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Opportunistic Distributed Space-Time Coding with Semi-Distributed Relay-Selection Method*

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Abstract: Cooperative diversity has been recently proposed as a way to form virtual antenna arrays that provide dramatic gains in slow fading wireless environments. Opportunistic Relaying (OR) and Distributed Space-Time Coding (DSTC) are two attractive cooperative diversity schemes. In this study, we introduce a new cooperative scheme: Opportunistic Distributed Space-Time Coding (ODSTC). In ODSTC scheme, more than one relays with best channel conditions are selected. It can achieve a good tradeoff between performance and complexity. We also propose a criterion to select between DSTC scheme and ODSTC scheme. Further, a semi-distributed relay-selection method is given, which can select more than one best relays without topology information.

Key words: Cooperative diversity, opportunistic relaying, distributed space-time coding, relay-selection method

INTRODUCTION

Cooperative diversity is a practical alternative to Multiple-Input Multiple-Output (MIMO) when the size of the wireless device is limited. Similar to MIMO, cooperation among different users can increase the achievable rates and decrease susceptibility to channel variations. In cooperative diversity, relays are assigned to help source in forwarding information to destination, by forming a Virtual Antenna Array (VAA). Various cooperative diversity protocols are proposed and analyzed (Laneman et al., 2004). Although hard to be employed in practice, Distributed Space-Time Coding (DSTC) scheme is comparatively more attractive due to its high bandwidth efficiency (Laneman and Wornell, 2003).

Note that the number of relays is variable due to the mobility and variety of propagation environment. Hence, providing practical distributed space-time codes for relays remains an open and challenging area for researchers. Indeed, Bletsas et al. (2006) proposed a new scheme called Opportunistic Relaying (OR), in which the best relay is used to forward data to the destination; based on instantaneous channel condition measurements. The proposed scheme can achieves the same diversity-multiplexing tradeoff as DSTC, without the knowledge of network topology. Bletsas et al. (2006) triggers a vast literature on OR (Madan et al., 2006; Beres and Adve, 2008; Cai et al., 2008).

Common to all of these studies is the assumption that source and relay subject to an aggregate power constraint. In this study, we assume that the source and each relay subject to separate power constraints, instead of an aggregate power constraint. This assumption is more practical for wireless networks, because source and relays are usually geographically separated and are supported by separate power supplies (Liang et al., 2007). In addition, Bletsas et al. (2006) evaluates the performance of OR with diversity-multiplexing tradeoff (DMT), which is mainly used in high-SNR regime. While cooperative diversity is usually used in the low-SNR regime. Hence, in this study, we use maximum mutual information to evaluate the performance of cooperative schemes.

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Zhang and Wang (2008) compares OR scheme with DSTC scheme in terms of maximum mutual information under separate power constrain for each relay. The researchers also demonstrates that under certain topology constraint, DSTC outperform OR. However, as previously mentioned, using DSTC scheme in reality is not a trivial task, especially when the number of relays keeps increasing.

In this study, we introduce a new cooperative scheme: Opportunistic Distributed Space-Time Coding (ODSTC). In this scheme, more than one relays with best channel conditions are selected. The scheme can achieve a good tradeoff between performance and complexity. We assume that relays are distributed within a circular area with radius R and the source located at the centre of the circular area. The distance between source and destination is denoted by L. Using geometric method, we demonstrate that there exist two bounds: low bound and high bound and the value of both bounds can be achieved. In addition, we proof the following selection criterion confirmed by Monte Carlo simulation results: for R/L smaller than the low bound, DSTC should be selected, for R/L larger than the high bound, ODSTC is preferred. Further, a semi-distributed relay-selection method for ODSTC scheme is given, which can select more than one best relays without topology information.

SYSTEM MODEL

We consider a wireless network with a source node s, a destination node d and at most m relays, denoted by r_i, $i \in \{1,2,...,m\}$. It is important to note that there may have more than m relays around s, we assume only these m relays that can decode data sent by s and d without errors.

