

Adaptive Cooperation via Relay Selection with Improved Diversity-Multiplexing Tradeoff

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Abstract—Cooperative communication has been recently proposed as a way to improve the performance of wireless communication. However, due to the half duplex constraint, most of the relay networks face a fundamental challenge in terms of multiplexing loss. In this paper, we present an adaptive cooperation via relay selection (ACRS) protocol that improves spectral efficiency. This protocol lets the source transmit most of the time and always allows source transmission to be forwarded only by the best transmitter available (maybe source itself) if needed. ACRS has the feature of adapting the system to the fluctuation of the wireless channel and trying to make a packet transmission finished in just one time slot. The diversity-multiplexing tradeoff (DMT) is used to show a remarkable improvement over previous relaying schemes. Simulation results are presented to verify our analysis.

I. INTRODUCTION

Recently, there is a growing interest in various forms of cooperative communication protocols that provide diversity and multiplexing gain for communication via wireless relays [1]. Also, relay is considered for Long Term Evolution-Advanced (LTE-A) as a tool to improve e.g. the coverage of high data rates, group mobility, temporary network deployment, the cell-edge throughput [2]. In practical implementation, relay selection is a useful cooperative technique since it only activates the best relay to forward source information to the destination. Apart from simplicity of signaling, relay selection avoids complex synchronization schemes (needed by most distributed space-time coding schemes) and reduces the power consumption of the terminals.

Compared to other multiple relay schemes, such as distributed space-time codes (DSTC) in [3], the opportunistic relaying (OR) achieves full diversity order while greatly reduces the complexity [4]. It was shown that the same diversity-multiplexing tradeoff (DMT) performance as OR can be achieved via very little information exchange [5]. In [6], Beres and Adve proposed the selection cooperation scheme. Recently, Sun [7] proposed a novel relay selection scheme combined with feedback and adaptive forwarding in cooperative communication systems. The above decode-and-forward (DF) protocols, as shown by the DMT curves in the following, are not suitable in the high rate regimes, which motivates our work.

In this paper, we propose a relay selection protocol called adaptive cooperation via relay selection (ACRS). This protocol

lets the source transmit most of time and only if the direct link transmission fails, the best transmitter would be called upon to forward the source packet. Whenever the direct link is in outage occasionally, ACRS would turn into a two-hop fashion as OR, making a great loss in spectral efficiency. But if this outage lasts for many times slots, ACRS will try to make each packet transmission finished in less than two time slots, for the purpose of compensating the loss in spectral efficiency. An adaptive method is introduced to make sure that the system could perfectly respond to any kind of situation. So the key feature of the proposed protocol is that the system can adapt to the fluctuation of the wireless channel and try to make a packet transmission finished in just one time slot. As shown in the paper, ACRS achieves better DMT performance over previous DF method across a large range of spectral efficiencies. We will also show by simulation results that ACRS outperforms OR in terms of outage performance.

The rest of the paper is organized as follows. The corresponding system model is presented in Section II. In Section III, we introduce our proposed adaptive cooperation protocol ACRS. After that, the DMT performance of ACRS is analyzed and compared with other relay selection schemes in Section IV. Simulation results of ACRS are presented in Section V. Finally, in Section VI, the summary and conclusions of this paper are presented.

II. SYSTEM AND CHANNEL MODELS

The system model consists of one source (S), one destination (D), and K_R half-duplex relays (\mathcal{R}_i for $i = 1, \dots, K_R$) as depicted in Fig. 1. Each node is equipped with a single antenna. The direct link exists between source and destination. It is assumed that there is a reliable feedback channel that can be used for relay selection from the destination to relays and the source. Aside from this, no transmit side channel state information (CSI) is available to the network nodes but receive side CSI availability is assumed.

