Performance Evaluation for the Cooperative Communication Systems in Decode-and-Forward Mode with a maximal ratio combining scheme

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Abstract: - Cooperative system is a tendency in the future communications because it provides a spatial diversity to improve the system performance. Three strategies including Amplify-and-Forward (AF) mode, Decode-and-Forward (DF) mode and Compress and Forward (CF) mode could be candidate to be employed in the system. This work considers the cooperative communication systems in DF Mode. The scenario includes one source station, M relay stations and N destinations. For the whole system, the maximum throughput approaching is the major purpose in this work. Hence, to select the relay stations for signal transmission could be the important scheme to achieve the best system performance. Based on the exhaustive search method, easily to realize, the optimal selection scheme could be found with a highly complicated calculation. In order to reduce the computational complexity, a sub-optimal solution with a greedy algorithm applied for the relay selection scheme is proposed. With different situations of the communication systems, the performances evaluations obtained by both the proposed algorithm and the exhaustive search method are given for comparison. It shows the proposed algorithm could provide a solution approaches to the optimal one. It is better to apply the proposed scheme when the number of relay stations is much larger than that of destination stations.

Key-Words: - Cooperative communication, Relay selection, Decode-and-Forward (DF) mode, Exhaustive search, Greedy algorithm

1 Introduction

Currently, the wireless communications provide a mount of multimedia services for the mobile devices. It increases a lot of mobile users and requests more advanced services. Although to access the wireless services is convenient for the mobile users, the degradation characteristics of the radio transmission are signal fading, multipath transmission, signal inferences, bandwidth limitation and so on. Under the limitation of transmission bandwidth, to improve system performance in the wireless systems becomes a significant work. Specially, to use the spatial diversity could be employed to improve the system performance [1]-[3]. For example, in the Multiple Input Multiple Output (MIMO) system, it provides a spatial diversity gain. However, the high implementation cost MIMO is with multiple antennas at both the transmitter and receiver [1]. Instead of MIMO technique, the cooperative communications with a relay channel increase the system capacity without extra antennas [2]-[4].

In the cooperative communication systems, the relay station functions with a character of spatial diversity. Comparing with multiple carrier modulation schemes and MIMO schemes, the relay stations not only forward the transmitted data but also process the received data. It provides a high throughput performance. The destination station could receive data with a spatial diversity with employing the relay selection scheme. Even though the destination station has no multiple antennas, by employing the relay station as the virtual antenna, it increases the transmission data rate and provides a reliable channel capacity [5]. With a consideration of low

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cost, the cooperative communication system is a tendency in the future communications.

Forwarding data through the relay stations, there are three different schemes in the cooperative communications. [2][6] One is Amplify-and-Forward (AF) mode. Another is Decode-and-Forward (DF) mode and the other is Compress and Forward (CF) mode. With AF mode, the transmitted signal could be amplified and retransmit to destination. It is easy to be implemented with a low complexity. For applications, it is good to those transmissions with a short distance. Within CF mode, the relay station does not have to decode the compressed signal. It uses the coding schemes to compress the received signal and retransmit to the destination. The relay station with DF mode decodes and demodulates the received signal at the first time instant. Then, at the second time instant, according to the available transmission bandwidth, the relay station recodes and modulates the signal to retransmit to the destination. However, if the relay station could not decode the received signal correctly, it will cause a catastrophic error.