When the direct link between s and d is broken, cooperation process begins to work. The whole cooperation process consists of two consecutive phases. In phase I, s broadcasts data x with power P_s, the received signal at each relay r_i is given by:

$$y_{r_i} = \sqrt{P_s} h_{sr_i} x + z_{r_i} \tag{1}$$

To note that phase I of DSTC and ODSTC are similar and phase II of these two schemes are different. In phase II for DSTC scheme, all m relays transmit data simultaneously using space-time code and d combines signals with a Maximum Ratio Combiner (MRC), so that:

$$y_d = \sum_{i=1}^{m} \sqrt{P_{r_i}} h_{r_i d} x_{r_i} + z_d \tag{2}$$

However, in ODSTC scheme, only n relays with best channel conditions help s forwarding data. n is larger than 1 and smaller than m.

$$y_d = \sum_{i=1}^{n} \sqrt{P_{r_i}} h_{r_i d} x_{r_i} + z_d, 1 < n < m \tag{3}$$

In (1-3), $h_{sr_i}, h_{r_i d}$ capture the effects of path loss, shadowing and frequency non-selective fading and z_{r_i}, z_d are Additive White Gaussian Noise (AWGN) at each r_i and d, capturing the effects of receiver noise and other forms of interference in the system. Statistically, we model $h_{sr_i}, h_{r_i d}$ as zero-mean, independent, circularly symmetric complex Gaussian random variables with variances $\sigma^2_{sr_i}, \sigma^2_{r_i d}$, so that the magnitudes $|h_{sr_i}|, |h_{r_i d}|$ are Rayleigh distributed and $|h_{sr_i}|^2, |h_{r_i d}|^2$ are exponentially distributed with parameters $1/\sigma^2_{sr_i}, 1/\sigma^2_{r_i d}$.

COMPARISON AND SELECTION BETWEEN DSTC AND ODSTC

Here, the present study compare DSTC and ODSTC in terms of maximum mutual information under individual power constraints. In DSTC, m relays help s to forward information to d; In ODSTC, only n best relays among the m relays are selected.

We assume m relays are uniformly and independently distributed in a circular area with radium R, as shown in Fig. 1 and s locates at the centre. The distance between s and d is denoted by L.

The maximum mutual information of DSTC and ODSTC can be denoted as follows:

$$\min \{I_1, I_2\} \tag{4}$$

I_1 represents the maximum mutual information achieved in phase I and I_2 denotes the maximum mutual information achieved in phase II. It is important to note that phase I can be modeled as Single-Input Multiple-Output (SIMO) channel and phase II can be modeled as Multiple-Input Single-Output (MISO) channel. TSE and Viswanath (2004) prove that the maximum mutual information is upper-bounded by the SIMO channel. Thus, (4) can be substituted by I_2. In the sequel, we only study I_2 for DSTC scheme and ODSTC scheme.

The mutual information for DSTC can be determined by Laneman and Wornell (2003) in the following:

$$I_2^{DSTC} = \frac{1}{2}\log_2(1 + \frac{2}{m+1}\sum_{i=1}^{m}\frac{P}{\sigma_n^2}|h_{r_id}|^2) \tag{5}$$

The factor 1/2 accounts for the fact that information is conveyed to d over two phases. Similarly, the mutual information for ODSTC can be determined in the following:

$$I_2^{ODSTC} = \frac{1}{2}\log_2(1 + \frac{2}{n+1}\sum_{i=1}^{n}\frac{P}{\sigma_n^2}|h_{r_id}|^2) \tag{6}$$

In Eq. (5-6), every relay transmits at maximum power P simultaneously. In addition, because of the variance of wireless communication, the instantaneous channel condition is hard to obtain, hence, we use mean channel gain $\sigma_{r_id}^2$ to substitute instantaneous channel gain $|h_{r_id}|^2$. In this study, we assume $\sigma_{r_id}^2 = C/d_{r_id}^{\alpha}$ (Chen *et al.*, 2008), where, d_{r_id} is the distance between node r_i and d. The constant C equals to 7×10^{-4}, α stands for the path-loss exponent, which is set to be 3. P = 0.5 W and σ_n^2 is assumed to be 10^{-10}.

