j,D}^2. \tag{33}$$

To get the close form of η_0, a special case of the symmetric relay node deployment is assume as in [9], where all relay nodes are placed symmetric and allocated with equal power.

Then, there is a simple relationship of $\alpha_j = \bar{\alpha}, \text{ for any } j \in R_M^i$. So for this case, there is $\eta_j = (1-\eta_0)/M$, for any $j \in R_M^i$ and Equation (32) can be turned into

$$\sum\nolimits_{j\in R_M^i} \sqrt{\bar{\alpha}^2\eta_0^2 + 4\bar{\alpha}\eta_0 / (M+1)} = \eta_0 \sum\nolimits_{j\in R_M^i} \bar{\alpha} + 2(1-\eta_0) \, . \tag{34}$$

Therefore, the power allocation factor η_0 is deduced and expressed as

$$\eta_0 = \frac{1}{(1-\bar{\alpha}M)}\left\{1-\frac{\bar{\alpha}M}{2(M+1)}\left[1-\sqrt{1+\frac{4(M+1)}{\bar{\alpha}}}\right]\right\}. \tag{35}$$

Then, the power allocation factor η_j at the relay node j ($j \in R_M^i$) is easily got by using Equation (35) and Equation (29) in sequence.

Therefore, the power of the source node and all relay nodes can be obtained by the above optimized power allocation. And they can be applied in Equation (8) to get the smallest outage probability of the entire relay system under the optimized power allocation constraint.

To evaluate the complexity of the proposed scheme, we compare it with an unoptimized exhaustive scheme. The exhaustive scheme is described as follows. The power allocation of all combinations from *N* participated relay nodes are figured out and the outage probability of them are obtained. In other words, the power and outage probability of all possible combinations from the *N* participated relay nodes are tentatively calculated. Then the global searching method is used to find the set of the minimum outage probability. The set is considered as the optimal relay node set, which can forward the source messages optimally. When *N* is large, the exhausting algorithm is too complex to be accomplished for the optimal calculation. However, in the proposed algorithm, the relay nodes to foward the messages are chosen according to Equation (18), *e.g.*, total *M* power calculations of Equation (27), which greatly reduces the complexity. Here, *M* is the number of selected relay nodes participating in fowarding the messages and it is usually less or equal than the total number *N* of all relay nodes. In the exhaustive scheme, there are *N* relay nodes forwarding message from the source node to destination node. In the proposed relay selection scheme, *M* relay nodes are chosen in the cooperation. So the parameter *M* represents the number of the relay nodes taking part in the cooperative relay selection. Finally, for a comparison, we evaluate some complexity of the proposed relay selection scheme and the contrast ones with some variables in the complexity computation. Given the actual participated relay node number *M* in the proposed scheme and the *N* relay nodes in the contrast exhaustive scheme, the complexity of them are compared as follows. In the proposed scheme, given *M* relay nodes in cooperation, there are only *N* relay nodes for order sorting to find *M* participated nodes, *N* calculations of V_k in Equation (15), and the NOPA computations of the *M* participated nodes. But in the exhaustive scheme, given *N* ($N \geq M$) relay nodes in the cooperation, there are total calculations of 2^N outage probability, 2^N minimum value selection, and 2^N power allocation. And the number 2^N just come from the exhaustive scheme by a combination theory under *N* relay nodes, where the calculation is carried out with a direct link from source node to destination node (S→D), plus siutuations of no relay node (0 chosen node from all *N* nodes) participated, 1 relay node (1 chosen node from all *N* nodes) participated, …, *N* relay nodes (*N* chosen nodes from all *N* nodes) participated, respectively. So there is a sum of 2^N for all possible cases as follow.

$$\begin{aligned} &Number\ of\ All\ Cases = C_N^0 + C_N^1 + \cdots + C_N^N \\ &= C_N^0 \times 1^0 \times 1^N + C_N^1 \times 1^1 \times 1^{N-1} + \cdots + C_N^N \times 1^N \times 1^0 = (1+1)^N = 2^N \, , \end{aligned} \tag{36}$$

where C_i^j is the combination expression and it represents the number of the cases of chosing *j* from a total *i*. So there are a total of 2^N calculations in the exhaustive scheme to cover all possible combinations of the relay forwarding cases. And there are 2^N calculations of the outage probability, minimum value sorting and near optimal power allocation, respectively.

