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Optimal Cooperative MAC Protocol for IEEE 802.11-based Mesh Networks

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Abstract—This paper presents a new cooperative MAC (Medium Access Control) protocol for IEEE 802.11-based mesh networks. The protocol is characterized by two features: on-demand relaying and selection of the best relay terminal. "On-demand relaying" means that a cooperative communication occurs only when a destination terminal fails in decoding the data transmitted by a source terminal. This approach allows minimization of bandwidth degradation due to both cooperation implementation and cooperative communications. "Selection of the best relay terminal" means that a relay selection is implemented when cooperation is needed. This feature allows maximization of the spatial diversity order. The outage probability of the new protocol is compared to the outage probability of other cooperative MAC protocols.

I. INTRODUCTION

Cooperative communications provide an interesting alternative to Multiple-Input-Multiple-Output (MIMO) techniques when wireless systems cannot support multiple antenna terminals. In a cooperative scenario, a source terminal S sends data to a destination terminal D. One or several relay terminals help the transmission by receiving the signal transmitted by S and forwarding the signal toward D (see Figure 1). Spatial diversity is the main advantage provided by cooperative transmissions whereas their main limitation lies in the bandwidth degradation due to both relay selection and relay transmission¹.

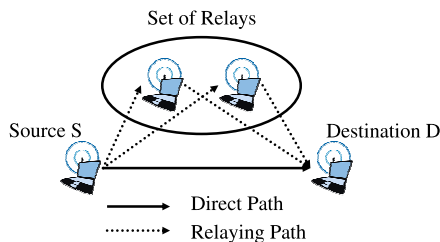


Fig. 1. Cooperation scenario with two relay terminals.

Several cooperation techniques have been proposed in order to both maximize the spatial diversity and minimize the bandwidth consumption [1]–[5]. When a single relay terminal is involved in a cooperation scenario, a minimum bandwidth degradation can be obtained using on-demand relaying [1], [6], [7]: the relay terminal is transmitting only when D fails in

decoding the data from S, and asks for cooperation with a signaling frame. Hence, the bandwidth consumption is minimized but the spatial diversity order is limited to a factor of two². When $(m - 1)$ relay terminals are used, a diversity order of m is achieved [3] but this improvement is counterbalanced by increased bandwidth consumption due to relay transmissions. This approach has been improved by implementing a selection of the best relay terminal [9]. Hence, a spatial diversity order of m can be achieved and the bandwidth degradation is minimized since only two terminals are transmitting (the source terminal S and the best relay terminal B). But the bandwidth consumption is still high compared to the one of an on-demand relaying scheme.

The proposed protocol aims at both maximizing the spatial diversity order and minimizing the bandwidth consumption. This new cooperative protocol is based on the IEEE 802.11 standard for wireless networks and exhibits the following features: on-demand cooperation and selection of the best relay terminal. Cooperation is activated only when needed, i.e. only when the destination terminal fails in decoding the data transmitted by the source terminal. This feature allows minimization of the bandwidth consumption. Moreover, when a cooperative communication is necessary, only the best relay terminal cooperates. This approach allows maximization of the spatial diversity order. Hence, an optimal solution can be implemented. In section II, the protocol is described in details. Simulation results are presented in section III and we conclude in section IV.

II. DESCRIPTION OF THE PROTOCOL

A. System model

We consider a slow Rayleigh fading channel model following [1]. Our analysis focuses on the case of slow fading and mesh networks. A half duplex constraint is imposed across each relay terminal, i.e., it cannot transmit and listen simultaneously. Moreover, transmissions are multiplexed in time, they use the same frequency band. Let h_{ij} be the channel gain between a transmitting terminal i and a receiving terminal j . The channel gain h_{ij} captures the effects of path-loss, shadowing, and Rayleigh fading. We consider scenarios in which each fading coefficient h_{ij} is accurately measured by

¹We use bandwidth as a general term for resource in a communication network. Bandwidth can be expressed in time slots, frequency bands, spreading codes, or space time codes.

²In [8], optimal protocols have been proposed when no feedback to the transmitting terminal is allowed.

the receiver j , but not known to the transmitter i . We also assume that the channel gain h_{ij} is identical to the channel gain h_{ji} . This assumption is relevant since both channels are using the same frequency band. Statistically, channel gains h_{ij} between any two pair of terminals i and j are modeled as i.i.d circularly symmetric complex Gaussian random variables with zero mean and equal variance σ^2 . Let P be the power transmitted by each terminal and σ_w^2 be the variance of the AWGN (Additive White Gaussian Noise) in the wireless channel. We define $SNR = P/\sigma_w^2$ to be the effective signal-to-noise ratio.

