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Splitting algorithm for DMT optimal cooperative MAC protocols in wireless mesh networks

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A B S T R A C T

A cooperative protocol for wireless mesh networks is proposed in this paper. The protocol implements both on-demand relaying and a selection of the best relay terminal so only one terminal is relaying the source message when cooperation is needed. Two additional features are also proposed. The best relay is selected with a splitting algorithm. This approach allows fast relay selection within less than three time-slots, on average. Moreover, a pre-selection of relay candidates is performed prior to the splitting algorithm. Only terminals that are able to improve the direct path are pre-selected. So efficient cooperation is now guaranteed. We prove that this approach is optimal in terms of diversity-multiplexing trade-off. The protocol has been designed in the context of Nakagami-*m* fading channels. Simulation results show that the performance of the splitting algorithm does not depend on channel statistics.

Keywords:
Cooperative communications
MAC protocols
Diversity-multiplexing trade-off

1. Introduction

Cooperative communications allow significant performance improvements in the context of Wireless Mesh Networks (WMNs) because they enable data transmission between two terminals through alternate paths. Cooperation between terminals mainly involves two protocol layers: cooperative transmissions are managed at the physical (PHY) layer whereas the set up of the cooperation is performed at the medium access control (MAC) layer. At the PHY layer, cooperative communications increase the reliability of the wireless link between a source terminal S and a destination terminal D (direct link) by allowing one or several relays to receive and forward source messages to D (see Fig. 1). Hence the direct link is made more robust to channel impairments but this is achieved through an increase in the bandwidth consumption [1–4].[1] The compromise between the robustness and the capacity of cooperative transmissions is usually characterized by a diversity-multiplexing tradeoff (DMT) curve [5]. The DMT analysis of a transmission scheme yields the diversity gain $d(r)$ achievable for a spatial multiplexing gain r. The diversity gain and the multiplexing gain characterize the robustness and the capacity of the link, respectively. When $(N-1)$ relays are available, an optimal DMT curve $d(r)$ is achieved by implementing on-demand relaying and a selection of the best relay [6–10]: $d(r) = N(1-r)$ for $0 \leq r \leq 1$. In an on-demand relaying scenario, relay terminals transmit only when the destination fails in decoding the source message. In cooperative protocols implementing a selection of the best relay, only on terminal is relaying the source message. These two features contribute in maximizing the robustness of the direct link while minimizing the bandwidth consumption.[2] Note however that DMT analyzes fail in taking into account the amount of bandwidth required to implement the cooperative network. For instance, when relay terminals are jointly transmitting using

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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.

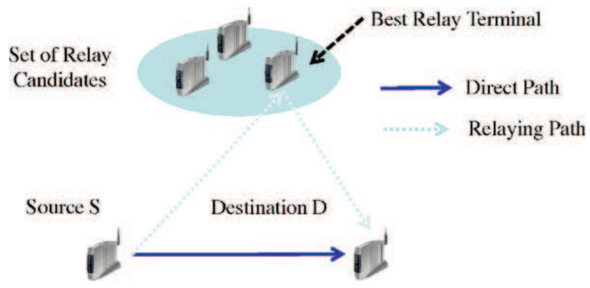

Fig. 1. Cooperation scenario with three relay terminals.

different space–time codes (STCs), the overhead induced by the allocation of STCs to relay terminals is not taken into account in the DMT computation [2]. 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 the design of cooperative MAC protocols. The selection process in [8,9] has some limitations. First, one relay is always chosen even if it cannot improve the direct path. 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 [10,7]. More generally, the optimization of the selection has not been included in the design of the cooperative protocols [11,12]. This issue has been addressed in [13,14] through splitting algorithms. However, splitting algorithms have not been included yet in the design of a DMT optimal cooperative MAC protocol.

The rationale of this proposal is to provide a fast and opportunistic method in order to overcome the temporary failures of a link between two wireless terminals. The use of cooperative communications in this context avoids the need to re-establish a whole route when one link is temporarily dropped. We start with the cooperative MAC protocols developed in [8,9]. They all implement on-demand cooperation and a selection of the best relay. It has been demonstrated that an optimal DMT is achieved when these two features are implemented. These protocols are improved with the following additional features:

- *splitting algorithm for fast relay selection*: a splitting algorithm finds a best relay terminal within less than three time-slots, on average, even for an infinite number of relay candidates [13,14].
- *pre-selection of the relay terminals*: only terminals that are able to improve the direct transmission are pre-selected. So the relevance of the selection is guaranteed. More precisely, the best relay should retransmit only when the relayed path has a mutual information greater than a given threshold [15]. Otherwise, the source terminal retransmits its message.

