DMT Optimal Cooperative Protocols with Destination-Based Selection of the Best Relay

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***Abstract*—We design a cooperative protocol in the context of wireless mesh networks in order to increase the reliability of wireless links. Destination terminals ask for cooperation when they fail in decoding data frames transmitted by source terminals. In that case, each destination terminal D calls a specific relay terminal B with a signaling frame to help its transmission with source terminal S. To select appropriate relays, destination terminals maintain tables of relay terminals, one for each possible source address. These tables are constituted by passively overhearing ongoing transmissions. Hence, when cooperation is needed between S and D, and when a relay B is found by terminal D in the relay table associated with terminal S, the destination terminal sends a negative acknowledgment frame that contains the address of B. When the best relay B has successfully decoded the source message, it sends a copy of the data frame to D using a selective decode-and-forward transmission scheme. The on-demand approach allows maximization of the spatial multiplexing gain and the cooperation of the best relay allows maximization of the spatial diversity order. Hence, the proposed protocol achieves optimal diversity-multiplexing trade-off performance. Moreover, this performance is achieved through a collision-free selection process.**

***Index Terms*—Cooperative communications, multiple access control (MAC) protocols, diversity multiplexing trade-off (DMT).**

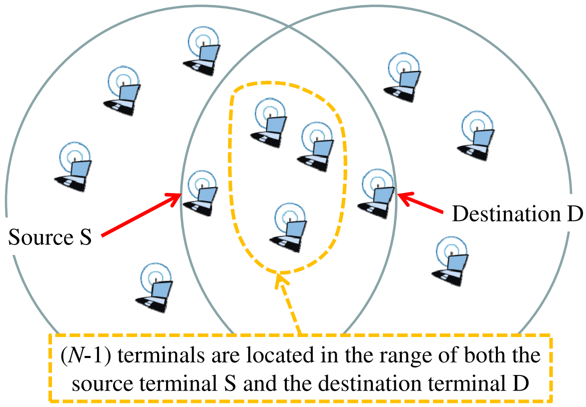

Fig. 1. Cooperation scenario with three relay candidates: $(N-1)=3$.

I. Introduction

THIS paper focuses on the design of cooperative MAC protocols in the context of wireless mesh networks (WMNs). This type of networks offers many optimization opportunities since long distances can be broken into a series of shorter hops. Indeed, shorter hops provide more robustness to channel impairments. Moreover, this robustness is improved thanks to the mesh architecture because this topology enables the cooperative forwarding of data packets through intermediate terminals. Cooperative communications provide an interesting contribution in this context. In a cooperative scenario, a source terminal S sends data to a destination terminal D through a direct path. One or several relay terminals help the transmission by receiving the source message and forwarding it to D through a relaying path (see Fig. 1).

Hence the direct path is rendered more robust [2]–[5]. However, this comes at the price of bandwidth consumption so that the system operates at diminished capacity[1]. Cooperative communications can be envisioned at several network layers. Basically, cooperative protocols are mainly implemented in two layers: cooperative transmissions are managed at the physical (PHY) layer whereas the set up of the cooperation is done at the Medium Access Control (MAC) layer. However, implementing the forwarding scheme at the lowest layers renders the protocol more reactive to network conditions and minimizes the transmission delay since each layer adds its own processing time and hence includes its own latency. At the PHY layer, the main purpose of cooperative communications consists in increasing the wireless link reliability while minimizing the resource devoted to the cooperative transmission.

In this context, one common way to compare cooperative transmission techniques is to compute the Diversity-Multiplexing Trade-off (DMT) [6]. The DMT analysis of a transmission scheme yields the diversity gain $d(r)$ achievable for a spatial multiplexing gain r. A transmission scheme is said to have a spatial multiplexing gain r and a diversity gain $d(r)$ when the spectral efficiency R scales like $r\log_2 SNR$, and the outage probability decays like $1/SNR^{d(r)}$, where SNR denotes the effective signal to noise ratio at the receiver. Hence, the diversity gain helps in quantifying the robustness of the cooperative link and the multiplexing gain gives an hint on the capacity of the link. A protocol achieves an optimal DMT curve when it maximizes both the diversity gain $d(r)$ and the multiplexing gain r, i.e., when the protocol achieves a target outage probability with both the lowest transmitted power and the lowest bandwidth consumption. When a cooperation

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[1]We 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.

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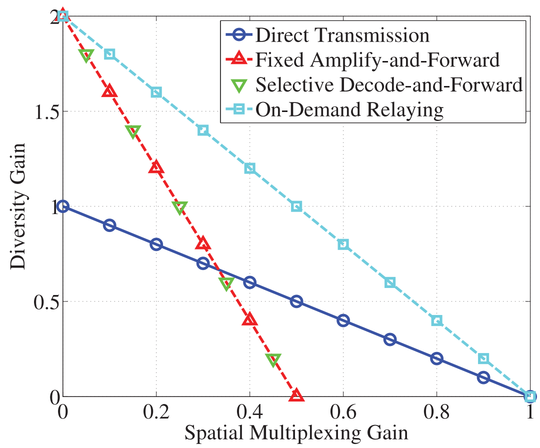

Fig. 2. DMT curves of a direct transmission and three cooperative transmission schemes involving one relay terminal: fixed amplify-and-forward, selective decode-and-forward, and on-demand relaying [7].