Relays distributed within a circular area make it hard to compare the maximum mutual information of different cooperative schemes. Hence, we use an equivalent scenario, shown in Fig. 2, to substitute the original one.
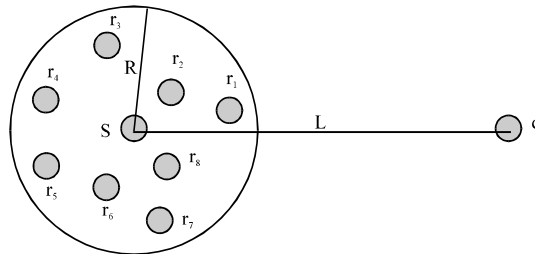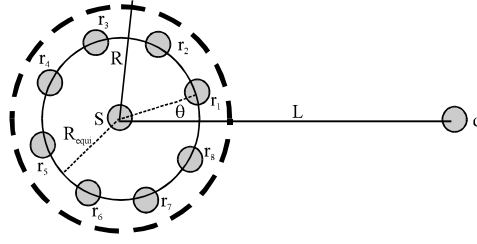

Fig. 1: Topology of the scenario

Fig. 2: Equivalent topology of the scenario

In Fig. 2, m relays are uniformly distributed on a circle, with radius R_{equi} and the phase of r_1 is denoted by θ. R_{equi} represents equivalent radius. We assume θ is distributed in $[-\pi/m, \pi/m]$. Naturally, when θ is distributed in this district, r_1 is the best relay, because $d_{r_1 d}$ is the smallest one among $d_{r_i d}$, $i \in \{1, 2, \cdots, m\}$. Because the topology is symmetrical when θ is distributed in district $[-\pi/m, 0]$ and $[0, \pi/m]$, only $\theta \in [0, \pi/m]$ is considered for simplification. Accordingly, the phase of relay r_i can be denote by $(\theta + (i-1)*2\pi/m)$, $i \in \{1, 2, \cdots, m\}$.

The value of R_{equi} can be calculated by (7), which is actually the expectation of the distances between relays and s.

$$R_{equi} = \iint_\Omega \sqrt{x^2 + y^2} f(x,y) dx dy \qquad (7)$$

where, Ω denotes the circular area with radius R. x, y represent the coordinate of relay and f(x, y) is the probability density function of the distributions for relays. Because relays are uniformly and independently distributed in Ω, hence f(x, y) equals to $1/\pi R^2$. By substituting f (x, y) into (7), we achieve $R_{equi} = (2/3)*R$.

In DSTC scheme, due to all m relays helping s to forward data to d, with geometric method, formula (5) can be converted to formula (8). In ODSTC scheme, only n relays with best channel conditions are selected to be the candidates. The phases of n candidate relays can be represented by

$$\theta + (-1)^{(i-1)} * \left\lfloor \frac{i}{2} \right\rfloor * \frac{2\pi}{m}, \, i \in \{1, \cdots, n\}$$

Correspondingly, formula (6) can be substituted by (9). It is important to know that I_2^{DSTC} and I_2^{ODSTC} in formula (8, 9) depend on the values of m, n, θ, R and L. Without loss of generality, we assume m = 8 and n = 2 in the sequel. It is easy to see that r_1 and r_8 should be selected in ODSTC scheme, because $d_{r_1 d}$ and $d_{r_8 d}$ are smaller than $d_{r_i d}$, $i \in [2, \cdots, 7]$. In Fig. 3, the curves of I_2^{DSTC} and I_2^{ODSTC} are demonstrated according to different values of R/L, while the value of θ is 0.