The channel h_{ij} between nodes i and j is described by a flat, quasi-static Rayleigh fading model with variance $1/\lambda_{ij}$. Thus, the effective instantaneous channel gain g_{ij} is exponential random variable with mean λ_{ij} . The channel between different nodes are assumed independent. Transmit power at source and relays is limited by an average power constraint P . The additive noise at each receiver is modeled as zero mean,

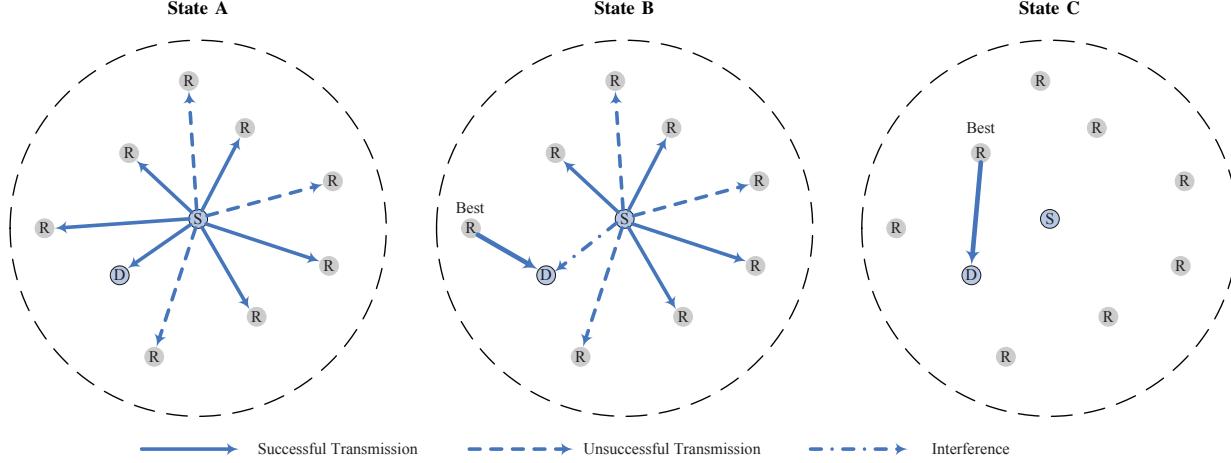


Fig. 1. State A: Source broadcasts to the other nodes. State B: The best relay forwards its decoded packet to destination while source broadcasts a new packet. State C: The best successful relay forwards alone to destination.

complex Gaussian random variable with variance N_0 . The average receive signal-to-noise ratio (SNR) at each receiver is given as $\rho = P/N_0$.

The diversity-multiplexing tradeoff [8] and outage probability [9] are used to evaluate the performance of the proposed protocol. Consider a family of codes $C(\rho)$ operating at SNR ρ and with rate $R(\rho)$. If $P_{out}(\rho)$ is the outage probability of the channel for rate R , then the channel is said to achieve multiplexing gain r and diversity order d :

$$r \triangleq \lim_{\rho \rightarrow \infty} \frac{R(\rho)}{\log(\rho)} \quad d \triangleq - \lim_{\rho \rightarrow \infty} \frac{\log P_{out}(\rho)}{\log(\rho)}. \quad (1)$$

In the following, a function $f(\rho)$ is said to be exponentially equal to ρ^a , denoted by $f(\rho) \doteq \rho^a$, if

$$\lim_{\rho \rightarrow \infty} \frac{\log(f(\rho))}{\log(\rho)} = a. \quad (2)$$

III. ADAPTIVE COOPERATION VIA RELAY SELECTION

In this section, we present a protocol for a multiple-relay network with limited feedback, called ACRS.

It has been well-known that repeating the source transmission limits the spectral efficiency when the direct link between source and destination is unavailable. So the work in this section shows that one may recover most part of rate loss with the protocol which could adapt to instantaneous channel conditions of the direct link.

Throughout this work, we define the best transmitter (r_i^*) as source or the relays with the highest instantaneous channel gain to the destination. If S is not the best transmitter ($r_i^* \neq s$), a channel gain ratio, which is denoted by b ($b \in (0, 1)$), is introduced to compare the instantaneous channel conditions of $S-D$ with r_i^*-D . When S is not the best transmitter and the channel gain of $S-D$ is small enough ($r_i^* \neq s \cap (g_{sd} < bg_{r_i^*d})$), r_i^* could forward one packet to D while S broadcasts another packet, the destination decodes the packet from r_i^* and can peel-off the interference signal from the source broadcasting. Note that b will not affect the DMT results.

