ARQ Based Joint Relay Selection and Cooperative Protocol Switch Cooperative Scheme

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Abstract—In this paper, we investigate the ARQ technology based wireless cooperative network, which can improve the spectral efficiency and decrease the collision probability. With the application of channel estimation, the source and the relays in our scheme can decide the best terminal and the optimal cooperation protocol by their timers. Comparing to opportunistic relay selection (ORS), the spectral efficiency and collision probability could be improved. Meanwhile, comparing to Incremental Transmit Relay Selection (ITRS), the new scheme benefits from AF cooperative protocol and obtains more power gains, it is also more robust to the networks topology. Additionally, the complexity in the destination becomes lower.

Index Terms—Automatic repeat-reQuest (ARQ), spectral efficiency, collision probability, outage probability.

I. INTRODUCTION

The proposal of cooperative diversity has broken up the bottleneck effect in the application of multiple input multiple output (MIMO) technology, such as the limitations in the terminal size, the system cost and the power consumption. Cooperative communication can realize virtual multiple antennas, which not only sufficiently improves the whole system robustness by using the spatial and temporal diversity gains of the distributed single-antenna terminals [1][2], but also considers the broadcast property of wireless channel. Therefore, the distributed joint optimization among the node selection, the cooperative protocol and the power allocation scheme can achieve more improvement in the system performance. However, cooperative system also has its own deficiencies. It is different from MIMO system, where a terminal can be equipped with multiple antennas and use half-duplex mode. For a cooperative system, it must use one time slot to broadcast the signals to the relays, which decreases the system efficiency, especially the spectral efficiency. Meanwhile, the destination terminal, according to the broadcast signals, decodes the signals correctly with certain probability. In this case, if the relays also retransmit the received signals, the freedom degree and the resources of wireless channel will be extremely wasted.

Automatic repeat-reQuest (ARQ) protocol belongs to data link layer in OSI model, which requires the destination sends ACK or NACK signaling to notify the source node whether the signals are decoded correctly or not. For traditional point to point communication with ARQ technology, when the destination can not correctly decode the signals, it sends NACK signaling to tell the source retransmit the signals. However, owing to the serious channel deterioration affected by the burst error or memorial channel, there always exists a bad channel between the source and the destination sometime, so the source has to retransmit the same signal to the destination continuously. Therefore, in cooperative communication, ARQ technology can significantly decrease the probability of source retransmission and overcome the deficiency of cooperative system, such as the improvement of spectral efficiency, that is, if and only if the destination node can not decode the signals correctly, the system will admit the transmission in the relays.

Considering the typical three nodes cooperative model, the system robustness can be improved through the consideration of direct transmission (DT), amplified and forward (AF) protocol, decode and forward (DF) protocol or a hybrid scheme with each other. With the average power allocation scheme and the optimized power allocation scheme, the cooperative system can adaptively switch the cooperative protocol according to the received signal to noise ratio (SNR) in relay [3]. As a matter of fact, in this paper, the hybrid scheme combining DF with AF will obtain extra performance gains. On the other hand, considering the network model, the spatial gains can be improved through the selection of cooperative node based on the distance, the instantaneous SNR and the maximal system volume. In [4]-[6], the relay estimates the channel gains according to ready to send (RTS) and clear to send (CTS) signaling in MAC layer from the source and the destination, respectively, and then starts the timer. The ‘best’ relay can be obtained whose timer has the smallest value. This relay selection scheme is called the opportunistic relay selection (ORS). Additionally, [7] proposes an incremental transmission relay selection (ITRS) scheme which increases the spectral efficiency employs with finite feedback information from the destination and the combination with DF protocol. The performance gains benefit from the protocol switch in the relay which decodes correctly and the source retransmission.
with ARQ technology. In this paper, we mainly take the low-cost distributed network into consideration, for example the wireless sensor network. Based on the previous works [8][9], which analyzed the outage probability in different cooperative scenarios, here we focus on the cooperative system which adopts the ARQ technology. Our joint optimization scheme in relay selection and cooperative protocol switch can increase the system spectral efficiency, obtain more performance gains and decrease the collision probability of the cooperative network.