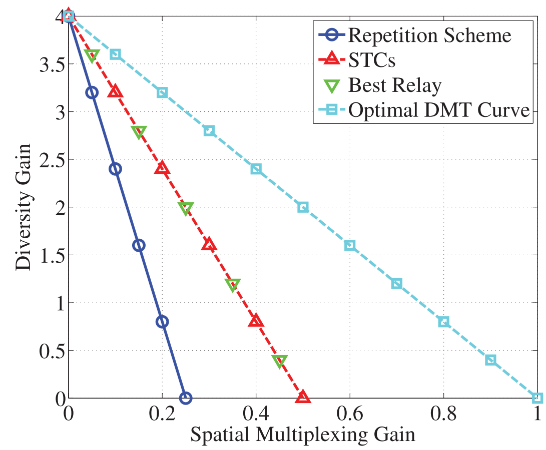

Fig. 3. DMT curves of three cooperative transmission schemes with N relay terminals ($N = 4$): fixed AF protocol using a repetition scheme at the relay terminals (Repetition Scheme) [7], the fixed AF protocol implementing STCs (STCs) [3], and the AF protocol based on the selection of the best relay terminal (Best Relay) [9], and the optimal DMT curve (Optimal DMT Curve) [10], [11].

scenario involves a single relay terminal, an optimal DMT curve can be obtained using on-demand relaying [7]. In an on-demand relaying scenario, the relay terminal is transmitting only when the destination terminal asks for cooperation[2]. The optimal DMT curve is given by $d(r) = 2(1-r)$ for $0 \leq r \leq 1$ (see Fig. 2). Even if the DMT curve is optimal, the diversity is limited to a value of two. To increase the diversity gain, several relay terminals should be considered.

When $(N-1)$ relay terminals are involved in a cooperative scenario, a diversity order of N can be achieved (see Fig. 2). When relay terminals are repeating the source message, the multiplexing gain is limited to the value of $1/N$. The DMT curve is: $d(r) = N(1-Nr)$ for $0 \leq r \leq 1/N$. The value of r can be increased to $1/2$ using Space-Time Codes (STCs) [3]. The DMT curve is then: $d(r) = N(1-2r)$ for $0 \leq r \leq 1/2$. An alternative solution consists in selecting the best relay terminal among the set of $(N-1)$ relay candidates [9]. Hence, only one terminal is forwarding the source message. The DMT curve is the same as the previous one and less resources are needed to implement the cooperation scheme (allocating space-time codes to the relay terminals). However, even if the spatial diversity order is N, the spatial multiplexing gain r is still limited to the value of $1/2$.

The optimal DMT curve $d(r)$ is achievable by protocols that implement both on-demand relaying and the selection of the best relay [10], [11]: $d(r) = N(1-r)$ for $0 \leq r \leq 1$. Thanks to the on-demand relaying [7], [12], the relay terminal transmits only when D fails in decoding the data transmitted by S. Thus, the bandwidth consumption due to cooperative transmissions is minimized. Moreover, when cooperation is needed, only the best relay terminal retransmits the source message [9]. This optimizes the robustness of the wireless link between the source terminal and the destination terminal through the property of spatial diversity while minimizing the resource consumption compared to the case of multiple relays. Hence, an optimal trade-off between link robustness and bandwidth consumption is reached. This optimal DMT curve can be achieved using either a fixed Amplify-and-Forward (AF) transmission scheme [10], [11] or a selective Decode-and-Forward (DF) transmission scheme [13]. Moreover, minimizing the number of relays also reduces the impact of cooperative communications on the rest of the network. Indeed, reducing the number of relays diminishes the contention area due to cooperative transmissions compared to the case of multiple relay transmissions. Note however that the DMT criterion fails in providing indications on the amount of bandwidth that is used at the MAC layer in order to implement the cooperative network. For instance, in [3], the overhead induced by the allocation of space-time codes to relay terminals has not been taken into account. Practically, further optimization is required at the MAC layer in order to reduce the overhead due to the implementation of the cooperative network. In particular, the fast selection of appropriate relay terminals is a main issue in the design of cooperative MAC protocols.

The selection process in [10], [11] has some limitations. First, collisions among relay candidates may occur. Even if the protocol can be adjusted to minimize the risk of a collision, the selection procedure may fail in finding a relay. Second, the duration of the selection step has not been optimized yet. Actually the amount of time devoted to this task cannot be predicted because the channel is accessed randomly and collisions occur between available relays [9], [12]. More generally, the optimization of the selection has not been included in the design of the cooperative protocols [14], [15]. This issue has been addressed in [16], [17] through splitting algorithms. However, the time devoted to the selection process, even though minimized, is still unpredictable. Third, one relay is always chosen even if it cannot improve the direct path. All these limitations show that resources are allocated to the selection of a best relay without any guarantee of success.

In order to tackle these issues, we propose a new cooperative MAC protocol. We call this protocol OXIDE: an On-demand Cooperation with a Selection of relays Initiated by the Destination Equipment. The main contribution of this paper consists in the design of a proactive mechanism in order to select the best relay. In our proposed protocol, each destination terminal

[2]In [8], other optimal DMT curves have been established when no feedback to the transmitting terminal is allowed.

maintains a table of potential relay terminals that can assist in its decoding by overhearing ongoing transmissions [15]. Each destination terminal maintains a table for each source terminal. When a source terminal sends a message, all the terminals in the range of the source terminal store the data frame and wait for an acknowledgment from the destination terminal. When the destination succeeds in decoding the source message, it transmits a positive acknowledgment and all the terminals in the range of the source terminal discard the source message. When the destination terminal fails in decoding the source message, it looks for a potential relay terminal in the table associated with the source terminal. When a relay terminal is successfully found, the destination terminal sends a negative acknowledgment for the source message with the address of the selected relay in a specific field. All the terminals in the range of both the source terminal and the destination terminal discard the source message except the selected terminal that retransmits the source message. When there are no relay available, or when the negative acknowledgment is not successfully decoded by the selected relay, the source terminal retransmits its message. This protocol guarantees efficient cooperation. Indeed, destination terminals use the negative acknowledgment frame only when they find terminals that can improve the direct transmission. The selection mechanism is centralized at destination terminals. So collision among relay candidates is now avoided [9], [10], [18]. In particular, the problem of hidden groups of relays is avoided. Moreover, no signaling frames are required to either implement the cooperative transmission or allocate a relay terminal to the direct transmission. The proposed protocol is optimal in terms of the DMT criterion since it implements the two basic functionalities: *on-demand cooperation* and *selection of a best relay terminal*. Moreover, the protocol relies on a selective DF transmission scheme since this scheme is more efficient than the fixed AF scheme in terms of outage probability [10], [11], [13]. The protocol recommends also that the destination terminal *discards the source message* when D fails in decoding the data transmitted by S. This provides optimization opportunities at the destination terminal. Basically, when $(N-1)$ relays are available, a diversity order of N can be achieved. This means that the outage probability of the transmission scheme decays like $1/SNR^N$. This property is similar to the one achieved by a Selection Combining (SC) receiver in a Single Input Multiple Output (SIMO) transmission. Selecting the best antenna in a set of N receiving antennas provides a diversity order of N. The diversity order is the same as the one that is achieved by the optimal receiver, the Maximum Ratio Combining (MRC) receiver. The outage probability achieved by the MRC receiver is lower than the one achieved by the SC receiver but the slope of the outage probability curve is the same for both receivers. So, dropping the erroneous frame at the destination terminal performs a kind of SC reception.