With the increase of N, the computational complexity of the exhaustive scheme grows quickly, approximately in proportion to the exponential growth. Also the complexity of the partial relay node participated AF scheme is similar to that of the proposed scheme with the same number of the relay nodes in cooperative relay selection, except for the random selection of the participated relay nodes. So the exhaustive scheme is too complex to be implemented, especially for large number N of the relay nodes in a cooperative network. Therefore, the proposed scheme has less increase in computational complexity, which makes it much more pragmatic and it can be efficiently applied in cooperative networks.

5. Numerical Results and Analysis

To validate the proposed relay selection and power allocation scheme with the exclusive method, the outage probability performance is simulated and compared with the contrast schemes. Following the multi-relay cooperative network model in **Fig. 1**, the simulation parameters are configured as follows. The channels between alternative two nodes in the multi-relay network are symmetric, quasi-static and flat fading channels. And they can be approximately modeled as the additive white Gaussian noises (AWGNs) with stochastic channel attenuation at each transmission. The variances of the fading channel coefficients are set according to the specific simulation scenarios. The channel parameters of the above channels are zero mean and different variances described in Section 3. Finally, three experimental instances are performed to verify the proposed scheme with different simulation parameters. The simulation results and the analyses are listed as follows.

Simulation I: under single data sequence, the outage probabilities of the proposed relay selection scheme and the contrast Partial Relay Node Participated AF (PRNP-AF) scheme with different number of participated relay nodes are simulated and compared. And the relay nodes are randomly chosen in the contrast PRNP-AF schemes.

Take a typical data sequence for an example, suppose that the source node is node 1, the nodes 2~7 are the potential relay nodes and the destination node is node D. The distance of the source node and destination node are normalized as 1 and other relay nodes are randomly scatted between them. The statistical characteristics of the channels between any two nodes are mainly related to the distance of them. So a typical group of the variances of the channel coefficients for different channel links is set and shown in **Table 2**.

Table 2. The variance of the channel coefficients of different channel links.

Channel link	*Channel coefficients (variances $\sigma_{i,j}^2$)~$N(0, \sigma_{i,j}^2)$*	*Simulation values*
$S_1 \rightarrow S_2$	$\sigma_{1,2}^2$	0.8
$S_1 \rightarrow S_3$	$\sigma_{1,3}^2$	0.4
$S_1 \rightarrow S_4$	$\sigma_{1,4}^2$	0.3
$S_1 \rightarrow S_5$	$\sigma_{1,5}^2$	0.2
$S_1 \rightarrow S_6$	$\sigma_{1,6}^2$	0.15
$S_1 \rightarrow S_7$	$\sigma_{1,7}^2$	0.1
$S_1 \rightarrow D$	$\sigma_{1,D}^2$	1.5
$S_2 \rightarrow D$	$\sigma_{2,D}^2$	1.2
$S_3 \rightarrow D$	$\sigma_{3,D}^2$	0.9
$S_4 \rightarrow D$	$\sigma_{4,D}^2$	0.4

$S_5 \rightarrow D$	$\sigma_{5,D}^2$	0.3
$S_6 \rightarrow D$	$\sigma_{6,D}^2$	0.2
$S_7 \rightarrow D$	$\sigma_{7,D}^2$	0.1

The power at each node is normalized as 1W and the total power is 7W for a source node and 6 relay nodes. The target rate is R=0.5bit/s. Then, the simulation results of the proposed scheme and the contrast Partial Relay Nodes Participated AF (PRNP-AF) schemes with different number of participated relay nodes are shown in **Fig. 5**.

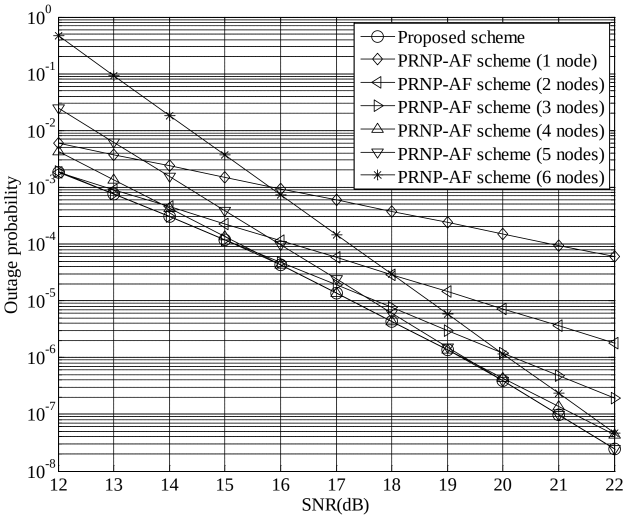


Fig. 5. Comparison of the outage probability of the proposed scheme and the contrast PRNP-AF scheme with different number of participated relay nodes.