In general, these three modes could effectively improve the system performance. Without the limitation of peer-to-peer transmission, the cooperative communication could obtain the system performance gain. Among those three kind modes in the cooperative communications, AF mode is with the characteristics of low complexity to be implemented [5]. However, under the condition of a higher signal to noise ratio (SNR), DF mode could have the benefits on the coding gain [7]. Also, the transmitted signal from the relay station could be the same signal as it is sent from the source station. It is without the effects on fading and interference. Based on DF mode, in this paper, a relay selection algorithm is proposed for the wireless cooperative systems. Usually, the algorithm is proposed based on the maximum amount of mutual information between the source and the destination. In this work, the capacity between stations is considered in the analysis. Relay selection could be an optimization by using an exhaustive search method which is simply realized. However, it takes a long time for a high computational complexity when the number of relay stations and the number of destination stations increase. For the real time applications, a sub-optimal relay selection scheme with a greedy algorithm applied is used to reduce the computational complexity. The following section introduces Decode-and-Forward (DF) mode in the cooperative systems. It begins with the single user environment and, then, the multi-destination user environment. Under the different situation, the theoretical derivations for the source-relay mutual information, the relay-destination mutual information and the source-destination mutual information are provided. The third section describes the proposed Relay Selection Algorithm. Also, the numerical results are shown for the comparison between the exhaustive search method and the proposed one. Finally, the conclusions are given in the last section.

2 Decode-and-Forward mode

In the cooperative communications, there are three elements in the system. One is the source station, another is relay station and the other is destination station. Each station has a transmitter, a receiver and an antenna. It assumes that each station could not transmit and receive simultaneously. First, consider a single user environment, as shown in Fig. 1. $h_{s,d}$ is denoted as the channel response between the source station to destination station. Similarly, $h_{s,r}$ and $h_{r,d}$ are denoted as the channel response between source station to resource station and the channel response between the resource station to destination station, respectively.

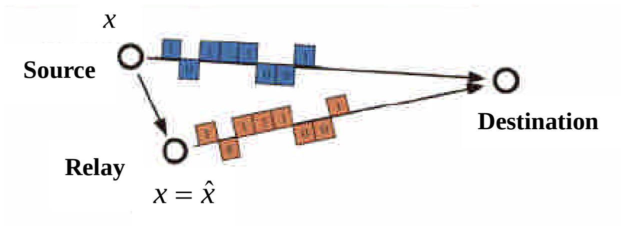

Fig. 1 DF mode transmission model

In Decode-and-Forward mode, after receiving the transmitted signal from the source station, the relay station begins to decode the signal and, then, transmit it to the destination station. In Fig. 1, the source station transmit the coded signal x at the first time. The relay station decodes the signal to be $\hat{x}$ and, then, recode and transmit the signal at the second time. To realize the function of DF mode, the mathematical analysis is given below.

At the first time, the received signal at the relay station and the destination station from the source station could be expressed in Eq. (1) and Eq. (2).

$$y_{s,r} = \sqrt{P_s} h_{s,r} x + n_{s,r} \tag{1}$$

$$y_{s,d} = \sqrt{P_s} h_{s,d} x + n_{s,d} \tag{2}$$

where *Ps* is the signal power from the source station, *x* is the transmitted coded signal from the source station, and $n_{s,r}$ and $n_{s,d}$ are AWGN with the variance N_0. In DF mode, the relay station retransmits the coded signal to the destination station. At the second time, the received signal, from the relay station, at the destination station is

$$y_{r,d} = \sqrt{p_s} h_{r,d} \hat{x} + n_{r,d} \tag{3}$$

where $\hat{x}$ is the decoded signal and $n_{r,d}$ is AWGN with the variance N_0. As the mentioned above, the decoded signal $\hat{x}$ should be the same as the one transmitted from the source station. Or, it will cause a catastrophic error. Hence, eq. (3) could be written as

$$y_{r,d} = \sqrt{p_s} h_{r,d} x + n_{r,d} \tag{4}$$

In order to evaluate the signal to noise ratio (SNR) at the instant time, SNR are defined as $SNR_{s,d} = \frac{P_s |h_{s,d}|^2}{N_0}$ for the source station to destination station, $SNR_{s,r} = \frac{P_s |h_{s,r}|^2}{N_0}$ for the source station to relay station, and $SNR_{r,d} = \frac{P_r |h_{r,d}|^2}{N_0}$ for the relay station to destination station. In a normalized channel, the mutual information between the source station and the destination station could be evaluated by

$$\mathrm{I}_{s,d} = \frac{1}{2}\log_2\left(1 + \frac{P_s}{N_0}|h_{s,d}|^2\right) \tag{5}$$