We consider Nakagami-m fading channels in order to encompass a variety of fading models followed in the literature. Classical Rayleigh fading model corresponds to the case $m = 1$ while the Rice fading model corresponds to the case $m = (\kappa+1)^2/(2\kappa+1) > 1$, where κ is the Ricean factor.

Though restricted to the context of WMNs and fixed ad hoc networks in this paper, this protocol can also be applied to other wireless architectures such as broadcast wireless systems. We believe that our proposal can benefit the delivery of broadband services in several contexts since it provides an efficient transmission scheme in terms of both bandwidth and energy consumption.

The cooperative MAC protocol is described in details in section II. In section III, we show that this new protocol provides an optimal performance in terms of DMT. Simulation results are presented in section IV and we conclude in section V.

II. On-demand Relaying with Selection of the Best Relay Terminal

In this section, we first present the system model, i.e., the channel model and assumptions on the scenario. Then, the OXIDE protocol is described at the MAC layer. The description focuses on the main task to be completed by the MAC layer of a cooperative protocol, i.e., the selection and allocation of the relay to a transmission between a source and a destination. Then the transmission algorithm is presented. This part shows the interactions between the PHY layer and the MAC layer.

A. System model

The Nakagami - m fading channel model is considered in this paper. We use this model because it encompasses a wide variety of fading models. Rayleigh and Rice fading channel models can be considered as special cases of Nakagami - m fading channel models. Our analysis also focuses on the case of slow fading. Indeed, maintaining relay tables in mobile environments with time varying channels is not possible. Channel conditions may drastically change between the time when the channel measure is done and the time when the measure is used to set up a cooperative network. This could lead to inappropriate relay selections. So we focus on fixed scenarios, for which the coherence time was found to be on the order of a few seconds. 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. The parameter h_{ij} is the channel gain between a transmitting terminal i and a receiving terminal j. We consider scenarios in which each fading coefficient h_{ij} is accurately measured by 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, the channel gain h_{ij} between any two pair of terminals i and j is distributed according to a Nakagami-m distribution. In particular, the random variable $|h_{ij}|^2$ is gamma distributed with scale parameter θ_{ij} $(\theta_{ij} > 0)$ and shape parameter κ_{ij} $(\kappa_{ij} > 0)$. So, the probability density function $f_{|h_{ij}|^2}(x; \kappa_{ij}, \theta_{ij})$ of the random variable $|h_{ij}|^2$ is

$$f_{|h_{ij}|^2}(x; \kappa_{ij}, \theta_{ij}) = \frac{x^{\kappa_{ij}-1}}{\theta_{ij}^{\kappa_{ij}}\Gamma(\kappa_{ij})}\exp(-\frac{x}{\theta_{ij}})$$

where $\Gamma(y)$ denotes the complete gamma function

$$\Gamma(y) = \int_0^{\infty} t^{y-1}\exp(-t)dt$$

Let P be the power transmitted by each terminal and σ_w^2 be the variance of the Additive White Gaussian Noise (AWGN) 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. This pair may belong to any route in the network. Amongst terminals within the range of both the source terminal and the destination terminal, we focus on $(N-1)$ specific terminals (see Fig. 1). These terminals are available for implementing a cooperative transmission and they are not allocated to any other transmission. However, these $(N-1)$ terminals are likely to cause collision if they try to transmit data all at once. All other terminals are assumed to remain silent because they do not implement a cooperation functionality, or their cooperation functionality has been switched off. Hence, no extra interference occurs from neighboring terminals. This also contributes to reduce the impact of cooperative communications on the rest of the network. So the selection of relays is made among the set of available terminals. This has been done with the purpose of reducing the contention level in the network. In any case, if a terminal should interfere with the cooperative transmission, the proposed protocol is implementing classical error recovery mechanisms.

B. Description of the protocol

The main task implemented at the MAC layer consists in allocating a relay terminal to a link between a source and a destination. This task involves four steps that are described in the following: activation of the cooperative mode, collection of cooperation information (CoI), relay selection, and notification of the terminals. Most of existing cooperative MAC protocols are implementing these steps [19]. In the following, we review these four tasks.

1) Activation of the Cooperation Mode: the OXIDE protocol is assumed to have been implemented on each terminal within the network coverage area. So there is no inter-operability issue. Up to now, it is not possible to ensure the inter-operability between legacy networks and networks implementing cooperative MAC protocols. This reason is twofold. First, the frame scheduling is changed since extra transmissions are required, namely relay transmissions. Second, setting up cooperative networks requires the transmission of additional signaling frames, or at least the modification of existing ones. We also assume that the cooperation functionality has been turned on, on all terminals. So, no terminal has to decide whether it should cooperate or not. This decision depends on many parameters and is still an open issue for future designs in cooperative networks. For instance, a terminal at a central point in the network may choose not to cooperate because other terminals will ask its cooperation too frequently and that will consume its resources too rapidly. At upper layer, this point also raises billing issues.