From **Fig. 5**, the average outage probability of the relay system with proposed scheme is always the minimum at the selected SNR range among all schemes in the simulations. When the SNR is low, especially smaller than 15.8dB, the outage performance of the PRNP-AF scheme with one relay node exceeds that of the same scheme but with full six relay nodes. Otherwise, the latter outperforms when the SNR is larger than 15.8dB. Other cases are also similar as described above, where the PRNP-AF scheme with fewer relay nodes has better outage performance than that with much more relay nodes at low SNRs. Or vice visa, when the two schemes work at much higher SNRs. At outage probability of 10^{-4}, the proposed scheme obtains about 5.8, 1.1, 0.1, 0.15, 0.6, 2.1 dB SNR gains, respectively, when compared with the contrast PRNP-AF schemes with different relay node number from 1 to 6. So only proper number of relay nodes can achieve best performance for a specific scheme given a total number of the participated relay nodes in a cooperative network. At high SNRs, a multiple-relay system with more relay nodes involving in the cooperation has the least average outage probability, thus exhibits better overall outage performance. At low SNRs, only some proper relay nodes bring best performance. This phenomena can be explained as follows. At high SNRs, more channel links are available for high quality transmission, and thus much diversity gain can be obtained for better outage performance. So more relay nodes help to improve the channel capacity and thus reduce the outage probability. For the proposed scheme, the relay selection threshold T_r in Equation (16) becomes **larger** and thus more relay nodes are remained for participating in the cooperation. It degenerates and approaches to the PRNP-AF scheme with full-relay-node participation. However, the performance gain by the increase of the relay nodes is at the cost of huge computational complexity, which greatly hinders the practical applications. At low SNRs, much more relay nodes may work at poor channel environment, which brings less performance gains. In other words, some relay nodes in cooperation of the poor channel links may hinder the overall performance, since they require more power in transmission, thus they occupy the bandwidth resources for worse performance. Therefore, only proper links with cooperative relay nodes contribute to the overall optimal performance and it can be optimized by the relay selection threshold suggested in the proposed scheme.

Simulation II: under the constraint of the equal power allocation (EPA), the outage probability of the proposed scheme and the contrast AAF and the SAF schemes are simulated and compared.

For the generalization of the experimental results, 8 nodes are randomly generated in a 2×2 two-dimensional plane in all simulation scenarios. Suppose that the channels are the quasi-stationary flat fading channels. The channel fading factor between any two node, *e.g.* node i and node j, satisfies the fading distribution with zero mean and variance $\sigma_{i,j}^2$. The relationship of the fading parameter $\sigma_{i,j}^2$ and the distance $d_{i,j}$ is $\sigma_{i,j}^2 = d_{i,j}^{-\tau}$, where τ is the path loss factor, and it is chosen as 3 in the simulations. The simulation iterations are 10^6 for the average outage probability. In the simulations, the transmission power for each node is all set as 1W, and the target information rate is R=0.5bit/s. The average outage probability of the relay system is defined as the average outage probability of all data sequences passing through all possible channels. Finally, the simulation results of the proposed scheme and the contrast AAF and SAF ones are shown in **Fig. 6**.