$$I_2^{DSTC} = \frac{1}{2} \log_2 (1 + \frac{2}{m+1} \sum_{i=1}^{m} \frac{P}{\sigma_n^2} \frac{C}{\sqrt{(L-R_{equi}*\cos(\theta + (i-1)*\frac{2\pi}{m}))^2 + (R_{equi}*\sin(\theta + (i-1)*\frac{2\pi}{m}))^2}^3})$$

$$= \frac{1}{2} \log_2 (1 + \frac{2}{m+1} \sum_{i=1}^{m} \frac{P}{\sigma_n^2} \frac{C}{\sqrt{L^2 - 2*L*\frac{2}{3}R*\cos(\theta + (i-1)*\frac{2\pi}{m}) + (\frac{2}{3}R)^2}^3}) \qquad (8)$$

$$I_2^{ODSTC} = \frac{1}{2}\log_2(1+\frac{2}{n+1}\sum_{i=1}^{n}\frac{P}{\sigma_n^2}\frac{C}{\sqrt{(L-R_{equi}*\cos(\theta+(-1)^{(i-1)}*\lfloor\frac{i}{2}\rfloor*\frac{2\pi}{m}))^2+(R_{equi}*\sin(\theta+(-1)^{(i-1)}*\lfloor\frac{i}{2}\rfloor*\frac{2\pi}{m}))^2}^3})$$

$$=\frac{1}{2}\log_2(1+\frac{2}{n+1}\sum_{i=1}^{n}\frac{P}{\sigma_n^2}\frac{C}{\sqrt{L^2-2*L*\frac{2}{3}R*\cos(\theta+(-1)^{(i-1)}*\lfloor\frac{i}{2}\rfloor*\frac{2\pi}{m}))+(\frac{2}{3}R)^2}^3}) \quad (9)$$

The crossover point in Fig. 3 indicates where the DSTC scheme and ODSTC scheme have the equal maximum mutual information. To note that the X-coordinate of the crossover of these two curves is 0.179, thus we use R*/L to denote the X-coordinate of the crossover for simplicity. For each value of θ, if R/L is larger that R*/L, ODSTC can achieve larger maximum mutual information; on the other hand, if R/L is smaller than R*/L, DSTC is preferred. In Fig. 4, we depict the relationship between R*/L and θ, where θ is changing from 0 to π/8.

From Fig. 4, we know that R*/L is monotonically decreasing over θ. The lowest R*/L is denoted by low bound and the highest R*/L is denoted by high bound. Specifically, in Fig. 4, low bound is 0.163 and high bound is 0.179. We propose the following selection criterion: when R/L is larger than
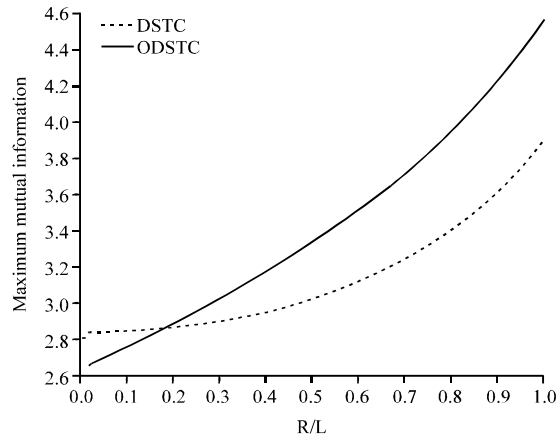

Fig. 3: Maximum mutual information for DSTC and ODSTC according to different value of R/L, with θ = 0, m = 8, n = 2