2) CoI Collection: a table of terminals, referred to as the *Relay-Table*, is maintained at each terminal. The stored terminals can be used as relays when cooperation is needed. One *Relay-Table* is maintained for each possible source address. The maintenance of a *Relay-Table* involves two tasks [15]: creation and updating. The two tasks are done by overhearing all ongoing transmissions. As soon as terminal D overhears a transmission between terminal S and terminal T, terminal T is considered as a potential relay for the transmission between S and D. Hence, whenever terminal T sends a message toward terminal D, terminal D stores the channel state information (CSI) related to the channel between T and D. This CSI can be a channel metric such as $SNR|h_{TD}|^2$, where h_{TD} is the channel gain between terminal T and terminal D, and SNR is the signal to noise ratio at the receiver. Since all the terminals use the same frequency band for transmission and reception, the channel between any two terminals is symmetric. So, we assume that h_{TD} equals h_{DT}. The fields contained in the *Relay-Table* are shown in Fig. 4. Entries are ordered by the timestamp values, based on the last time a frame from that terminal is overheard. The first column in Fig. 4, namely the *ID* field, stores the MAC address of a potential relay terminal T learned from the data frames transmitted by terminal T. The *Time* field stores the time of the last frame transmission heard from terminal T. The *CSI* field stores the channel metric $SNR|h_{TD}|^2$ from terminal T to the destination terminal. The last field in the table, *NbFailures*, tracks the number of sequential failures associated with the particular terminal T. When this number exceeds a predefined threshold value[3], the corresponding entry is removed from the *Relay-Table*. The value of *NbFailures* is incremented after every failed transmission attempt through terminal T, and this value is reset to zero after a successful transmission through terminal T. Each of these entries is updated to reflect the current channel conditions and status.

ID 6 bytes	*Time* 1 byte	*CSI* 4 bytes	*NbFailures* 1 byte
MAC address of terminal T	The time of the last frame transmission heard from terminal T	The channel metric from terminal T to terminal D	The number of sequential failures associated with terminal T

Fig. 4. Format of the *Relay-Table* for terminal D.

3) Relay Selection Algorithm: in order to select useful relay terminals, a terminal D should select a terminal T in its *Relay-Table* when terminal T satisfies

$$I_{TD} > \frac{R}{2}$$

where I_{TD} denotes the mutual information of cooperation transmission through the channel between T and D and R denotes the spectral efficiency of the direct transmission between S and D. The $1/2$ factor comes from the following fact. The mutual information of the cooperative transmission through terminal T cannot be higher than $R/2$ since the cooperation uses two links with a spectral efficiency of R. Note that D can compute the spectral efficiency R by knowing the frequency band of the transmission, the duration field in the data frame, and other physical layer parameters, such as the modulation type. Thus, only terminals that can improve a transmission will be selected as relay terminals in a *Relay-Table*. When selective DF is considered, the mutual information of the cooperative transmission, I_{TD}, is defined as

$$I_{TD} = \frac{1}{2}\log_2(1 + SNR|h_{TD}|^2) \tag{1}$$

[3]The recommended value in [15] is 3.

This expression differs from the one that is usually given

$$\frac{1}{2}\log_2(1 + SNR|h_{SD}|^2 + SNR|h_{TD}|^2)$$

This is due to the fact that the destination terminal discards the source message in case of a decoding failure. The $1/2$ factor in (1) comes from the fact that cooperation uses twice the bandwidth. When the *Relay-Table* has more than one entry, terminal D select the terminal that maximizes the mutual information of the cooperative transmission I_{TD}. Let's denote this terminal, terminal B (B for Best terminal).

4) Notification of the terminals: terminal D notifies the result of the relay selection by sending a negative acknowledgment on the data frame transmitted by terminal S, denoted CFC for Claim For Cooperation following [12], [20]. The CFC frame includes the MAC address of terminal B.

C. Remarks on the Protocol Design

We give here some additional comments on the protocol design:

- *Use of signaling frames before the transmission of the data frame*: several cooperative MAC protocols rely on the exchange of modified signaling frames before the transmission of the data frame by the source terminal. For instance, Request-to-Send (RTS) and Clear-to-Send (CTS) signaling frames are modified when cooperative MAC protocols are implemented in the context of IEEE 802.11-based networks [14], [15], [18]. 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 beyond the scope of this paper.
- *The negative acknowledgement approach*: an additional CRC (Cyclic Redundancy Check) is appended to the control field of the source message. This additional CRC is only dedicated to the detection of errors in the destination address field. So a terminal is able to know whether the destination address is correct or not. Hence, when the CRC of the entire frame is wrong and the additional CRC is correct, the destination terminal can send a negative acknowledgment frame, i.e., the CFC, that triggers the frame forwarding at the selected relay provided that such a relay has been found in the corresponding *Relay-Table*.
- *Error recovery mechanism*: a timeout is used at the source terminal to avoid blocking states. In particular, as soon as a frame is missing or when the set of relay is empty, the protocol returns to its starting point according to a given timeout.
- *Storage Overhead*: the storage overhead may become an issue when the network density increases because the size of the *Relay Table* is increasing accordingly. A first solution to limit the size of the tables consists in limiting the number of allowed failures per relay terminal to one failure. Hence, a terminal is discarded from the table as soon as a failed cooperative transmission occurred through the terminal. This reduces the number of entries in the table. We consider that the procedure does not alter the capability of destination terminals to find a relay. Indeed, as the network density increases, it can be inferred that cooperation opportunities are also increasing. Further optimization is possible by limiting the number of entries N_e in relay tables. The number N_e must not be limited to one. Instead, the thorough adjustment of this parameter should take into account the network density and mobility metrics. One solution could consists in maintaining two tables: one table for trusted relays and a backup table that tracks potential relays for future use. The complete study of this issue is left for future work.
- *Opportunistic Approach*: the OXIDE protocol is an opportunistic protocol that takes advantage of the fact that terminals in the vicinity of terminal S have been able to decode the source message. The protocol has been designed with the objective to reduce the signaling overhead due to relay selection. Hence, as soon as a cooperative trial has failed, the transmission mode switches to a direct transmission mode. There is no selection of a second best relay. Note also that the selection process guarantees a good channel quality between the best relay terminal and the destination terminal. But the best relay may fail in decoding the source message. Here also, the option consists in switching to the direct transmission mode in order to avoid sending additional signaling frames, even if there could be other potential relays.

D. Transmission Algorithm

The flow charts at the source terminal S, the destination terminal D, and a potential relay terminal T are depicted in Fig. 6 to 8 and the frame exchange sequence is presented in Fig. 5.