The remaining parts of the paper are organized as follows. Section II introduces the system model and the analysis of channel capacity. The new relay selection scheme and the corresponding system analysis with protocol switch are presented in Section III. Section IV provides the numerical results. In the end, the conclusions are drawn in Section V.

II. SYSTEM MODEL AND CHANNEL CAPACITY

A. Cooperative System Model

In cooperative system, we always assume that there are two time slots in each terminal used to transmit the signals from the source, broadcast slot and cooperative slot. During these two time slots, the terminal transmits its own information. As described in Fig.1, during the broadcast slot, the source \( S \) synchronously transmits the information signal \( X_s \) to the relays \( R \) and the destination \( D \). In the cooperative slot, the best relay can be selected with the relay selection scheme and it forwards \( X_s \) which is decoded by the best relay to the destination. In this paper, we assume that the channels between any two terminals are independent identically distributed (iid) following the quasi-static flat Rayleigh distribution. We define that \( \alpha_{i,j} \) stands for the fading coefficient between terminal \( i \) and terminal \( j \), which can be expressed as \( \alpha_{i,j}^2 = |h_{i,j}|^2K\beta d_{i,j}^\beta \), where \( h_{i,j} \) is the channel fading coefficient between terminal \( i \) and terminal \( j \), \( K \) is the power loss coefficient related to the reference distance \( d \), \( S \) is the shading effect subject to the log-normal distribution, \( d_{i,j} \) is the ratio of the distance between two terminals to the reference distance \( d \), \( \beta \) is the path loss exponential whose value varies from 2 to 4. Additionally, the receiver is also influenced by additional Gaussian white noise (AWGN) with zero mean and variance \( N_0 \). To simplify the analysis, the synchronization, feedback information and channel estimation are assumed to be ideal.

With the transmission of \( X_s \) from the source, the relay and the destination node obtain the received signals as \( r(t) \) and \( d(t) \), respectively,

\[
r(t) = a_{s,r}X_s + n(t),
\]

from \( S \) to \( D \) (DT) : \( d_1(t) = a_{s,d}X_s + n_1(t), \)

from \( R \) to \( D \) (DF) : \( d_2(t) = a_{r,d}X_s + n_2(t), \)

from \( R \) to \( D \) (AF) : \( d_3(t) = a_{r,d}X_s + n_3(t), \)

where \( X_s \) stands for the symbol which relay decodes from the original symbol \( X_s \) transmitted by the source node with AF protocol.

B. Channel Capacity Analysis

We assume that the source and the relays all use the same Gaussian code book. Let \( C(\gamma) \) denotes the channel capacity between the transmitter and the receiver. According to the channel capacity formula in AWGN channel deduced by Shannon, the channel capacity for flat Rayleigh fading channel can be written as follows,

\[
C(\gamma_{i,j}) = \log(1 + |\alpha_{i,j}|^2SNR),
\]

where \( SNR = P/N_0 \), \( P \) is the power for each terminal, \( N_0 \) is the normalized power spectral of white Gaussian noise. \( \gamma_{i,j} \) is the instantaneous SNR received by the terminal \( j \) from the terminal \( i \), which is expressed as,

\[
\gamma_{i,j} = |\alpha_{i,j}|^2SNR.
\]

Additionally, the signals transmitted through the direct path in the broadcast slot are also taken into account. The direct transmission, the source retransmission (SRT), the AF scheme and the DF scheme leading to different channel capacity are analyzed as follows,

1) Case of DT: The system can be considered as a single input single output (SISO) model. Its channel capacity can be calculated as,

\[
C_{DT} = \log(1 + \gamma_{s,d}) = \log(1 + |a_{s,d}|^2SNR).
\]

2) Case of DT with SRT: The destination can not decode the signals correctly at first time, the channel capacity is expressed as,

\[
C_{SRT} = \frac{1}{2} \log(1 + \gamma_{s,d} + \gamma'_{s,d})
= \frac{1}{2} \log(1 + |a_{s,d}|^2SNR + |a'_{s,d}|^2SNR),
\]

where \( \alpha'_{s,d} \) denotes the fading coefficient in the cooperative time slot from the source to the destination and \( \gamma'_{s,d} \) is the corresponding received SNR in the destination.