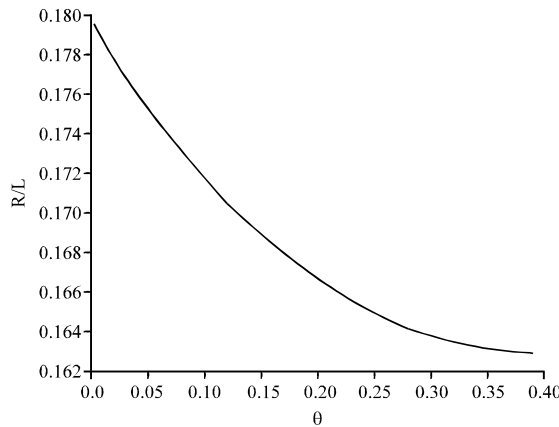Fig. 4: Relationship between R*/L and θ, m = 8, n = 2

high bound, the ODSTC definitely outperform DSTC and should be selected, regardless of the value of θ; when R/L is smaller than low bound, DSTC is preferred to be selected, regardless of the value of θ. Present selection criterion can not handle the situation when the value of R/L is between low bound and high bound.

RESULTS AND DISCUSSION

Here, we use Monte Carlo simulation to verify the validity of the selection criterion. The simulation results are obtained by averaging over ten thousand realizations. In present simulation, the scenario is similar to Fig. 1. Specifically, m = 8, n = 2, L equals to 50 m and R is changing from 1 to 50 m.

Simulation results demonstrate the maximum mutual information obtained by ODSTC and DSTC, as shown in Fig. 5. To easily compare, the low bound and high bound are highlight. It is easy to see that, whenever R/L is smaller than low bound, DSTC scheme can achieve larger maximum mutual information and whenever R/L is larger than high bound, ODSTC scheme can obtain larger mutual information. The simulation results verify the validity of the selection criterion and the rationality of two bounds.
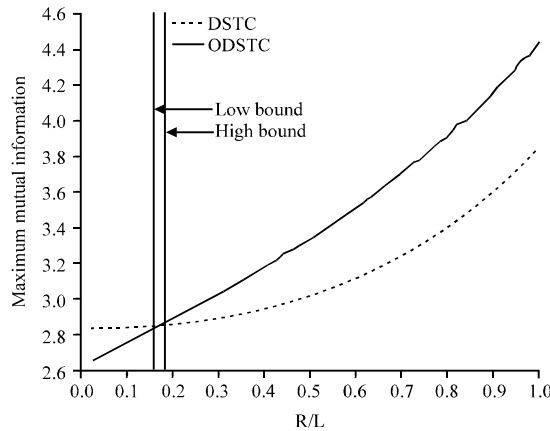

Fig. 5: Comparison between ODSTC and DSTC in terms of maximum mutual information by Monte Carlo simulation, m = 8, n = 2
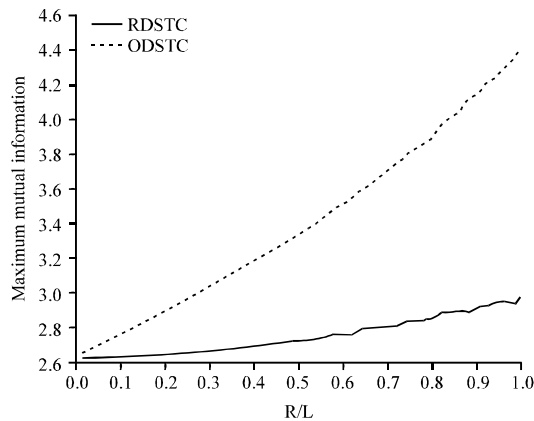

Fig. 6: Comparison between ODSTC and RDSTC in terms of maximum mutual information by Monte Carlo simulation, m = 8, n = 2

In the next, to indicate that the performance of ODSTC scheme heavily depends on selecting approximate relays, we comparing ODSTC scheme with another cooperative scheme: random DSTC (RDSTC), which can be treated as a special case of ODSTC. To simplify, we still consider the scenario in which m = 8 and n = 2. In ODSTC scheme, two best relays are selected from eight potential relays. On the contrary, in RDSTC scheme, two relays are selected randomly from eight relays. We compare these two schemes in terms of maximum mutual information by Monte Carlo simulations, as shown in Fig. 6.