1) Source Terminal S:

- S waits for data to send. As soon as S has data to send, S enters the subsequent step.
- S sends the data frame and triggers a timeout. When the source terminal S sends its message, each terminal in the range of S can overhear the transmission. This event triggers the storage of the source message at the relay candidates.
- When no acknowledgment frame (positive or negative) has been successfully received by S before the timeout, S goes to the previous step. Otherwise, S proceeds to the next step.
- S tests whether it has received a positive ACKnowledgment (ACK) frame or a negative acknowledgment frame CFC.
  - When S receives an ACK frame, it goes back to the first step.
  - When S receives a CFC frame, it adjusts its timer according to a new timeout in order to take into account the transmission of the best relay. Then, S waits for a positive acknowledgment frame ACK from D.
- When S successfully receives a positive acknowledgment

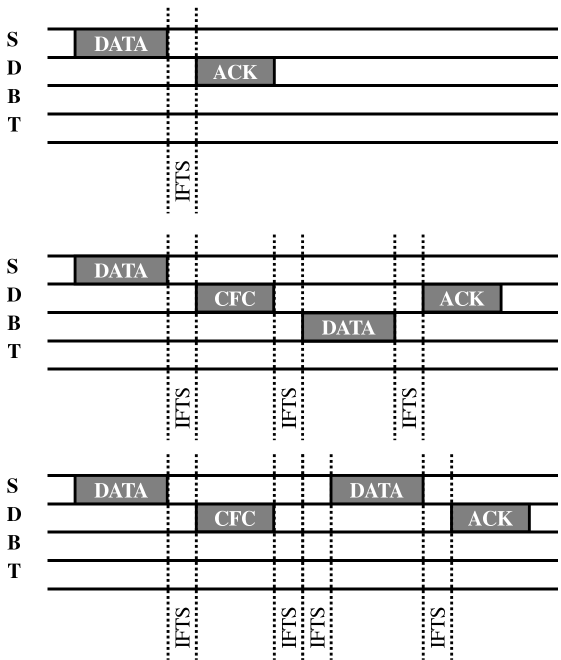

Fig. 5. Frame exchange sequence in the OXIDE protocol (S is the source terminal, D is the destination terminal, B is the best relay terminal, and T is a relay candidate). The top figure represents the case when D succeeds in decoding the data frame from S. The middle figure represents the case when D asks for cooperation and B is relaying. The bottom figure represents the case when the cooperation fails and S must retransmit its frame.

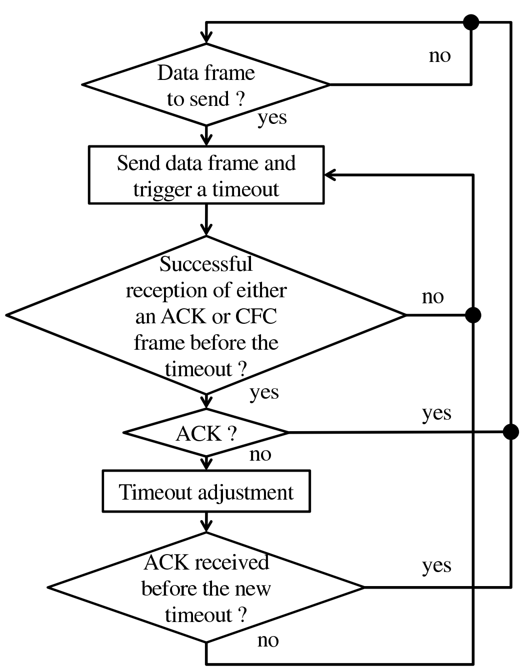

Fig. 6. Flow chart at the source terminal S.

frame ACK from D, it proceeds to the first step. Otherwise, it retransmits the data frame.

2) Destination Terminal D: a flag bit F is defined and set to 0.

- When set to 0, the flag bit indicates that D is waiting for a data frame from a source terminal.
- When set to 1, the flag bit indicates that D is waiting for a data frame transmitted by a selected relay.

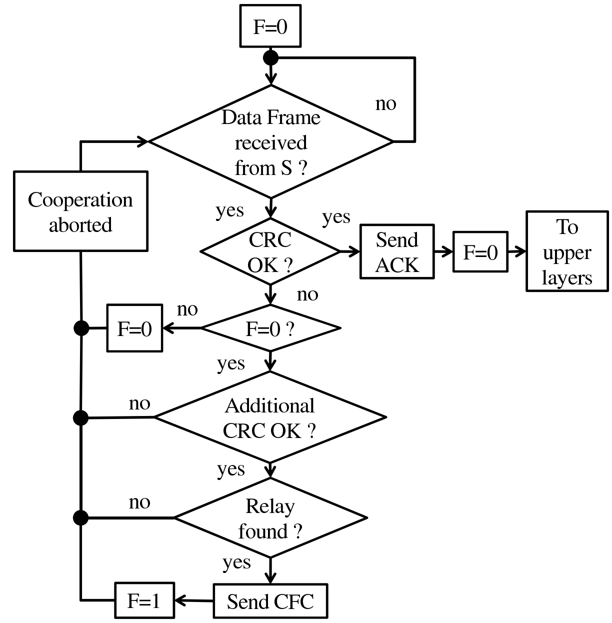

Fig. 7. Flow chart at the source terminal D.

Whenever D receives a data frame from a terminal, it checks the CRC.

- When the data frame passes the CRC check, the data frame is sent to upper layers, D sends a positive acknowledgment frame (ACK), and the flag F is set to 0. So D is now waiting for another frame from a source terminal.
- When the data does not pass the CRC check, the received frame is erroneous. The flag F has to be checked.
  - When the flag bit is 0, that means that the frame being processed has been sent by a source terminal. So, D checks the additional CRC on the destination address field.
    - ∗ When the additional CRC is correct, terminal D searches for a relay terminal in the *Relay-Table* dedicated to terminal S.
      - · When a relay is found, D sends a negative acknowledgment frame CFC, and set the flag F to 1. Even in that case, the data frame is discarded. This allows processing optimization at the destination terminal without sacrificing the optimality of the DMT.
      - · Otherwise, the cooperation is aborted.
    - ∗ When the additional CRC is not correct, the cooperation is aborted.
  - When the flag bit is 1, that means that the frame being processed has been sent by the selected relay. At that point, the relaying has failed because the two frames - the one from the source and the one from the selected relay - have been received with errors. So, the cooperation is aborted.