In this paper, Nakagami-m fading channels are considered in order to encompass a variety of fading models followed in the context of WMNs. The 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 Rician factor. We show that this on-demand relaying protocol with selection of the best relay terminal provides an optimal performance in terms of DMT. This cooperative protocol has been designed in the context of IEEE 802.11-based mesh networks. Though restricted to this standard in this paper, we believe that our proposal can also be applied to other wireless systems such as wireless sensor networks, broadband wireless networks, and broadcast wireless systems. In Section 2, we describe the protocol in detail. The DMT analysis of the protocol is presented Section 3. Two relaying scheme are investigated: a fixed amplify-and-forward (AF) relaying scheme and a selective decode-and-forward (DF) relaying scheme. Simulation results are presented in Section 4 and a conclusion is given in Section 5.

2. On-demand relaying with selection of the best relay terminal

2.1. System model

The wireless fading channel between any pair of terminals is assumed to be frequency flat fading with Nakagami-m distribution. A half duplex constraint is imposed across each relay terminal, i.e. it cannot transmit and listen simultaneously. Transmissions are time-multiplexed, i.e. they use the same frequency band. Each channel coefficient h_{ij} between an emitter i and a receiver j is accurately measured by the receiver, but not known to the transmitter. Moreover, the channel coefficient h_{ij} is identical to the channel coefficient h_{ji}. The link symmetry assumption is relevant since the forward and backward channels are using the same frequency band. Statistically, the channel gain $|h_{ij}|$ is distributed according to a Nakagami-m distribution with shape parameter m_{ij} ($m_{ij} > 0$) and scale parameter θ_{ij} ($\theta_{ij} > 0$). So the random variable $|h_{ij}|^2$ is gamma distributed with shape parameter m_{ij} and scale parameter θ_{ij}/m_{ij}.

The power transmitted by each terminal is denoted P and σ_w^2 denotes the variance of the additive white Gaussian noise (AWGN) in the wireless fading 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 link may be any segment of any route in the network.

2.2. Protocol description

We start the protocol description by fixing a design constraint: not all the terminals in the range of both the source terminal and the destination terminal are allowed to compete for best relay. Instead, a terminal is considered as a potential relay candidate only when it is available for implementing a cooperative transmission, i.e. it has not been allocated to any other transmission. In the following, we assume that there are $(N - 1)$ such terminals. These $(N - 1)$ terminals are likely to cause collision if they try to transmit data all at once. All other terminals are not interfering because either they do not implement a cooperation functionality (or their cooperation functionality has been switched off) or they are currently allocated to another transmission. Hence, no extra interference occurs from neighboring terminals. This also contributes to reduce the impact of cooperative communications on the rest of the network since potential interferers are requested to remain silent during cooperative transmissions. Note, however, that reducing the number of interfering terminals also reduces the opportunities to achieve a maximum diversity order. Clearly, the best spatial diversity gain is no longer achievable since part of possible relays has been excluded from competition. However, this has been done with the purpose of reducing the contention level in the network. Further studies should addressed this trade-off between spatial diversity and interference level. In any case, if a terminal should interfere with the cooperative transmission, the proposed protocol is implementing classical error recovery mechanisms.

2.2.1. *Cooperation mode activation*

There are $(N-1)$ relay candidates denoted $R_i,\ 1 \leq i \leq (N-1)$. The cooperation process is triggered at terminal R_i when it receives a data frame from any source terminal S. The data frame is stored at terminal R_i when R_i is implementing the cooperation functionality and R_i is not already involved in any other transmission. When terminal D succeeds in decoding the data frame and sends an acknowledgment frame (ACK), R_i discards the source message. Otherwise, terminal D discards the data frame and sends a call for cooperation (CFC) [7]. Discarding the data frame at the destination terminal saves processing time since there is no more need to combine the two signals from the source and relay. Indeed, the DMT analysis shows that the same diversity order can be achieved with or without combining the signals from both terminals. A similar result is obtained when comparing receiver architectures with multiple antennas. A receiver selecting the antenna providing the highest signal to noise ratio (selection combining) achieves the same diversity order as the receiver combining all the signals from all the antennas (maximum ratio combining).