In this protocol, we use the notation $D(s)$ [3] to denote the set of relays that can decode the packet of source successfully while n is set as a constant. If $|D(s)| > n$, we hold that there are enough relays for selected if needed. This means that at least n relays are available at any time slot, ensuring the minimal diversity order.

As shown in Fig. 1 and Fig. 2, the overall communication process of ACRS can be expressed as follow:

- 1) State A stands for that source broadcasts a packet alone in the network.
At State A, if the destination successfully decodes the packet, it broadcasts an ACK and system returns to State A. Otherwise, destination broadcasts a NACK and system steps into the transient state State O.
- 2) At State O, the relays in $D(s)$ and source declares their status via one-bit ready-to-send (RTS) packet.
Upon the RTS, destination estimates channel gains, and picks up the best transmitter (r_i^*) from among source and successful relays and then broadcasts the index of the best transmitter. And if $(r_i^* \neq s) \cap (g_{sd} < bg_{r_i^*d}) \cap (|D(s)| > n)$, the destination broadcasts one-bit packet N and system steps into State B, otherwise, Y and system steps into State C.
- 3) State B represents that the best relay (must not S) forwards its decoded packet to destination, at the same time source broadcasts a new packet. The destination decodes the packet from r_i^* while relays try to decode new source packet in the presence of interference. Then the system return to State O with probability of 1, which is expressed by $P=1$. The best relay in this state will be in outage in all the following time slots.
- 4) State C means that the best transmitter (maybe S) forwards its decoded packet alone to destination. Then the system return to State A.

Notice that all states except State O take one time slot and system shifts among states base on the control information

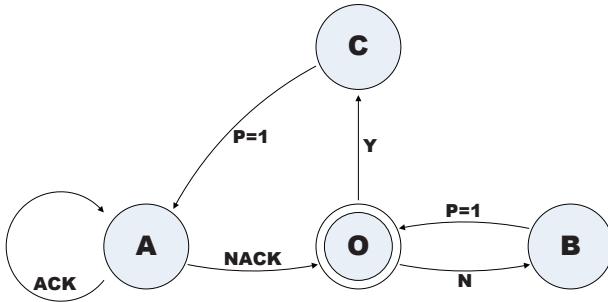


Fig. 2. The state transition diagram of the system.

such as Y or N and ACK or NACK.

ACRS begins at State A, and when it returns to State A, we denote it as a cycle. As shown in Fig. 2, there are three possibilities of one cycle in the system:

- 1) The first one is cycle A-A, denoted by Cycle \mathcal{R} .
- 2) The second one is cycle A-O-C-A, which is called Cycle \mathcal{P} .
- 3) The third one is cycle A-(O-B)_mO-C-A, denoted by Cycle \mathcal{Q} , where (O-B)_m stands for m consecutive times of O-B-.

The channel gains are assumed to remain constant during State O-B and State O-C.

ACRS includes source in the competition for the retransmission, thus improving the diversity order. In Cycle \mathcal{R} and \mathcal{P} , a packet transmission lasts for less than two time slots. This improves the spectral efficiency.

Notice that in Cycle \mathcal{Q} , due to the half-duplex constraint, whenever a relay is selected to forward, it cannot receive. Hence, in the following time slots, it is operating at a disadvantage because it cannot peel-off the interference signal from the source transmission. Thus, many relays fail in decoding immediately after transmission. At the end of a cycle, the best transmitter (maybe source) transmits alone without any interference so that last packet can be cleared to the destination.

The limited feedback in the proposed protocol has two usage: it feedbacks the index of best transmitter and also enables retransmission (HARQ). The ACRS protocol requires $1 + \frac{\log(K_R+1)}{K_R+1} [1 - \exp(-\frac{2^{R-1}}{\rho \lambda_{sd}})]$ bits of overhead per transmitting node per packet.

IV. PERFORMANCE ANALYSIS

For an entire packet transmission from source to destination, the mutual information of various states are as follows.