Besides, the mutual information at the destination station might be obtained by employed a maximal ratio combining (MRC) with the transmission from both the source station and the relay station, i.e.

$$I_{MRC,s,d} = \frac{1}{2}\log_2(1 + SNR_{s,d} + SNR_{r,d})$$
$$= \frac{1}{2}\log_2\left(1 + \frac{p_s |h_{s,d}|^2}{N_0} + \frac{p_r |h_{r,d}|^2}{N_0}\right) \tag{6}$$

The mutual information achieved at the destination station in DF mode could be expressed as

$$I_{DF} = \min\left\{I_{s,d}, I_{s,d}^{MRC}\right\} \tag{7}$$

Then, consider a multiple user environment where there are one source station, M relay stations and N destination stations, as shown in Fig. 2. $R=\{r_1,r_2,\ldots r_M\}$ and $D=\{d_1,d_2,\ldots d_N\}$ are defined as the set of relay station and the set of destination stations, respectively. N is less than M. The channel response between the source station to destination station *j* is denoted as $h_{s,dj}$.

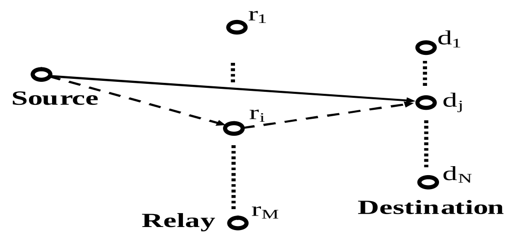

Fig. 2 Multiple user cooperative Communication system

Similarly, $h_{ri,dj}$ is denoted as the channel response between the relay station *i* and destination station *j*. The source station transmits the information to N destination stations with the cooperative communication through M relay stations. At the first time, at the destination station, the information is transmitted from the source station. At the second time, the information is transmitted from the employed relay station. Using the above derivation, the mutual information between the source station and the destination station *j* in DF mode could be expressed by

$$I_{s,r_i} = \frac{1}{2}\log_2\left(1 + \frac{p_s |h_{s,r_i}|^2}{N_0}\right) \tag{8}$$

and

$$I_{MRC,r_i,d_j} = \frac{1}{2}\log_2\left(1 + \frac{P_{r_i}|h_{r_i,d_j}|^2}{N_0} + \frac{P_s |h_{s,d_j}|^2}{N_0}\right) \tag{9}$$

In the multi-user network under the condition of limitation of transmission power and bandwidth, the major aim is to achieve the maximum throughput for more users to use the system. Hence, the mathematical model for the multiple user environment could be expressed as

$$I_{Total} = \max_{\rho_{ij},\forall i,\forall j} \sum_{i=1}^{M}\sum_{j=1}^{N} \rho_{ij} \min\left\{\mathrm{I}_{s,r_i}, \mathrm{I}_{MRC,r_i,d_j}\right\} \tag{10}$$

To assign the appropriate relay station *i* to the destination *j* is to achieve the maximum mutual information in eq. (10). The pair assignment scheme is proposed in the following section.

3 Relay Selection Scheme

Under the above derivation, considering each destination station receives the signal from one relay station only, this work intends to find the pairs to match these N destination stations and the corresponding relay stations. Hence, the limitation to this problem could become

$$\max_{\rho_{ij,\forall i,\forall j}} \sum_{i=1}^{M}\sum_{j=1}^{N} \rho_{ij} \min\left\{ \mathrm{I}_{s,r_i}, \mathrm{I}_{MRC,r_i,d_j} \right\} \tag{11}$$

under the conditions

$$\sum_{i=1}^{M} \rho_{ij} = 1 \;, \forall\ j = 1,2,..,N \tag{12}$$

and

$$\sum_{j=1}^{N} \rho_{ij} \le 1 \;, \forall\ i = 1,2,...,M \tag{13}$$

$\rho_{i,j}$ is defined as the connection between relay station *i* to destination station *j*. In eq. (12), for each destination belonging to *D*, there is only one corresponding relay station connected to the destination station, $\rho_{i,j}$=1 when there is a connection between relay station *i* to destination station *j* and $\rho_{i,j}$=0 for other situations. In eq. (13), for each relay station belonging to *R*, the relay station could connect at most one destination station only.