An additional control field is appended to the data frame from S. This field contains a CRC (Cyclic Redundancy Check) that enables the detection of errors in the source address field. Hence, when the checksum of the whole frame is not correct and the checksum of the source address field is correct, the destination terminal is able to send a CFC with the source address. When a terminal R_i stores the source message, it waits for either an ACK frame or a CFC frame. When any of these two frames is not received within a given time-slot, the source message is discarded at terminal R_i.[3] So, a terminal is considered as a potential relay when it has successfully decoded both the source message and the CFC frame.[4] Moreover, terminals that satisfy the previous constraints must also satisfy the following condition. The ability of a relay to improve the direct transmission is measured by a suitability metric U: the mutual information of the cooperative transmission between the source terminal and the destination terminal through the relay. Hence, each terminal R_i is characterized by a realization of the metric U, denoted u_i. More precisely, the suitability metric u_i of R_i is defined in (5) (resp. in (9)) when a fixed AF (resp. a selective DF) transmission scheme is implemented. Hence, a relay candidate is pre-selected if the capacity of the cooperative transmission through this relay is above a given threshold. This threshold is the target data rate R. The metric is also used in the splitting algorithm in order to evaluate the relay candidates. So the best terminal is the one that achieves the best link capacity. Note that the computation of the mutual information in (5) and in (9) requires the knowledge of the channel coefficients h_{SR_i} and h_{R_iD}. These coefficients are estimated at terminal R_i using the signals corresponding to the data frame and the CFC frame respectively. Note also that a simplified expression of the metric can be obtained when using a selective DF transmission scheme. Indeed, finding the highest $I_{\mathrm{DF}}^{(i)}$ in (9) is equivalent to finding the highest $|h_{R_iD}|^2$ parameter.

2.2.2. *Splitting algorithm*

A time-slotted system is considered, with $(N-1)$ relay candidates. Each terminal R_i has a suitability metric u_i, defined as the mutual information of the cooperative transmission from S to D, through terminal R_i. The metrics are continuous, independent and identically distributed (i.i.d.) with complementary CDF (CCDF) denoted by $F_c(u) = \Pr[u_i > u]$. Therefore, the $F_c(.)$ is monotonically decreasing and invertible. The goal of the splitting algorithm consists in selecting the terminal with the highest metric. This goal is achieved through the exchange of short information frames between the relay candidates and the destination terminal. The core of the algorithm is the following transmission rule: a terminal R_i transmits at time slot k if and only if its metric u_i satisfies $H_L(k) < u_i < H_H(k)$, where $H_L(k)$ and $H_H(k)$ are the lower and upper metric thresholds, respectively [13]. The destination initiates the algorithm by sending the first thresholds, i.e. $H_L(1)$ and $H_H(1)$, to the relay candidates. Then the relay candidates respond according to the value of their metric. Three outcomes may occur:

- An empty slot is obtained when no metric lies in the interval transmitted by the destination terminal.
- A collision occurs when several metrics lie in the interval.
- A success outcome is achieved when the best metric lies in the interval.

According to the observed outcome, the destination terminal computes a two-bit feedback and send it to the relay candidates that update their thresholds accordingly. The procedure is repeated until a success outcome has been observed. The destination terminal terminates the algorithm by sending a last feedback frame with the address of the selected terminal. The algorithm steps are given below.

Initialization: the parameters are initialized as follows (for $k=1$): $H_L(1) = F_c^{-1}(1/N_r)$, $H_H(1) = \infty$, and $H_{\min}(1) = 0$. $H_{\min}(k)$ tracks the largest value of the metric known up to slot k above which the best metric surely lies. The number of possible relays is denoted N_r. This parameter is set to $(N-1)$. The destination terminal sends N_r in the

3 Note that timeouts should be delayed to take into account possible cooperative transmissions.

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

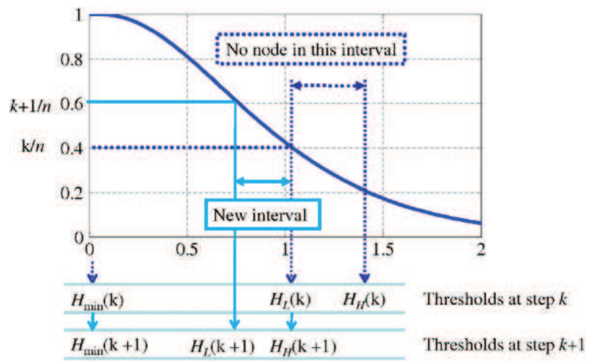

Fig. 2. Threshold adjustments of the splitting algorithm at terminal R_i when the feedback is 0 (idle) and no collision has occurred so far.