The mutual information across $\mathcal{S} - \mathcal{D}$ channel in State A can be written as

$$I_A = \log(1 + \rho g_{sd}). \quad (3)$$

If system enters into State C from State A-O, which means the best transmitter (maybe \mathcal{S}) is asked to retransmit its decoded packet after the direct link transmission failed in State A, the mutual information of the equivalent channel between source and destination is

$$I_{AOC} = \frac{1}{2} \log(1 + \rho(g_{sd} + g_{r_i^*d})). \quad (4)$$

On condition that the system enters into State B from State A-O, which means the best transmitter (must not \mathcal{S}) is requested to forward its decoded packet under the interference of source broadcasting a new packet, the mutual information of the equivalent channel is given by

$$I_{AOB} = \frac{1}{2} \log\left(1 + \rho g_{sd} + \frac{P g_{r_i^*d}}{N_0 + P g_{s^*d}}\right) \quad (5)$$

where g_{s^*d} means the channel gains of $\mathcal{S} - \mathcal{D}$, when the new packet broadcasted from \mathcal{S} . This new packet is seen as interference at destination.

When system stays in State B for more than one time slot, the mutual information of the relay channel is as follow:

$$I_{BOB} = \log\left(1 + \frac{P g_{r_i^*d}}{N_0 + P g_{s^*d}}\right). \quad (6)$$

At the end of Cycle \mathcal{Q} , the system would enter into State C from State B-O, whose mutual information is

$$I_{BOC} = \log(1 + \rho g_{r_i^*d}). \quad (7)$$

A. DMT of Cycle \mathcal{P}

In the following, we use $(x)^+$ to stand for $\max\{x, 0\}$.

Theorem 1. *The Cycle \mathcal{P} achieves the following DMT:*

$$d_{CY\mathcal{P}}(r) = (K_R + 2)^+(1 - 2r)^+ \quad (8)$$

which is equivalent to the DMT of OR with $K_R + 1$ relays [10].

Proof: Suppose that we select a code with rate $R = r \log \rho$. The probability of outage can be expressed as

$$\begin{aligned} P_{out,CY\mathcal{P}} &= \sum_{t=0}^{K_R} \Pr\{I_{AOC} < R | I_A < R, |D(s)| = t\} \\ &\quad \times \Pr\{I_A < R\} \times \Pr\{|D(s)| = t\} \\ &= \sum_{t=0}^{K_R} \Pr\{I_{AOC} < R | |D(s)| = t\} \times \Pr\{|D(s)| = t\}. \end{aligned} \quad (9)$$

To have exactly t correctly decoding relays, $K_R - t$ relays must be in outage. The probability is given by [3]:

$$\begin{aligned} \Pr\{|D(s)| = t\} &= \left(\frac{K_R}{t}\right) \exp\left(-\frac{2^{2R} - 1}{\lambda_{si}\rho}\right)^t \\ &\quad \times \left[1 - \exp\left(-\frac{2^{2R} - 1}{\lambda_{si}\rho}\right)\right]^{K_R-t} \\ &\doteq \rho^{(K_R-t)(2r-1)}. \end{aligned} \quad (10)$$

Therefore, the outage probability conditioned on the decoding set is as follow:

$$\begin{aligned} &\Pr\{I_{AOC} < R | |D(s)| = t\} \\ &= \Pr\left\{\frac{1}{2} \log(1 + \rho(g_{sd} + g_{r_i^*d})) \leq r \log \rho | |D(s)| = t\right\} \\ &\leq \Pr\{g_{sd} \leq \rho^{2r-1} | |D(s)| = t\} \times \Pr\{g_{r_i^*d} \leq \rho^{2r-1} | |D(s)| = t\} \\ &\doteq \rho^{(t+1)(2r-1)} \\ &= \rho^{(t+2)(2r-1)}. \end{aligned} \quad (11)$$

Substituting (10) and (11) into (9), we get (8) ■

It is noted that in this cycle, if the direct link fails, the best transmitter for retransmission could be the source itself. This guarantees even if no relay decodes the source packet successfully, source itself could retransmit the packet, leading one more diversity order over conventional OR [5].

B. DMT of Cycle Q under Successive Cancellation Decoding

In Cycle Q , we use successive decoding method at the relays. The scheme is based on successive cancellation. The key feature in successive cancellation is that, after each relay transmission, due to interference, it cannot recover its own decoding diversity order, therefore it cannot contribute to the overall diversity order any longer. It is observed that across time, a family of DMT curves with varying diversity order are produced.