3) Case of DT with AF: The relay receives the signals and linearly amplifies the signals to send, the channel capacity is obtained as,

\[
C_{AF} = \frac{1}{2} \log(1 + \gamma_{s,r} + f(\gamma_{s,r},\gamma_{r,d}))
= \frac{1}{2} \log(1 + \{ |a_{s,d}|^2 + f(|a_{s,d}|^2,|a_{r,d}|^2) \} SNR).
\]
III. NEW RELAY SELECTION SCHEME BASED ON ARQ TECHNOLOGY AND PERFORMANCE ANALYSIS

In this paper, we assume that there exists a network with one source node, one destination node and $M$ relay nodes in the cooperative system. The diagram of the relay selection scheme with ARQ protocol is shown in Fig.2. Let the information bit rate be $R$ and the set of the relays which can decode correctly is $S_k$, with the cardinality $|S_k| = k$ for $k \in \{0, 1, ..., M\}$.

A. New Relay Selection Scheme

In this cooperative system, we assume that ARQ signaling always can be obtained without error and there is no delay. The new relay selection scheme is proposed as follows,

1) The source sends the information to the destination and the relays overhear it through the wireless channel considering the broadcast case. Then, the receiver employs the coherent detection to decode the information and use cyclic redundancy check (CRC) to judge whether the decoding is correct or not.

2) For the destination node, there exit two conditions,
   - The decoding of the received signals is correct. Then, the destination broadcasts ACK signaling and notifies the source to send next information frame and lets the relays flush their register buffer.
   - The decoding of the received signals is wrong. Then, the destination broadcasts NACK signaling and the cluster training sequence. The source and the relays estimate the CSI through the received NACK signaling and obtain the corresponding channel gains $|a_{s,d}|^2$ and $|a_{r,d}|^2$, respectively.

3) With the new relay selection protocol, the source and the relays will start their timers synchronously.

4) The source and the relays whose timer first expires to zero will send the RTS signaling to the destination, then handshakes with the destination and receives the CTS signaling from the destination to acknowledge, and finally forwards the information. The destination will combine the received signals in two slots to detect and decode the original signals.

The relay selection protocol mentioned above can be expressed as,

$$
\Lambda = \max\{|a_{s,d}|^2 (i \in S_k), |a'_{s,d}|^2, \frac{|a_{s,d}|^2 + |a'_{s,d}|^2}{1 + |a_{s,d}|^2 + |a'_{s,d}|^2} (j \notin S_k \cap j \in M)\}. \quad (11)
$$

We set the initial value of the timer to be $T_i = \frac{\lambda}{3}$ms, $\lambda$ is just a variable which is the times of the timer’s resolution and depends on the timer’s unit time and the channel gains.

B. Outage Probability Analysis

Let $\tau = \left(\frac{2^M-1}{SNR}\right)^{\frac{1}{M}}$, following the previous analysis, we can obtain the channel capacity of the new scheme as,

$$
C_{New} = \frac{1}{2} \log \left[1 + \max\{|a_{s,d}|^2 (i \in S_k), |a'_{s,d}|^2, \frac{|a_{s,d}|^2 + |a'_{s,d}|^2}{1 + |a_{s,d}|^2 + |a'_{s,d}|^2} (j \notin S_k \cap j \in M)\}\right], \quad (12)
$$

where $|S_k| = k$, $k \leq M$.