We also restrict our study to a single source-destination pair. It is assumed that $(m - 1)$ wireless terminals are available in the range of both terminal S and terminal D. They are not participating in any other transmission but they are likely to cause collision if they transmit the source message all at the same time. Any other terminal is assumed to remain silent because it does not implement a cooperation functionality, or its cooperation functionality has been switched off. Hence, no extra interference occurs from neighboring terminals. In any case, if a terminal should interfere with the cooperative transmission, the proposed protocol is implementing classical error recovery mechanisms.

B. Protocol Description

The implementation of cooperative MAC protocols in the context of IEEE 802.11-based networks can be modeled by four main tasks [10]. In the following, we review these four tasks.

1) *Cooperation Mode Activation*: We consider that terminals are always in a cooperative mode, i.e. the cooperation mode is always activated. How to turn the cooperation mode on and off on a terminal is left for further study. Moreover, the activation of the relay selection at a given terminal R_i , $1 \leq i \leq (m - 1)$ is reactive, i.e. based on the reception of signaling MAC frames. When the source terminal S sends its data frame, every terminal R_i in the range of S stores this frame. When terminal D succeeds in decoding the data frame, terminal D sends an acknowledgment frame (ACK). Otherwise, D sends a short signaling frame (CFC for Claim For Cooperation) [7]. When the CFC frame is lost, the protocol implements a classical error recovery mechanism³. Note that the timeout should be delayed to take into account possible cooperative transmissions. When a terminal R_i stores the source message, it waits for either an ACK frame or a CFC frame. If any of these two frames is not received within a given time-slot, the source message is discarded at terminal R_i . Hence, only terminals that have received both the data frame and the CFC frame trigger the relay selection process⁴.

2) *CoI Collection*: Once the relay selection process has been triggered at terminal R_i , CoI is collected. The CoI is

³When the source terminal does not receive an acknowledgment before a timeout, it retransmits the frame until it receives an acknowledgment or exceeds a predefined number of re-transmissions.

⁴Terminals that just receive either an ACK frame or a CFC frame ignore the signaling frame.

not directly used to proceed to the selection. Rather, the CoI parameterizes terminal R_i during the notification step. With the data frame (resp. the CFC frame), terminal R_i estimates the channel gain h_{SR_i} (resp. h_{R_iD}) between S (resp. D) and R_i .

3) *Relay Selection Algorithm*: When a terminal R_i activates this task, it already satisfies all the necessary conditions to be selected as a possible relay terminal [9], [11]: it implements the cooperation functionality, it has received the data frame and the CFC frame, and it does not participate to any other cooperative transmission. So, this block is empty and the next task is immediately activated.

4) *Relay Notification*: The objective of this step consists in both completing the selection process and notifying the result of the selection to the participating terminals: source terminal S, destination terminal D, and any other relay terminal. The best relay terminal will be the one that will notify its presence first. Several approaches have been proposed to implement this notification step. In [9], a timer T_i is associated to each terminal R_i . The timer T_i is inversely proportional to a channel metric. As soon as the timer expires, the terminal transmits a short duration signaling frame. In [11], busy tones are transmitted in two busy-tone slots. This step is critical since collision may occur between relay candidates. When the notification step is completed, the best relay terminal sends a copy of the data frame using a fixed Amplify-and-Forward (AF) forwarding scheme⁵. The destination terminal D receives the signal and combine it with the one from the source terminal. When D succeeds in decoding the data frame, D sends an ACK frame (see Figure 2). Otherwise, D remains silent and the timeout at the source terminal triggers a re-transmission.

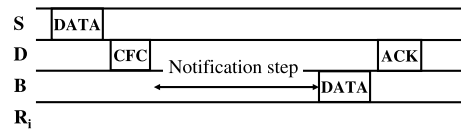


Fig. 2. Frame exchange sequence in the OB protocol (S is the source terminal, D is the destination terminal, B is the best relay terminal, and R_i is a relay candidate).

5) Remarks on the protocol design:

- Several cooperative MAC protocols rely on the exchange of modified Request-to-Send (RTS) and Clear-to-Send (CTS) signaling frames [11]–[13]. If CTS frames transmitted by the destination terminal D can be modified, we can infer that channel state information is available at the transmitter. Hence, the source can actually choose not to transmit when it cannot support a given spectral efficiency R . This gives rise to new cooperative protocols, the study of which is left for future work.
- The Network Allocation Vector (NAV) values at each terminal should be increased according to the new frame

⁵We restrict ourselves to a fixed AF relaying scheme. A selective Decode-and-Forward (DF) forwarding scheme is also applicable.

scheduling, just like the timeout at the source terminal. This should avoid unnecessary soundings by neighboring terminals.