When cooperation is aborted at the destination terminal, D discards the data frame, remains silent, and waits for a retransmission of the data frame by the source terminal. The retransmission will be triggered by a timeout at the source terminal.

3) Potential Relay T: whenever T successfully overhears and decodes a data frame from a source terminal S, it stores the data frame and waits for an acknowledgment frame from the corresponding destination terminal D.

- When T successfully decodes a positive acknowledgment frame from D, it discards the data frame from S and goes back to the Initial Waiting State (IWS).
- When T successfully decodes a negative acknowledgment frame from D, i.e., a CFC frame, T checks the destination address.
  - When the destination address corresponds to the address of terminal T, T induces that it has been selected as best relay. So T retransmits the data frame from S, then discards the data frame, and goes back to the IWS.
  - Otherwise, T discards the data frame and goes back to the IWS.
- Otherwise T discards the data frame and goes back to the IWS after a timeout.

When the best relay B fails in decoding either the source message or the negative acknowledgment, terminal B remains silent according to the selective DF forwarding scheme and S re-transmits its data frame. No second best relay is selected at that point since the protocol is essentially opportunistic. Indeed, as soon as the cooperation fails, a typical Automatic Repeat reQuest (ARQ) mechanism is implemented. So the re-transmission of source S is triggered by one of these two events:

- S receives the CFC frame and the medium is free after a time period larger than an inter-frame time,
- a timeout expires at terminal S.

All the frames are separated by Inter-Frame Time-Slots (IFTSs). Note that an extra IFTS is added to the waiting time of terminal S in order to avoid collision between its retransmission and the forwarding of terminal B[4]. This time slot equals an IFTS[5].

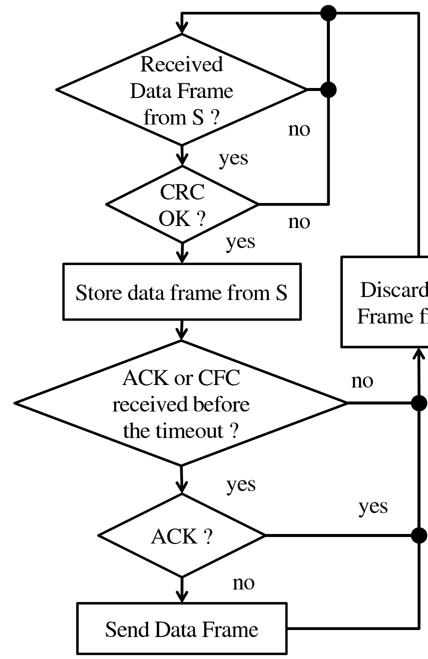

Fig. 8. Flow chart at a potential relay T.

III. Performance Analysis of the OXIDE Protocol

The DMT curve of the OXIDE protocol is studied in this section. Our channel models are characterized using the system model described in the previous section, and a time-division notation[6]. We define three discrete time received signals. Here, $y_{ij}(n)$ denotes the signal received by terminal j and transmitted by terminal i. The destination terminal D and the best relay terminal B are receiving signals from S during a first time-slot

$$y_{SD}(n) = h_{SD}x(n) + w_{SD}(n)$$
$$y_{SB}(n) = h_{SB}x(n) + w_{SB}(n)$$

for $n = 1, 2, ..., T_M/2$, where T_M denotes the duration of time-slots reserved for each message. No signal is transmitted by the best relay terminal B when terminal D succeeds in decoding the data frame from S. Otherwise, a new signal is transmitted by B, using a selective DF scheme, i.e., if and only if it has been able to decode the source message. So we consider that the estimation of signal $x(n)$, denoted $\hat{x}(n)$, is error free. Hence, D is receiving a signal from B during the second time slot

$$y_{BD}(n) = \begin{cases} h_{BD}x(n) + w_{BD}(n), & \text{if } I_{SB} > R \\ 0, & \text{if } I_{SB} \leq R \end{cases}$$

for $n = T_M/2+1, ..., T_M$, where the mutual information I_{SB} is given by

$$I_{SB} = \log_2(1 + SNR|h_{SB}|^2)$$

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 $x(n)$. Without loss of generality, we impose the same power constraint at both the source and the relay: $E[|x(n)|^2] \leq P$. The source and the relay are assume to each transmit orthogonally on half of the time-slots. Perfect synchronization is assumed at the block, carrier, and symbol level.

The diversity gain $d_{OXIDE}(r)$ of the OXIDE protocol is defined by

$$d_{OXIDE}(r) = \lim_{SNR \to \infty} -\frac{\log[p_{OXIDE}^{out}(SNR, r)]}{\log(SNR)}$$

The probability $p_{OXIDE}^{out}(SNR, r)$ is the outage probability for a signal to noise ratio SNR and a spatial multiplexing gain r defined by

$$r = \lim_{SNR \to \infty} \frac{R}{\log_2(SNR)}$$

where R is the spectral efficiency of the direct transmission (in b/s/Hz). For high SNR values, we use

$$R = r \times \log_2(SNR) \quad (2)$$

[4]Note that the source terminal does not need to overhear the CFC frame from D. Its retransmission is triggered by a given timeout.

[5]This time is referred to as a SIFS (Short Interframe Space) in IEEE 802.11-based networks.

[6]Frequency-division counterparts to this model are straightforward.