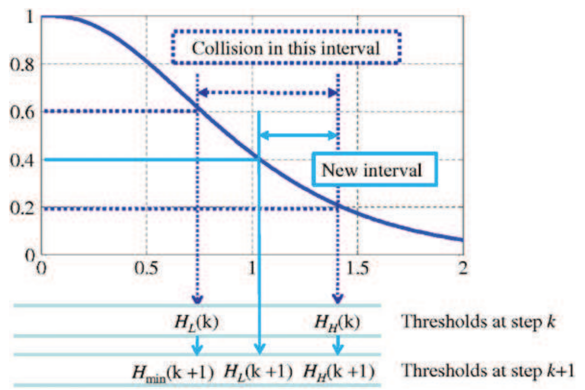

Fig. 3. Threshold adjustments of the splitting algorithm at terminal R_i when the feedback is e (collision).

CFC frame, so the relay candidates can initiate the selection process. Parameter N_r is available at the destination terminal when the routing protocol provides the number of two-hop neighbors for each terminal. Otherwise, the parameter can be overestimated based on the number of one-hop neighbors when this parameter is known by the upper layer.

Transmission rule: each terminal locally decides to transmit if and only if its metric lies between $H_L(k)$ and $H_H(k)$.

Feedback generation: the destination terminal broadcasts to all terminals a two-bit feedback at the end of each slot: (i) 0 if the slot was idle (when no terminal transmitted), (ii) 1 if the outcome was a success (when exactly one terminal transmitted), or (iii) e if the outcome was a collision (when at least two terminals transmitted).

Response to feedback: we define a split function as follows: $\text{split}(a, b) = F_c^{-1}\left(\frac{F_c(a)+F_c(b)}{2}\right)$. Then, the following updates are performed according to the feedback:

- If the feedback (of the kth slot) is an idle (0) and no collision has occurred so far, then set $H_{\min}(k+1) = 0$, $H_L(k+1) = F_c^{-1}\left(\frac{k+1}{N_r}\right)$, and $H_H(k+1) = H_L(k)$ (see Fig. 2).
- If the feedback is a collision (e), then set $H_{\min}(k+1) = H_L(k)$, $H_L(k+1) = \text{split}(H_L(k), H_H(k))$, and $H_H(k+1) = H_H(k)$ (see Fig. 3).
- If the feedback is an idle (0) and a collision has occurred in the past, then set $H_{\min}(k+1) = H_{\min}(k)$, $H_L(k+1) = \text{split}(H_{\min}(k), H_L(k))$, and $H_H(k+1) = H_L(k)$ (see Fig. 4).

A selective DF transmission scheme is considered in order to illustrate the operation of the splitting algorithm in Figs. 2–4. The suitability metric u_i for terminal R_i is defined in (9). It can be noted that the channel coefficient $|h_{R_iD}|^2$ between terminal R_i and the destination terminal D can be used directly as the suitability metric. The channel gain $|h_{R_iD}|$ is a random variable with a Nakagami-m distribution with shape parameter $m = 3$ and scale parameter $\theta = 1$.

Termination: the algorithm terminates when the outcome is a success (1).

2.2.3. Data transmission

The best relay terminal sends a copy of the data frame using either a fixed AF forwarding scheme or a selective DF forwarding scheme after the destination terminal had sent its last feedback. Terminal D sends an ACK frame when it succeeds in decoding the data frame (see Fig. 5). Otherwise, D remains silent and the timeout triggers a re-transmission at the source terminal. In the section II.B of [9] additional design constraints are given in order to implement this cooperative protocol in an IEEE 802.11-based network.

3. DMT analysis of the on-demand cooperative protocol

The DMT analysis of the proposed transmission scheme is investigated in this section. Note that the analysis is only intended for the characterization of properties related to the PHY layer. In particular, the signaling overhead due to the set up of the cooperative transmission is not taken into account in DMT analyses. More precisely, this includes the signaling for the relay selection. This approach has been adopted since the early work on DMT analyzes [2,6]. Moreover, the number of relay candidates has been limited in order to reduce the interference level. So the proposed transmission scheme is shown to be optimal in terms of diversity order given this reduced number of competitors. Further studies should provide a means to include MAC overhead in the capacity computing and then in DMT analyses. A first step toward this objective has been proposed in [16].