Assuming $\rho_1$, $\rho_2$, $\rho_3$ to be the variance of channel fading coefficients from the source to the destination, from the source to the relays and from the relays to the destination, respectively, we can obtain the outage probability that $k$ relays can correctly decode the original signal as,

$$
P_{Outage} = \frac{Pr\{\log(1 + |a_{s,r}|^2 \cdot SNR) \geq R\}}{Pr\{\log(1 + |a_{s,r}|^2 \cdot SNR) < R\}}^k \cdot \left(1 - \exp\left(-\frac{\tau \rho_1}{\rho_2}\right)^2 \cdot \left(1 - \exp\left(-\frac{\tau \rho_2 + \rho_3}{\rho_2}\right)ight) \cdot \left(1 - \exp\left(-\frac{2\tau \rho_2 + \rho_3}{\rho_2}ight) + \exp\left(-\frac{2\tau \rho_2 + 3\rho_3}{\rho_2}\right)\right)^M\right). \quad (14)
$$

C. Collision Probability Analysis

In this scheme, there exists a problem incurred due to the application of the distributed timers. That is, during the unit time (timer’s resolution), if there are two or more cooperative terminals intending to retransmit the information as the relays, while at this time, the destination will consider the signals
form the other terminals as noise comparing with the 'best' relay, then degrades the performance of the whole system. In a word, when we design the relay selection scheme in this cooperative network, the collision probability is a key issue for the system performance. Herein, for the space limitation of this paper, we will directly employ the collision model introduced in [4] and compare this scheme with the opportunistic relay selection scheme in the case of DF cooperative protocol. If the destination cannot decode correctly according to the signals from the direct path, then the system will start to make the relay selection. During the time interval $c$, we assume that there are two or more terminals whose timers expire to zero, then the collision will appear (every terminal is not hidden from each other in this network). The value of $c$ can be expressed as,

$$c = r_{\text{max}} + |n_b - n_j|_{\text{max}} + d_s,$$  \hfill (15)

where $r_{\text{max}}$ is the maximal propagation delay and $|n_b - n_j|_{\text{max}}$ is the difference of the maximal propagation delay between the maximal propagation delay from terminal $b$ to the destination and that from terminal $j$ to the destination, $d_s$ is the processing time from the signal receiving to the signal transmitting which depends on the hardware device. Let the 'best' relay be $b$, then, the collision probability is calculated as,

$$P_{\text{collision}} = \Pr\{\text{any}T_j < T_b + c|j \neq b\} \equiv \Pr\{Y_2 < Y_1 + c\},$$  \hfill (16)

where $T_i$ stands for the value of timer in terminal $i$. For the M terminals in this network, we assume $T_b = \min\{T_i\} = Y_2$ and $Y_2$ is the second minimal value in sequence $\{T_i\}$. According to Theorem 1, Lemma 1 and equations (12), (13) in [4], we can get that,

$$P_{\text{collision}} = \Pr\{Y_2 < Y_1 + c\}
= 1 - M(M-1) \int_{e^{-\infty}}^{\infty} f(y)[1 - F(y)]^{M-2} F(y-c) dy. \hfill (17)$$

Following the proposed scheme, we obtain the probability distribution function in Rayleigh channel as shown in [4], its cumulative distribution function can be obtained as,

$$F(t) = \exp(-\frac{\rho \lambda t}{t}). \hfill (18)$$

The probability density function is,

$$f(t) = \frac{\rho \lambda}{t^2} \exp(-\frac{\rho \lambda t}{t}), \hfill (19)$$

where $\rho$ is the variance of the channel fading coefficients. The collision probability of this cooperative system can be written as,

$$P_{\text{collision}} = \Pr\{I_{\text{DT}} < R\} \bigcap \{Y_2 < Y_1 + c|I_{\text{DT}} < R\}
= \Pr\{I_{\text{DT}} < R\} \cdot \Pr\{Y_2 < Y_1 + c|I_{\text{DT}} < R\}
= \Pr\{I_{\text{DT}} < R\} \cdot \sum_{k=0}^{M} \Pr\{Y_2 < Y_1 + c|S_k = k\}
\cdot \Pr\{|S_k| = k\}
\geq 1 - (M+1) M \int_{e^{-\infty}}^{\infty} \frac{\lambda}{t^2} \exp(-\frac{\rho \lambda t}{t})[1 - \exp(-\frac{\rho \lambda t}{t})]^{M-1} \exp(-\frac{\rho \lambda t}{t}) dt \cdot \Pr\{I_{\text{DT}} < R\}, \hfill (20)$$