- As soon as a frame is missing or when the set of relays is empty, the protocol returns to its starting point according to a given timeout.

C. Outage Probability Analysis

We characterize our channel models using the system model described in the previous section, and a time-division notation; frequency-division counterparts to this model are straightforward. We use a base-band-equivalent, discrete-time channel model for the continuous-time channel. Three discrete time received signals are defined in the following. Here, $y_{ij}(n)$ denotes the signal received by terminal j and transmitted by terminal i . During a first time-slot, D and the best relay terminal B are receiving signals from S

$$\begin{cases} y_{SD}(n) = h_{SD}x(n) + w_{SD}(n) \\ y_{SB}(n) = h_{SB}x(n) + w_{SB}(n) \end{cases}$$

for $n = 1, 2, \dots, T_M/2$, where T_M denotes the duration of time-slots reserved for each message. When terminal D succeeds in decoding the data frame from S, no signal is transmitted by the best relay terminal B. Otherwise, B transmits a new signal using a fixed AF scheme, and D is receiving

$$y_{BD}(n) = h_{BD}[\beta y_{SB}(n)] + w_{BD}(n)$$

for $n = T_M/2+1, \dots, T_M$. The noise $w_{ij}(n)$ between transmitting terminal i and receiving terminal j are all assumed to be i.i.d. circularly symmetric complex Gaussian with zero mean and variance σ_w^2 . Symbols transmitted by the source terminal S are denoted $x(n)$. For simplicity, we impose the same power constraint at both the source and the relay: $E[|x(n)|^2] \leq P$ and $E[|\beta y_{SB}(n)|^2] \leq P$. We implement a fixed AF cooperation scheme. So the normalization factor β must satisfy

$$\beta^2 = \frac{P}{|h_{SB}|^2 P + \sigma_w^2}$$

We assume that the source and the relay each transmit orthogonally on half of the time-slots. We also consider that a perfect synchronization is provided at the block, carrier, and symbol level.

We compute the outage probability p_{OB}^{out} of the On-demand relaying with selection of the Best relay terminal (OB protocol). The OB protocol operates at spectral efficiency R when the direct transmission is successful, and operates at spectral efficiency $R/2$ when the best relay terminal must amplify and forward the source message. So, we have that

$$\begin{aligned} p_{OB}^{out} &= \Pr[I_D \leq R] \Pr[I_A^{(B)} \leq R/2 | I_D \leq R] \\ &= \Pr[I_A^{(B)} \leq R/2] \end{aligned} \quad (1)$$

where I_D the mutual information of a direct transmission

$$I_D = \log_2(1 + SNR|h_{SD}|^2) \quad (2)$$

The mutual information $I_A^{(B)}$ is the mutual information of the cooperative MAC protocol implementing both a fixed amplify-and-forward relaying scheme and the selection of the best relay terminal B in [9]

$$\begin{aligned} I_A^{(B)} &= \frac{1}{2} \log_2[1 + SNR|h_{SD}|^2 \\ &\quad + f(SNR|h_{SB}|^2, SNR|h_{BD}|^2)] \end{aligned} \quad (3)$$

where

$$f(x, y) = \frac{xy}{x + y + 1}$$

The subscript A stands for fixed AF relaying scheme and the superscript (B) stands for terminal B, the best relay terminal. The second equality in (1) follows from the fact that the event $[I_D \leq R]$ is included in the event $[I_A^{(B)} \leq R/2]$ according to (2) and (3).

First, we compare the outage probability p_{OB}^{out} with the outage probability p_{BR}^{out} of the protocol in [9]. This protocol implements a selection of the best relay (BR) terminal. In the BR protocol, terminal B is always retransmitting the source message, even if the source message has been successfully decoded by D. The outage probability of the BR protocol is

$$p_{BR}^{out} = \Pr[I_A^{(B)} \leq R]$$

Since $\Pr[I_A^{(B)} \leq R/2] \leq \Pr[I_A^{(B)} \leq R]$, we have that

$$p_{OB}^{out} \leq p_{BR}^{out}$$

So the OB protocol exhibits better performance than the BR protocol. This property is explained by the on-demand characteristic of the OB protocol.