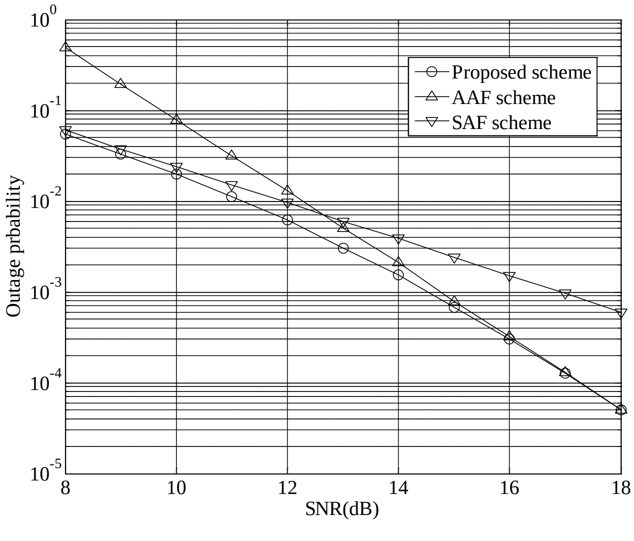


Fig. 6. Comparison of the outage probability among the proposed relay selection scheme, the AAF and the SAF schemes.

In **Fig. 6**, the outage performance of the proposed scheme outperforms those of the AAF and the SAF schemes. When the outage probability is 10^{-2}, the proposed scheme has about 1.3 dB and 1dB performance gain over those of the AAF and the SAF schemes, respectively. When the outage probability is 10^{-3}, the proposed scheme outperforms the AAF and the SAF schemes about 0.3 dB and 2.5 dB, respectively. At low SNRs, the performance of the proposed scheme has a little better than that of the SAF scheme, and it surpasses that of the AAF scheme much. At high SNRs, the proposed scheme overtakes the AAF scheme negligibly, but it superiors to the AAF scheme much. The possible reasons are explained as follows.

Firstly, the reasons for the performance improvement of the proposed scheme over the AAF scheme are listed as follows. At low SNRs, more relay nodes take part in the cooperative forwarding, which occupies much channel resources, such as the estimation of the CSI, the bandwidth spectrum and so on. However, due to poor channel, little gain can be obtained and the transmission of different channels may interference with each other to further degrade the outage performance. Also, some channels with worst channel state may drag back overall performance. So the transmission efficiency is cut down and the outage performance decreases too. At high SNRs, more relay nodes help improve the reliability, which improves the outage performance apparently. The proposed scheme can obtain similar performance, because more relay nodes are retained at high SNRs according to Equation (18). So it gradually degenerates to the AAF scheme for good performance but at the cost of less reduced complexity.

Secondly, since the relay selection in the proposed scheme is optimized for the best outage performance at high SNRs, it surely outperforms the SAF scheme, which only uses a fixed optimal single-relay node for cooperation. However, at low SNRs, more relay nodes are associated with poor channels, which may damage the overall performance. So only limited relay nodes with good channel contribute to good performance. For the proposed scheme, there are more relay nodes to satisfy Equation (18) for exclusion at low SNRs. In some extreme cases, it even chooses a relay node for cooperation, which is just the SAF scheme.

Simulation III: the comparison of the outage probability among the proposed scheme with the near optimal power allocation (NOPA) and the equal power allocation (EPA), respectively, and the exhaustive scheme with the NOPA.

The nodes are randomly generated in a 2×2 two-dimensional plane the same to those in **Simulation II**. Given a total number of the nodes as 8, two group of the 4 of them are assigned for the data sequence nodes and destination nodes, respectively. For a single data sequence, there are 6 potential relay nodes. In the simulations, the transmission power of each node is set as 1W, the target rate is R=0.5bit/s. The above schemes with the NOPA or the EPA are adopted in simulations. Finally, the simulation results are simulated and shown in **Fig. 7**.

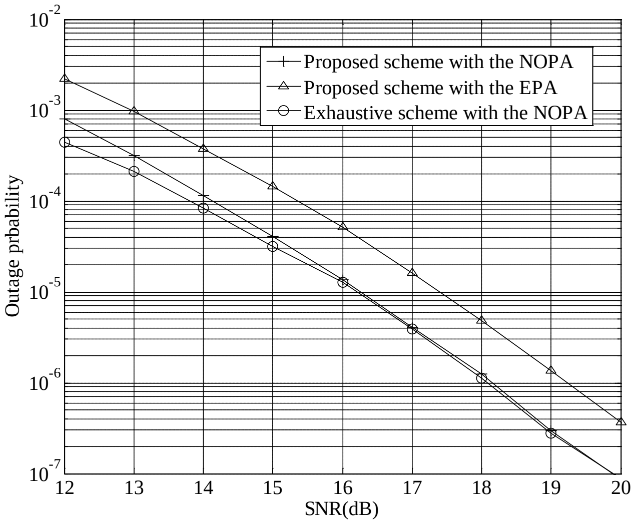


Fig. 7. Comparison of the outage probability among the proposed scheme with the NOPA and the EPA, and the optimal exhaustive scheme with the NOPA.