Figure 6 demonstrates that ODSTC scheme outperform RDSTC scheme dramatically. Hence, selecting the best relays dominate the performance of ODSTC.

SEMI-DISTRIBUTED RELAY-SELECTION METHOD

Here, we introduce a semi-distributed relay-selection method for ODSTC scheme, which can select more than one best relays, based on local measurements of the instantaneous channel conditions. There are several studies focusing on relay selection, such as (Bletsas *et al.*, 2006; Madan *et al.*, 2006; Cai *et al.*, 2008; Liu *et al.*, 2007). Bletsas *et al.* (2006) is most representative, which chooses one best relay in distributed methods, requiring no topology information and based on local measurements of the instantaneous channel conditions. However, Bletsas *et al.* (2006) can only choose one best relay in each process and results in a non-zero probability of two relays sending flag packets concurrently. Zhang *et al.* (2007) is close to present study, however, the relay-selection method for DSTC is completely distributed, which is sub-optimal and may fail due to packets collision. Cai *et al.* (2008) represents a relay-selection method, where each relay can make decision on its feasibility individually and the ultimate decision is made in centralized manner. Similar to Bletsas *et al.* (2006), this relay-selection can only select one relay in each process. Liu *et al.* (2007) propose a cooperative MAC protocol: CoopMAC. Nevertheless, CoopMAC protocol can only support selecting one relay in each process.

In the next, we propose a relay-selection method which has the following features:

- The method can select more than one relays in semi-distributed way. Each relay makes local channel measurements and the source node makes the final decision which relays are selected
- Relay selection is based on instantaneous channel conditions in slow fading wireless environments. No prior knowledge of topology
- The amount of overhead involved in selecting the best relays is minimal, due to the fact that this method requires no explicit communication among the relays

Without loss of generality, we use the scenario similar in Fig. 1, in which a source node s transmits data to a destination node d, with the help of at most m relay nodes, denoted by r_i, i $\in$ {1,...,m}. For the ODSTC scheme, only n relays with best channel conditions are selected to help s with the constraint 1<n<m. We explicitly illustrate the semi-distributed relay-selection method in the sequel. To make analyzing more concisely, we depict the relay-selection procedure for s and r_i, i $\in$ {1,...,m} in Fig. 7 and 8, respectively.

When s communicates with d, m potential relays overhear the ready-to-send (RTS) packet and clear-to-send (CTS) packet. The transmission of RTS from s allows for the estimation of the instantaneous wireless channel h_{sr_i} between s and r_i, at each r_i. Similarly, the transmission of CTS from d allows for the estimation of the instantaneous wireless channel h_{r_id} between r_i and d, at each r_i.

When the direct link between s and d is broken, s and d can not communicate with each other. Then, s initiates a relay-selection procedure, by broadcasting a selection packet which includes the anticipant number of relays, n in this case. As soon as each relay receives the selection packet, it starts a timer from a parameter h_{r_i} based on the instantaneous channel measurement h_{sr_i} and h_{r_id}. The notation of h_{r_i} is given below:
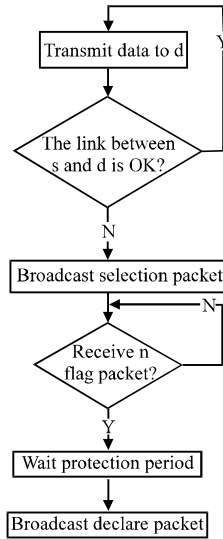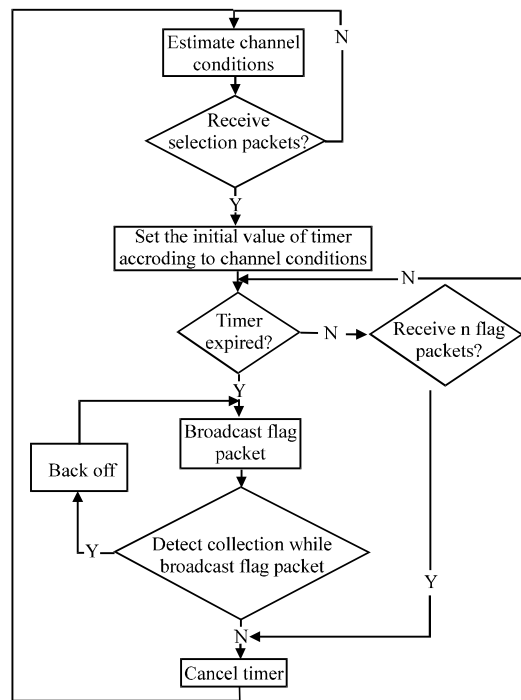
Fig. 7: Relay-selection procedure for source node s