Second, we compare the outage probability p_{OB}^{out} with the outage probability of the on-demand relaying (OR) protocol in [1]. The OR protocol implements on-demand relaying but no selection of the best relay terminal is implemented. To ensure fair comparison, we assume that $(m-1)$ terminals are located in the range of both the source terminal S and the destination terminal D. Hence, if one of these terminal is chosen as a relay terminal, R_i , for $1 \leq i \leq (m-1)$, then the outage probability of the OR protocol, p_{OR}^{out} , is

$$p_{OR}^{out} = \Pr[I_A(R_i) \leq R]$$

Since $I_A^{(R_i)} \leq I_A^{(B)}$, we have that

$$p_{OB}^{out} \leq p_{OR}^{out}$$

So the OB protocol exhibits better performance than the OR protocol. The selection of a best relay terminal among a set of $(m-1)$ terminals, explains this property.

III. SIMULATION RESULTS

For simulation purposes, we consider a single source-destination pair. We assume that there are $(m-1)$ terminals available for cooperation in the range of both source and destination terminals: they implement the cooperation functionality, and they are not involved in any other communication (direct or cooperative). Moreover, we assume that the notification step

has been designed so that no collision occurs during this step. We assume slow fading Rayleigh channels between each pair of terminals, with equal variance: $\sigma^2 = 1$. The channel gains are assumed to be known at the receiver side. Each channel gain has a constant value during the transmission of a frame and this value may change from one frame to another.

We compare the performance of four transmission schemes: direct transmission, BR protocol [9], OR protocol [1], and OB protocol. We recall that the BR protocol is based on the selection of a best relay terminal among a set of $(m - 1)$ terminals. So it corresponds to the OB protocol without the on-demand relaying functionality. Similarly, the OR protocol is based on an on-demand relaying scheme with one single relay terminal. So, the OR protocol corresponds to the OB protocol without the selection of the best relay terminal. Moreover, to ensure fair comparison, all the protocols use the same number of relay candidates: $(m - 1)$. The performance of the transmission schemes is given in terms of outage probability. For large SNR values, Figure 3 shows that the direct transmission and the OR protocol with one relay terminal achieve respectively spatial diversity orders of 1 and 2. Note that $(m - 1)$ equals 0 (resp. 1) for the direct transmission (resp. the OR protocol with one relay). Also, the OB and BR protocols are both achieving a full spatial diversity order of m . So all the outage probability curves decay like $1/SNR^m$. Moreover, the OB protocol achieves a better outage probability than the BR protocol. This is consistent with the results presented in the previous section. Note also that the OB protocol uses less resource than the BR protocol because it implements an on-demand transmission.

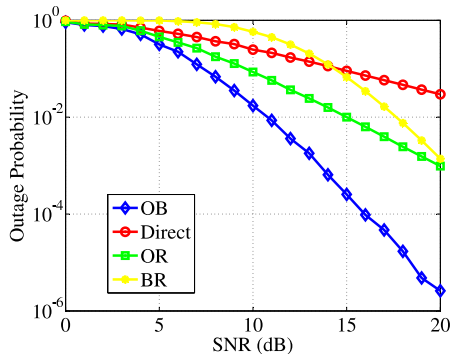


Fig. 3. Outage performance of noncooperative and cooperative protocols ($m = 4$): OB protocol, direct transmission (Direct), on-demand relaying with one relay (OR), cooperation with the selection of the best relay terminal (BR).

IV. CONCLUSION

In this paper, a new cooperative protocol has been proposed. This protocol is based on the IEEE 802.11 standard for wireless mesh networks and exhibits the following features: on-demand cooperation and selection of the best relay terminal. When a destination terminal D fails in decoding a data message from a source terminal S, D asks for cooperation with a signaling frame (on-demand approach). Terminals that have overheard the source message and the call from D,

enter a competition step. The terminal with the best channel gain transmit a signaling frame first. This step concludes the selection of the best relay terminal. Then, this terminal sends a copy of the data message so D can transmit an acknowledgment frame when the combination of the two versions of the data message has been successfully decoded. When $(m - 1)$ terminals are located in the range of both a source terminal S and a destination terminal D, a full spatial diversity order of m is provided while bandwidth consumption is minimized. This protocol has been applied to a fixed AF relaying scheme but it can be also applied to a selective DF cooperation scheme. The context of this study has been restricted to a single (S,D) pair. However, the OB protocol has been designed so that a cooperative transmission can be implemented even if there are interfering terminals in the range of S, D and other relay candidates: any interfering frame causing a collision will trigger the discarding of the source message at the relay terminals. Then a timeout at the source terminal triggers a re-transmission. The optimization of the OB protocol with interfering terminals is left for further study.

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