In **Fig. 7**, the outage performance of the proposed power allocation scheme of NOPA outperform that of it with the EPA for about 1-1.2 dB at all SNRs. The outage performance of the proposed scheme of the NOPA approach closely to that of the globally optimal exhaustive scheme and there are still 0.2-0.5 dB performance gap when the SNR is less than 15dB. But the performances of them are getting closer with the increase of the SNR. These phenomenon can be explained as follows.

Given the same proposed scheme, the EPA allocates the power of all rely nodes equally. Due to different channel states, some power allocation can not be efficiently used for the relay nodes related to poor channels. This can be explained by the well-known water-filling theory in the information theory, where more power should be allocated in the channel with better channel conditions for better channel capacity. Therefore, the EPA scheme are not optimal in the power allocation. However, based on the above analysis in Section 4, the NOPA are sub-optimal scheme to approach the results of the water-filling theory with acceptable complexity. Under the same sub-optimal NOPA, the proposed scheme can approach to the optimal exhaustive scheme since it uses some best chosen reliable rely nodes for coopertion, which contribute most of the performance, but at the cost of low complexity.

6. Conclusion

In this paper, an optimized relay selection and power allocation by an exclusive method in a single-source and multi-relay cooperative network is proposed with high outage performance, good power efficiency and low complexity. By the statistical channel characteristic, it mainly excludes all relay nodes with higher equivalent channel gain over a fixed threshold to prevent them from deteriorating the average outage probability of the entire cooperative system. In addition, the threshold is deduced from the analysis of the reduction of the overall outage probability. It need not update the instantaneous channel state information of all channels to get the optimal relay selection, which reduces much complexity and improves the resource utility. Moreover, a NOPA scheme for the above relay selection is also proposed by a Lagrange multiplier method to optimize the power efficiency. Numerical simulations and theoretical analyses show that the proposed relay selection scheme obtains better outage performance than those of the contrast AAF, SAF and partial-relay-node-participated AF schemes and so on. Furthermore, the NOPA for the proposed relay selection obtains similar power efficiency of the optimal exhaustive schemes, but with much lower complexity. Therefore, the proposed relay selection and power allocation scheme is much efficient and pragmatic in single-source multi-relay cooperative networks with high outage probability performance, good power efficiency, and low computational complexity.

References

[1] F. Gomez-Cuba, R. Asorey-Cacheda, and F. J. Gonzalez-Castano, “A survey on cooperative diversity for wireless networks,” *IEEE Communications Surveys & Tutorials*, vol. 14, no. 3, pp. 822-835, Third Quarter, 2012. Article (CrossRef Link).

[2] C. X. Wang, X. Hong, and X. Ge , *et. al.*, “Cooperative MIMO channel models: a survey,” *IEEE Communications Magazine*, vol. 48, no. 2, pp. 80-87, February 2010. Article (CrossRef Link).

[3] X. Wang, J. Zhou, and D. Wang, “Joint relay-and-antenna selection and power allocation for AF MIMO two-way relay networks,” *KSII Transactions on Internet and Information System*, vol. 10, no. 3, pp. 1016-1033, March, 2016. Article (CrossRef Link).

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing uplink capacity via user cooperation diversity," in *Proc. of 1998 IEEE International Symposium on Information Theory*, 1998. Proceedings. IEEE, pp. 156, 1998. Article (CrossRef Link).

[5] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. Part I. system description," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927-1938, November 2003. Article (CrossRef Link).

[6] X. Yuan, T. Yang, and I. B. Collings, "Multiple-input multiple-output two-way relaying: a space-division approach," *IEEE Transactions on Information Theory*, vol. 59, no. 10, pp. 6421-6440, Octorber 2013. Article (CrossRef Link).

[7] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information theory*, vol. 50, no. 12, pp. 3062-3080, December 2004. Article (CrossRef Link).