Fig. 8: Relay-selection procedure for each relay node r_i, $i \in \{1,..,m\}$

$$h_{r_i} = \min \{|h_{sr_i}|^2, |h_{r_i d}|^2\} \tag{10}$$

After receive selection packet, each relay will start its own timer with an initial value T_{r_i}, inversely proportional to h_{r_i}, according to the following equation:

$$T_{r_i} = \frac{\lambda}{h_{r_i}} \qquad (11)$$

Here, λ is a constant. The units of λ depend on the units of h_{r_i}. Since h_{r_i} is a scalar, λ has the units of time. The timer of the relay with best end-to-end channel conditions will expire first. That relay transmits a short duration flag packet, signaling its presence. In the flag packet, the quantified value of h_{r_i} is included. Then, the timer of the relay with second best end-to-end channel conditions expires and transmits flag packet, respectively, until n flag packets are broadcasted. As a consequence, the other relays cancel their timer and the selection procedure is finished. As to s, it should wait another period of time, called protection period. We will explain later why this protection period is necessary. As soon as protection period expires, s broadcasts a declare packet which include the ID number of the selected relays.

Similarly at the relay-selection method by Bletsas *et al.* (2006), the probability for two or more relays' timers expire within a same time interval is non-zero. However, in present method, the collisions of flag packets won't affect the final results. When one relay detect collision while broadcast flag packet, it just back off independently and retransmit again. During the back off period, unwanted relays may send flag packets, because their timers expire and there are less than n flag to be received. In the end, s receives more than n flag packets. Because in each flag packet, the quantified value of h_{r_i} are included, thus, s can pick the best n relays correctly by means of comparing h_{r_i} of different relays and then broadcast a declare packet which include the ID number of the selected relays. Then, the relay-selection procedure is finished.

It is important to note that, if the protection period does not exist and s send the declare packet as soon as it receives n flag packets, those relays, which detected collisions while broadcasting flag packets and backed off independently, would be omitted. Hence, the final results won't be the optimal. Comparing with the distributed relay-selection method by Bletsas *et al.* (2006) and Madan *et al.* (2006), in present relay-selection method, s acts as a referee when there are more flag packets received. Hence, the method is called semi-distributed and the appropriate relays can always be selected.

CONCLUSION AND FUTURE STUDY

In this study, we introduce a novel cooperative scheme: ODSTC, which can be treated as a good tradeoff between performance and complexity. Further, a semi-distributed relay-selection method is introduced, which can select more than one best relays without topology information. This method can always obtain the optimal performance, comparing with the other relay-selection methods.

Theoretically, more relays can bring us the chance to pursue better performance. In fact, the more relays are involved, the more inter-user interference are produced and the more power are consumed. How to tradeoff the performance, interference and power consumption is beyond the scope of this study and will be considered in the future.

Although present semi-distributed relay-selection method can always select the most appropriate relays, it also brings extra delay, especially the protection period. The performance of cooperative scheme, concerning the delay factor should be evaluated in the future. Furthermore, in present relay-selection method, relays' will and residual power have not been taken in account. Actually, relays can adjust their timers according their own wills and residual power, besides the instantaneous channel conditions.

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