The event that the relay has successfully decoded the data transmitted by S with a spectral efficiency R is equivalent to the event that the mutual information of the channel between S and the best relay B, I_{SB}, lies above the spectral efficiency R [3], [9]. When $(N-1)$ terminals are available, the OXIDE protocol is in outage if all the $(N-1)$ relay candidates fail in improving the direct transmission

$$\begin{aligned} p^{out}_{OXIDE}(SNR,r) &= \Pr[I_{SD} \leq R] \\ &\times \Pr[\bigcup_{i=1}^{N-1} (I^{(i)}_{OXIDE} \leq \frac{R}{2}) | I_{SD} \leq R] \end{aligned} \quad (3)$$

where $I^{(i)}_{OXIDE}$ is the mutual information of the relayed transmission using selective DF cooperation scheme at terminal R_i and implementing frame dropping at the destination terminal (the source message is discarded at the destination terminal when cooperation is needed)

$$I^{(i)}_{OXIDE} = \begin{cases} \frac{1}{2}\log_2(1+SNR|h_{SD}|^2), & \text{if } I_{SR_i} \leq R \\ \frac{1}{2}\log_2(1+SNR|h_{R_iD}|^2), & \text{if } I_{SR_i} > R \end{cases}$$

where the mutual information I_{SR_i} is defined by

$$I_{SR_i} = \log_2(1+SNR|h_{SR_i}|^2)$$

and the mutual information I_{SD} is defined by

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

The probability $p^{out}_{OXIDE}(SNR,r)$ can be expressed as the sum of $2^{(N-1)}$ terms

$$p^{out}_{OXIDE}(SNR,r) = \sum_{j=1}^{2^{(N-1)}} P_j$$

where P_j is given by

$$P_j = P^E_j \prod_{i=1}^{N-1} \Pr[\epsilon^{(i)}_j] \quad (4)$$

where

$$P^E_j = \Pr[I_{SD} \leq R] \times \Pr\{\bigcup_{i=1}^{N-1} [I^{(i)}_{OXIDE} \leq \frac{R}{2} | (\epsilon^{(i)}_j, I_{SD} \leq R)]\}$$

The event $\epsilon^{(i)}_j$ equals the event $I_{SR_i} \leq R$ or $I_{SR_i} > R$ according to the value of index j, $1 \leq j \leq 2^{(N-1)}$.

Using (6) and (7) from [1], we have that

$$\lim_{SNR\to\infty} \frac{\log[P_j]}{\log(SNR)} = (\kappa_{SD} + \sum_{k\in K_j} \kappa_{SR_k} + \sum_{l\in L_j} \kappa_{R_lD})(r-1)$$

for every j, $1 \leq j \leq 2^{(N-1)}$, where κ_{ij} is the shape parameter or the random variable $|h_{ij}|^2$, where i (resp. j) denotes the transmitting (resp. receiving) terminal. For $1 \leq i \leq (N-1)$, we define $\kappa_i = \min\{\kappa_{SR_i}, \kappa_{R_iD}\}$. So, we have that

$$\lim_{SNR\to\infty} \frac{\log[P_j]}{\log(SNR)} \leq (\kappa_{SD} + \sum_{i=1}^{N-1} \kappa_i)(r-1)$$

So, we deduce that

$$\lim_{SNR\to\infty} -\frac{\log[p^{out}_{OXIDE}(SNR,r)]}{\log(SNR)} \geq (\kappa_{SD} + \sum_{i=1}^{N-1} \kappa_i)(1-r)$$

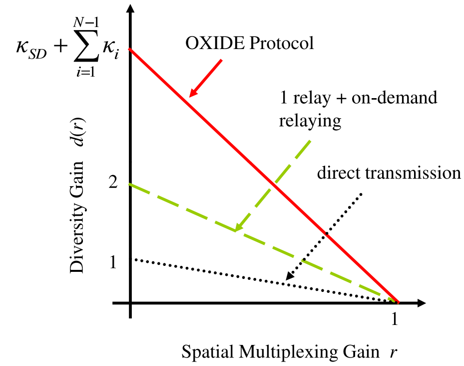

Fig. 9. DMT curve of three protocols : the OXIDE protocol, the direct transmission, and the on-demand cooperation with one relay terminal [7]. For the special case of Rayleigh fading, $\kappa_{SD} + \sum_{i=1}^{N-1} \kappa_i = N$.

Hence, the diversity curve $d_{OXIDE}(r)$, i.e., the DMT of the OXIDE protocol, is lower bounded by the following expression

$$d_{OXIDE}(r) \geq (\kappa_{SD} + \sum_{i=1}^{N-1} \kappa_i)(1-r) \quad (5)$$

For the special case of Rayleigh fading, i.e $\kappa_{SD} = \kappa_i = 1$ for $1 \leq i \leq (N-1)$, we have that

$$d_{OXIDE}(r) = N(1-r)$$

So, the OXIDE protocol achieves the optimal DMT curve (see Fig. 9). That means that the data rate of the overall transmission scales like the data rate of a direct transmission, even in presence of a cooperative relaying. In particular, the overheard induced by the additional signaling frame (CFC) does not appear in (5) because the DMT analysis is just providing a rough estimate of the achieved multiplexing gain r, not a precise value. Hence, the spatial multiplexing gain scales like 1. This results is consistent with the one obtained with other on-demand cooperation techniques [7].

IV. Simulation Results

The simulations focus on the cooperative communications, i.e., on the PHY layer. We consider a single source-destination pair. We assume that there are $(N-1)$ terminals available for cooperation in the range of both source and destination terminals, i.e., they all implement the cooperation functionality. We assume slow fading Nakagami-m channels with $m = 1$ (Rayleigh fading) between each pair of terminals, with equal variance: $\sigma^2 = 1$. The channel gains are assumed to be known at the receiver side. We assume that the coherence time of wireless channels is much greater than the duration of a MAC frame so that the time variations of the channels can be easily tracked [21]. The simulation is organized as follows. The channel gains are drawn for each trial. An outage event occurs when

- none of the relay candidates is able to improve the direct transmission,
- the selected relay failed in decoding the source message and thus cannot forward the message to the destination.

These events are characterized by the mutual information of the wireless channels being lower than a given threshold

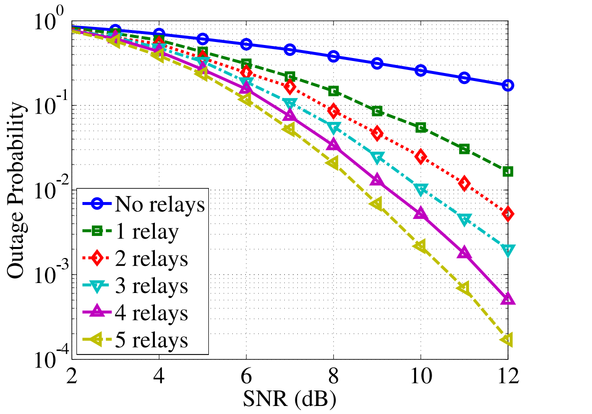

Fig. 10. Outage performance of direct transmission (0 relay) and cooperative transmissions using the OXIDE protocol (from one to four relays).