Theorem 2. For Cycle Q under successive cancellation decoding at relays, the following DMT is achievable for the packet c , where $|D(s)| = K_R - c + 1 \geq n$, $c \in \{1, \dots, K_R - n + 1\}$.

$$d_{C_{yQ}}(r, c) = (K_R - c + 1)^+ \left(1 - \frac{K_R - n + 2}{K_R - n + 1} r\right)^+. \quad (12)$$

Proof: The outage can be expressed as

$$\Pr\{I_{BOB} < R\} = \sum_{t=n}^{K_R} \Pr\{I_{BOB} < R \mid |D(s)| = t\} \times \Pr\{|D(s)| = t\}. \quad (13)$$

The probability that t relays successfully decode the source packet at the beginning of Cycle Q is given by [11]

$$\Pr\{|D(s)| = t\} \doteq \rho^{(K_R-t)(r-1)}. \quad (14)$$

Subsequently, a relay is chosen as r_i^* to forward its decoded packet while source broadcasts a new packet. Based on successive cancellation decoding, this relay will lose its diversity for all the following slots, until the end of the cycle. Then, the number of available relays will be reduced one by one. Therefore, for packet c , the probability that there are t relays could forward the packet in Cycle Q can be written as

$$\Pr\{|D(s)| = t\} \doteq \rho^{(K_R-c-t+1)(r-1)}. \quad (15)$$

Conditioned on the decoding set, the destination outage is expressed by [3]

$$\begin{aligned} \Pr\{I_{BOB} < R \mid |D(s)| = t\} &= \left(1 - \exp\left(-\frac{2^R - 1}{\rho \lambda_{r_i^* d}}\right)\right)^t \\ &= \left(1 - \exp\left(-\frac{\rho^{r-1}}{\lambda_{r_i^* d}}\right)\right)^t \\ &\doteq \rho^{t(r-1)}. \end{aligned} \quad (16)$$

Combining (15) and (16), the outage probability is

$$\Pr\{I_{BOB} < R\} \doteq \rho^{(K_R-c+1)(r-1)}. \quad (17)$$

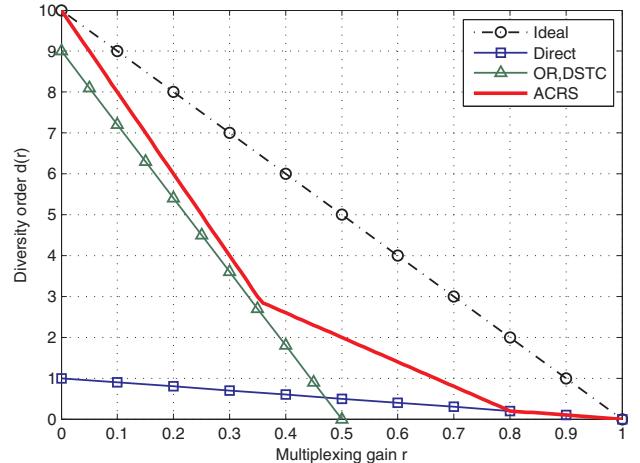


Fig. 3. DMT of different protocols with eight relays.

Finally, we must take account of a fractional rate loss, because in Cycle Q , overall $K_R - n + 1$ packets are transmitted in $K_R - n + 2$ time slots, due to the outage in the first time slot. Accordingly, we have to make the adjustment $r \rightarrow \frac{K_R-n+2}{K_R-n+1}r$. Therefore the DMT of Cycle Q can be expressed as Theorem 2. ■

However, we may not be interested in a multiplicity of DMT, the diversity order across different time slots should be dominated by the smallest one, i.e.,

$$d_{C_{yQ}}(r) = \min_c d_{C_{yQ}}(r, c) = (n+1)^+ \left(1 - \frac{K_R - n + 2}{K_R - n + 1} r\right)^+. \quad (18)$$

Note that for packet $c = K_R - n$, the diversity order is $n+1$. But for packet $c = K_R - n + 1$, destination feedbacks Y due to $|D(s)| = n$, then system steps into State C, in which source is included in the competition for retransmission, resulting in the smallest diversity order still $n+1$.