According to the above equations related to the relay selection, the problem turns to find an optimal solution to the eq. (11) with the limitations of eq. (12) and eq. (13). To achieve the optimal solution to eq. (11), the exhaustive search method could be employed. With the exhaustive search method, the algorithm should begin to calculate eq. (8) and eq. (9).

Step 1, for each relay station *i*, calculate $|h_{s,ri}|^2$, $|h_{ri,dj}|^2$ and $|h_{s,dj}|^2$.

Step 2, calculate $I_{s,ri}$ and $I_{MRCri,dj}$.

Step 3, create an MxN array, calculate $I_{DF,(ri,dj)}$ in eq. (11) and recode in the MxN array such as

$i \backslash j$	d_1	d_2	…	d_N
r_1	$\min\{I_{s,r1},I_{MRCr1,d1}\}$	$\min\{I_{s,r1},I_{MRCr1,d2}\}$	…	$\min\{I_{s,r1},I_{MRCr1,dN}\}$
r_2	$\min\{I_{s,r2},I_{MRCr2,d1}\}$	$\min\{I_{s,r1},I_{MRCr2,d2}\}$	…	$\min\{I_{s,r2},I_{MRCr2,dN}\}$
⋮	⋮	⋮	⋱	⋮
r_M	$\min\{I_{s,rM},I_{MRCrM,d1}\}$	$\min\{I_{s,rM},I_{MRCrM,d2}\}$	…	$\min\{I_{s,rM},I_{MRCrM,dN}\}$

Step 4, iterative calculate the (*i*, *j*) combination for maximum value in eq. (11) under the limitation of eq. (12) and eq. (13). The optimal mapping for the relay station and destination station could be found with $C_N^M N!$ combination calculations.

It is with a high complicated computing to implement, although the solution is optimal. Specially, the computing complexity is high for the burst traffic arriving. It will cause a time delay in calculation. Hence, the optimal solution could not really be applied to the real time communications. In order to reduce the computational complexity, a suboptimal relay selection scheme with a greedy algorithm applied is proposed. The greedy algorithm benefits to quickly find the approximate optimal solution without a long time calculation [9]. It provides a straightforward way to approach the optimal problem. Also, it can be easy to understand. Consider the cooperative system mentioned above, the suboptimal Relay Selection scheme could be modified from the exhaustive search method and be given in the following.

Step 1, similarly, calculate $|h_{s,ri}|^2$, $|h_{ri,dj}|^2$ and $|h_{s,dj}|^2$ for all relay stations.

Step 2, create an MxN array, calculate $I_{DF,(ri,dj)}$ and recode in the array as same as the second step in the exhaustive search method.

Step 3, according to the array, assign the maximum value of $I_{DF,(ri,dj)}$ to the pair of relay station *i* and destination station *j*. Randomly choose one of maximum value to assign if there more than one maximum value appeared. Record the pair (*i*,*j*) to represent the i^{th} relay station is assigned to sever the j^{th} destination station. At the mean time, corresponding to the chosen cell, delete all other row cells in the array. It means the chosen relay station could not serve for other destination stations. Similarly, corresponding to the chosen cell, delete all other column cells in the array. It means the chosen destination is served by one relay station only. Then, a new reduced matrix is created.

Step 4, repeat step 3 till finishing the assignment work.

Step 5, according to the pair assignment, calculate the mutual information $I_{Total.}$

With different relay station selection schemes, exhaustive search method and the proposed one, the performance based on the throughput of system is evaluated for different numbers of destinations. Fig 3 and Fig. 4 show the channel capacity comparisons for different selection schemes and different number of relay stations and destinations, respectively.