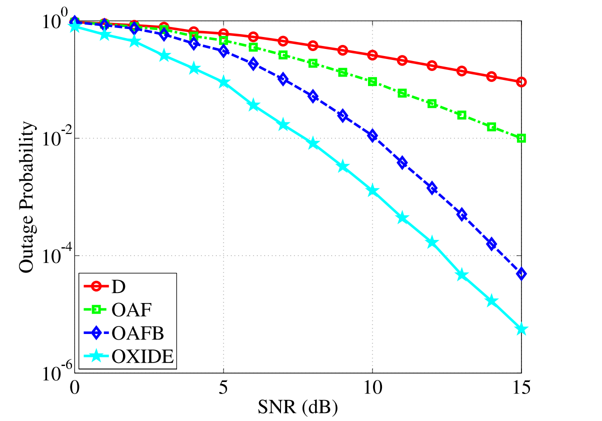

Fig. 11. Outage performance of noncooperative and cooperative protocols ($N = 5$): direct transmission (D), on-demand AF relaying with one relay (OAF), on-demand AF relaying with selection of the best relay terminal (OAFB), and OXIDE protocol (OXIDE).

of the spectral efficiency. The simulation is stopped when one hundred outage events have been counted. Hence, the outage probability is estimated with a relative mean square error of 10^{-2}. This precision is sufficient since we are only interested in the order of magnitude of the outage probability. Fig. 10 shows the simulation results for several values of the signal-to-noise ratio SNR and for several values of N, the number of transmitting terminals, i.e., one source and $(N-1)$ relay candidates. For large SNR values, the slopes of the curves indicate that the spatial diversity order of the transmission scheme increases with the number of relays. Moreover, the slope of each curve equals the number of transmitting terminals: N. So, we deduce from Fig. 10 that the OXIDE protocol achieves full diversity order. This result is consistent with the expression of the DMT curve in (6).

We now compare the outage probability of four transmission schemes: the direct transmission (D), the on-demand AF relaying with one relay (OAF) [7], the on-demand AF relaying with non collision-free selection of relays (OABF) [10], and the OXIDE protocol. The OAF protocol implements on-demand relaying with one single relay terminal. First, the source terminal transmits its information. Then the destination indicates success or failure by broadcasting a single bit of feedback to the source and relay. When the feedback signals a success, the relay does nothing. Otherwise, the relay amplify and forward the signal received from the source. Note that the relay selection is not addressed in [7]. The diversity order of this transmission scheme should be 2. The OABF implements also on-demand relaying and an AF transmission scheme. When the destination fails in decoding the source message, it asks for cooperation and the relay candidates enter a competition step. Each relay signals its presence after a waiting time inversely proportional to some CSI. So the selected relay is the one that signals its presence first. This transmission scheme cannot ensure the absence of collision between relay candidates, so the selection process may fail in choosing a relevant relay for the cooperative transmission. This protocol achieves a full diversity order, i.e., a diversity order of N, the number of transmitting terminals. Note that the risk of a failure in the selection process has not been taken into account in the DMT analysis of the OABF protocol. The same procedures are used to simulate these protocols and the OXIDE protocol. Channels gains are drawn and outage events are counted according to the mutual information of the wireless channels between participating terminals. We assume slow fading Nakagami-m channels between each pair of terminals, with equal variance: $\sigma^2 = 1$. The channel gains are assumed to be known at the receiver. To ensure fair comparison, the OAFB and the OXIDE protocols use the same number of relay candidates $(N-1)$. Moreover, the single relay for the OAF protocol is chosen randomly among the set of N potential relays. As Fig. 11 indicates, all the presented protocols achieve full diversity. The direct transmission achieves a full diversity order of 1 since there is only one transmitter. The OAF protocols achieves a diversity order of 2 because there are exactly two transmitting terminals: the source and the relay. The OAFB and the OXIDE protocols achieve full spatial diversity of order N, the number of cooperative terminals, for sufficiently large SNR. In other words, the outage probability of these protocols scales like $1/SNR^N$ where N is the number of transmitting terminals. Moreover, the new OXIDE protocol achieves a better outage probability because it uses a selective DF transmission scheme instead of a fixed AF transmission scheme [7].

V. Conclusion

This paper presented the design of a new cooperative MAC protocol in the context of WMNs: the OXIDE protocol. This protocol relies on two basic features. First, cooperation is activated only when needed, i.e., a destination terminal asks for cooperation when it fails in decoding a data frame transmitted by a source terminal. Second, the cooperation is provided by a relay that has been selected by the destination terminal. For that purpose, the destination terminal maintains tables of relay terminals, one for each possible source address. These tables are constituted by passively overhearing ongoing transmissions and they contain parameters characterizing each relay candidate. Hence, when cooperation is needed for the transmission between a source S and a destination D, and when a relay B is found by terminal D in the relay table associated with terminal S, the destination terminal sends a negative acknowledgment frame that contains the address of

B. When the best relay B has successfully decoded both the source message and the call for cooperation, it sends a copy of the data frame to D using a selective DF transmission scheme.

The on-demand approach allows maximization of the spatial multiplexing gain and the cooperation of the best relay allows maximization of the spatial diversity order. Hence, The OXIDE protocol achieves an optimal DMT curve. Moreover, this performance is achieved through a collision-free selection process.

The simulation of the OXIDE protocol focused on a single wireless link between a source terminal and a destination terminal. The performance and the impact of the protocol should now be assessed at an upper level. Indeed, the overall throughput of the network may be affected by the implementation of the OXIDE protocol. In particular, the increase of contention areas due to cooperative communications should be addressed. Moreover, this paper focused on the trade-off between the spatial diversity gain and the spatial multiplexing gain. This issue takes into account the fading due to the mobility of the network, i.e., the motion of the terminals and the motion of obstacles between the terminals. Channel fading is also due to free-space losses and shadowing effects. Taking into account these phenomenons may lead to new optimization opportunities, namely in terms of energy savings. Future versions of the OXIDE protocol will address this issue.

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