C. Achievable DMT under Adaptive Cooperation

The DMT of Cycle \mathcal{R} can be easily obtained $(1-r)^+$.

Theorem 3. The overall DMT of ACRS is bounded below by

$$d_{ACRS}(r) = \max\{(1-r)^+, (K_R+2)^+(1-2r)^+, (n+1)^+ \left(1 - \frac{K_R - n + 2}{K_R - n + 1} r\right)^+\}. \quad (19)$$

Proof: In case that the direct link is always good, the system will be at high spectral efficiencies without the help of relays as in Cycle \mathcal{R} . Whenever the direct link is in outage occasionally, system will turn into a two-hop fashion as in Cycle \mathcal{P} , making a great loss in spectral efficiency. But if this outage lasts for many time slots, the introduction of Cycle Q will compensate the loss in spectral efficiency. This calls for an adaptive method. Since ACRS, for each time slot, chooses its best way among the cycles, so the DMT of ACRS protocol is bounded below by the three DMT of the cycles. ■

In Fig. 3, it compares the DMT of several dominating DF-based protocols in a half-duplex relay network with $K_R = 8$

and $n = 4$. The ACRS protocol attains better DMT performance across a large range of spectral efficiencies, compared with DSTC and OR.

V. NUMERICAL AND SIMULATION RESULTS

In this section, we present the Monte Carlo simulation to verify our analytical results. All the nodes are uniformly distributed over a circular disk. The following parameter setting is assumed: $\lambda_{ij} = 1$, $N_0 = 1$ and $b = 0.1$.

Fig. 4 presents numerical examples of the outage probability as a function of P/N_0 for the DF strategy at $S - D$ spectral efficiency $R = 1$ bit/s/Hz. In this figure, we compare the performance of (i) ACRS protocol with $K_R = 8$ and $n = 4$; (ii) OR scheme with $K_R = 8$; (iii) ACRS protocol with $K_R = 7$ and $n = 3$; (iv) equal-power multiple-relay (MR) scheme, and (v) single relay scheme. It can be seen that with the same number of relays ($K_R = 8$), ACRS performs better than other schemes. Moreover, with 7 relays, ACRS could perform slightly better than OR with 8 relays. Also, it is obvious that ACRS with 8 relays performs better than with 7 relays. The performance gain of ACRS is due to two factors. First, the utilization of feedback makes relay retransmission occur only when it is needed, which improves the spectral efficiency. Second, when retransmission is necessary, ACRS tries to make a packet transmission finished in just one time slot, which further improves the outage performance greatly.

VI. CONCLUSIONS

In this work, an adaptive cooperation via relay selection protocol is proposed. This protocol can adapt the system to the fluctuation of the channel, enabling the system to choose its best way among different states. And only the best transmitter available is activated for retransmission when it is needed. Most of all, the protocol tries to make a packet transmission finished in just one time slot, thus, recovering the spectral efficiency. We analyze its performance from an information theoretic point of view, which shows that ACRS can achieve better DMT performance compared with previous multiple relay schemes. Simulation results show that ACRS outperforms a variety of existing schemes in terms of outage performance.

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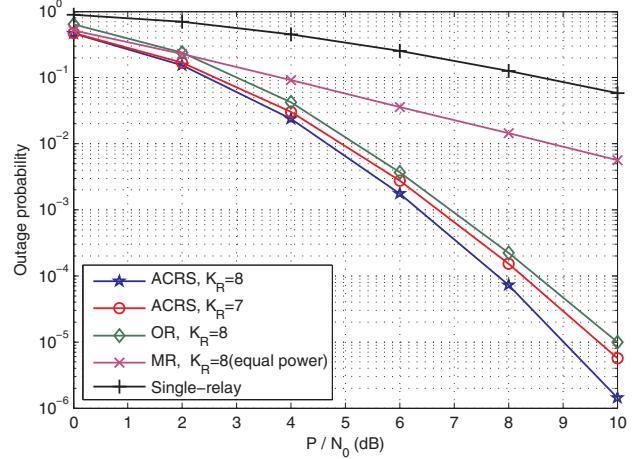


Fig. 4. Outage probability as a function of P/N_0 for the DF strategy at the source-to-end spectral efficiency $R = 1$ bit/s/Hz.

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