In Fig. 3, while M=N=2, the results show there is no difference whether the scheme is with exhaustive research method or with the proposed algorithm. When the number of relay stations increases, the difference on the capacity lightly increases. This phenomenon by increasing the number of relay stations is existed because the relay selection patterns increases.

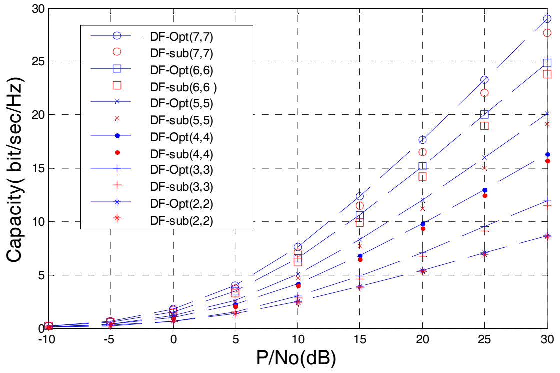

Fig. 3 Comparison to two different selection schemes

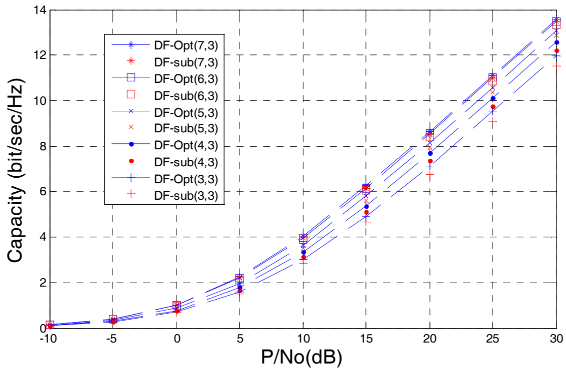

Fig. 4 Comparison to two different number of relay stations and destinations (M≠N)

For example, M=N=2, there are 2 selection patterns with exhaustive research method. It is as same as that the proposed algorithm does. So, there is no difference between these two algorithms. On the other hand, M=N=7, there are 7! (=5040) selection patterns with exhaustive research method. There are only 49 selection patterns with the proposed algorithm. These selection patterns are included in those with exhaustive research method. Unfortunately, the optimal solution does not fall in the patterns with the proposed algorithm. However, without complicated calculation to find the optimal solution, the proposed algorithm could achieve the approximate optimal solution with a less computing. It could be applied to the real-time voice and video applications.

In Fig. 4, the results show the capacity distribution according the variable number of relay stations with a fixed number of destination stations. One can tell that if the number of destination stations is closed to the number of relay stations, the numerical results with the proposed algorithm are much closed to the ones with exhaustive research method. Although both algorithms could obtain the similar results, exhaustive research method takes a long time calculation. However, comparing with the case of M=7 and the one of M=3, the significant difference is shown. It represents that when the number of relay stations increases, the more selections could be chosen. It is convenient for the proposed algorithm to find the best solution. At the mean time, the proposed scheme could spend a less time in computing comparing to that with exhaustive research method. Again, the proposed relay selection scheme benefits to real-time voice and video applications in the cooperative communications.

4 Conclusion

With a character of low cost, the cooperative communication system is a tendency in the future. In this application, the relay station works not only the amplifier but also the decode-coder. With the error correction capacity, it provides a function of repeater in the multi-user environment. For the purpose of analysis, the source-relay, relay-destination, and source-destination mutual information is derived. With a high SNR, coding scheme working well, the capacity is considered under the worst case. Hence, the theoretical mutual information in the system is based on the maximization the worst capacity cases. However, the pair matching of the corresponding relay station and destination station becomes complex if the number of relay stations and destination stations increases. Although the exhaustive search method could achieve the optimal solution to the problem, the computing complexity could be the difficulty. This paper uses the numerical results to show the efficiency of the proposed relay selection scheme. By the way, the proposed scheme could be appropriately applied to the real-time and voice communications with a cooperative system..

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