Fig. 3 shows the comparison of the outage probability between our scheme and the ITRS scheme considering the four cooperative topologies. As Fig. 3 describes, for the four network topologies, the advantages of the new scheme is not significant compared with ITRS scheme which is the optimal outage probability case. We can still have about $0.5 \text{dB}$ in case (d), about $0.2 \text{dB}$ in case (b). In the case of (a) and (c), the performance is similar. But there are two obvious merits for the proposed scheme, the low requirement of the calculation ability in the destination and almost the same complexity of the whole network. Additionally, in low SNR region, considering the limitation of the terminals’ power, network topology (d) has the best performance followed by (b), (c), and (a), but

Note: In this scheme, if there are collision issues for many terminals and the destination could select the 'best' relay and send CTS signaling with relay ID, then the collision will be avoided. But in this condition, the complexity of the cooperative network will increase.

IV. NUMERICAL RESULTS

In this section, we present the simulation results. Outage probability and collision probability of the new scheme are provided comparing with ORS and ITRS scheme, respectively. We assume that the distance between the source and the destination is $d$ and the path loss has exponential $\beta = 2$. Let $E(|\alpha_{s,d}^2|) = K d_{s,d}^{-\beta} = 1$, and $d_{s,r}, d_{r,d}$ represent the distances from the source to the relay and from the relay to the destination, respectively. Then the ratio of the variance of the channel fading coefficients is expressed as $\rho_{s,r} : \rho_{r,d} : \rho_{s,d} = d_{s,r}^2 : d_{r,d}^2 : 1$. There are four cooperative network topologies considered as follows,

- Topology a: $\rho_{s,r} : \rho_{r,d} : \rho_{s,d} = 1 : 1 : 1$
- Topology b: $\rho_{s,r} : \rho_{r,d} : \rho_{s,d} = 4 : 4 : 1$
- Topology c: $\rho_{r,d} : \rho_{s,d} = 16 : \frac{10}{9} : 1$
- Topology d: $\rho_{r,d} : \rho_{s,d} = \frac{16}{9} : 16 : 1$

Fig. 3 shows the comparison of the outage probability between our scheme and the ITRS scheme considering the four cooperative topologies. As Fig. 3 describes, for the four network topologies, the advantages of the new scheme is not significant compared with ITRS scheme which is the optimal outage probability case. We can still have about $0.5 \text{dB}$ in case (d), about $0.2 \text{dB}$ in case (b). In the case of (a) and (c), the performance is similar. But there are two obvious merits for the proposed scheme, the low requirement of the calculation ability in the destination and almost the same complexity of the whole network. Additionally, in low SNR region, considering the limitation of the terminals’ power, network topology (d) has the best performance followed by (b), (c), and (a), but
considering from the coverage of the system, network topology (a) has the largest coverage.

As we know that ORS scheme is the optimal collision probability case. The collision probability comparison between the proposed scheme and ORS scheme for different network topologies is shown in Fig.4 considering SNR being 6.0dB and 12.0dB. As seen from Fig.4, when SNR is 6.0dB, the collision probability of the proposed scheme outperforms the ORS scheme significantly for the network topology (c) and (d). Even for the topology (b) and (a), with the increase of the relay nodes, their collision probabilities will reach those of the ORS scheme. When SNR is 12.0dB, the proposed scheme has an obvious advantage in the case of network topology (a), (b) and (d). For the poor performance in network topology (c), the reason is that the small distance between the relay and the source causes the variances of the channel fading coefficients for the relay and the destination are similar, which increases the collision probability of RTS signaling between the source and the relays. In a word, we know that the proposed scheme has better robustness for different network topologies, which not only obtains the better outage probability, but also decreases the collision probability of the relays.

V. CONCLUSIONS

In this paper, we consider the relay selection and the cooperative protocol adaptive switch inherently under ARQ technology, a new joint optimization scheme is proposed. The proposed scheme considers the network spatial gains induced by the relay selection and the system gains induced by the cooperative protocol switch together, which increases the spectral efficiency with ARQ technology and also decreases the information handshaking collision probability among distributed terminals. Additionally, the better outage probability can be obtained. Simulation results and theoretical analysis show the efficiency and robustness of the proposed scheme for different network topologies.

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