[8] J. N. Laneman, and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transactions on Information theory*, vol. 49, no. 10, pp. 2415-2425, March 2003. Article (CrossRef Link).

[9] R. Annavajjala, P. C. Cosman, and L. B. Milstein, "Statistical channel knowledge-based optimum power allocation for relaying protocols in the high SNR regime," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, pp. 292-305, Feb. 2007. Article (CrossRef Link).

[10] C. E. Shannon, "Two-way communication channels," in *Proc. of 4th Berkeley Symp. Math. Stat. Prob.*, 1, pp. 611-644, 1961. Article (CrossRef Link).

[11] Y. Jing, and B. Hassibi, "Distributed space-time coding in wireless relay networks," *IEEE Transactions on Wireless communications*, vol. 5, no. 12, pp. 3524-3536, December 2006. Article (CrossRef Link).

[12] B. Rankov , A. Wittneben, "Spectral efficient protocols for half-duplex fading relay channels," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, pp. 379-389, Febrary 2007. Article (CrossRef Link).

[13] W. Nam, S. Y. Chung, and Y. H. Lee, "Capacity bounds for two-way relay channels," in *Proc. of 2008 IEEE International Zurich Seminar on Communications*, IEEE, pp. 144-147, March 2008. Article (CrossRef Link).

[14] P. Popovski, and H. Yomo, "Physical network coding in two-way wireless relay channels," in *Proc. of 2007 IEEE International Conference on Communications*. IEEE, pp. 707-712, June 2007. Article (CrossRef Link).

[15] C. C. Hu, G. F. Liu, and B. H. Chen, "Joint relays/antennas selection and precoding design for two-way MIMO amplify-and-forward relaying systems," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 7, pp. 4854-4864, August 2017. Article (CrossRef Link).

[16] Y. Jing, "A relay selection scheme for two-way amplify-and-forward relay networks," in *Proc. of International Conference on Wireless Communications & Signal Processing, 2009*. WCSP 2009. IEEE, pp. 1-5, November 2009. Article (CrossRef Link).

[17] Y. Zhao, R. Adve, and T. J. Lim, "Improving amplify-and-forward relay networks: optimal power allocation versus selection," *IEEE Transactions on Wireless Communications*, vol. 6, no. 8, pp. 3114-3123, August 2007. Article (CrossRef Link).

[18] Z. Lin, E. Erkip, and A. Stefanov, "Cooperative regions and partner choice in coded cooperative systems," *IEEE Transactions on Communications*, vol. 54, no. 7, pp. 1323-1334, July 2006. Article (CrossRef Link).

[19] A. Bletsas, A. Khisti, and D. P. Reed, *et. al.*, "A simple cooperative diversity method based on network path selection," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 659-672, March 2006. Article (CrossRef Link).

[20] A. Bletsas, A. Lippnian, and D. P. Reed, "A simple distributed method for relay selection in cooperative diversity wireless networks, based on reciprocity and channel measurements," in *Proc. of 61st IEEEVehicular Technology Conference 2005*(*VTC2005*), IEEE, pp.1484-1488, 2005. Article (CrossRef Link).

[21] Z. Bai, Y. Xu, and D. Yuan, et. al., "Performance analysis of cooperative MIMO system with relay selection and power allocation," in *Proc. of 2010 IEEE International Conference on Communications* (*ICC2010*), IEEE, pp. 1-5, May 2010. Article (CrossRef Link).

[22] J. Bao, D. He, and X. Xu, et. al., "Optimal relay selection and power allocation in an improved low-order-bit quantize-and-forward scheme," *KSII Transactions on Internet and Information Systems*, vol. 10, no. 11, pp. 5381-5399, 2016. Article (CrossRef Link).

[23] Q. Zhang, J. M. Zhang, and C. J. Shao et. al., "Power allocation for regenerative relay channel with Rayleigh fading," in *Proc. of 59th IEEE Vehicular Technology Conference, 2004 Spring*(*VTC2004*), IEEE, pp. 1167-1171, May 17-19, 2004. Article (CrossRef Link).

[24] B. Zhong, D. Zhang and Z. Zhang, "Power allocation for opportunistic full-duplex based relay selection in cooperative systems," *KSII Transactions on Internet and Information System*, vol. 9, no. 10, pp. 3908-3920, October, 2015. Article (CrossRef Link).

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