3.1. DMT analysis for a fixed AF transmission scheme

The channel models are characterized using the system model described in the previous section. Signals are multiplexed in time and the base-band-equivalent channel model is considered. Three discrete time received signals are defined in the following. Here, the discrete time signal received by terminal j and transmitted by terminal i is denoted $y_{ij}(n)$. During a first time-slot, S sends a signal that is received by D and the best relay B. These two signals are denoted $y_{SD}(n)$ and $y_{SB}(n)$, respectively

$$y_{SD}(n) = h_{SD}x(n) + w_{SD}(n) \quad (1)$$

$$y_{SB}(n) = h_{SB}x(n) + w_{SB}(n) \quad (2)$$

for $n = 1, 2, \ldots, T_M/2$, where T_M denotes the duration of time-slots reserved for each message. When terminal

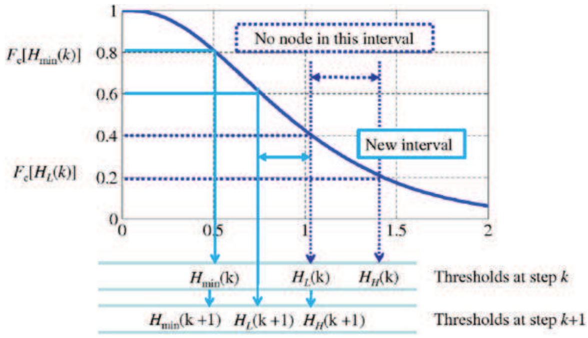

Fig. 4. Threshold adjustments of the splitting algorithm at terminal R_i when the feedback is 0 (idle) and a collision has occurred in the past.

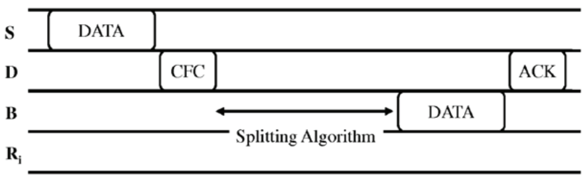

Fig. 5. Frame exchange sequence in the protocol using the basic IEEE 802.11 access method (S is the source terminal, D is the destination terminal, B is the best relay terminal, and R_i is a relay candidate).

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 $n = T_M/2+1, \ldots, T_M$. 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 the sake of fairness, the same power constraint at both the source and the relay is imposed: $E[|x(n)|^2] \leq P$ and $E[|\beta y_{SB}(n)|^2] \leq P$. A fixed AF cooperation scheme is implemented. So the normalization factor β must satisfy $\beta^2 = P/(|h_{SB}|^2 P + \sigma_w^2)$. It is assumed that the source and the relay each transmit orthogonally on half of the time-slots. We also consider that perfect synchronization is provided at the block, carrier, and symbol level. The diversity order $d_{AF}(r)$ of the protocol using an fixed AF transmission scheme is defined by

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

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

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

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

$$R = r \times \log_2(SNR). \tag{3}$$

Assuming that $(N-1)$ terminals are available, the protocol is in outage if all the relay terminals fail in improving the direct transmission. So the outage probability $p_{AF}^{out}(SNR, r)$ is

$$p_{AF}^{out}(SNR, r) = \Pr[I_{SD} \leq R] \times \Pr\left[\bigcup_{i=1}^{N-1}\left(I_{AF}^{(i)} \leq \frac{R}{2}\right) | I_{SD} \leq R\right]$$

where I_{SD} is the mutual information of the direct transmission

$$I_{SD} = \log_2(1 + SNR|h_{SD}|^2) \tag{4}$$

and $I_{AF}^{(i)}$ is the mutual information of the relayed transmission using a fixed AF cooperation scheme at terminal R_i and implementing frame dropping at the destination terminal

$$I_{AF}^{(i)} = \frac{1}{2}\log_2[1 + f(SNR|h_{SR_i}|^2, SNR|h_{R_iD}|^2)] \tag{5}$$

where $f(x, y) = \frac{xy}{x+y+1}$. The expression of the mutual information $I_{AF}^{(i)}$ differs from the one that is usually used [6]. Indeed, the term $SNR|h_{SD}|^2$ is missing because the source message is now dropped at the destination terminal D when D fails in decoding the message from S. This can save the processing time required to combine the source signal and the relay signal, without sacrificing the optimality of the DMT. Dropping the source message at the destination terminal should be considered as an option in the signal combination process, not as a constraint. Since the event $I_{SD} \leq R$ is independent of the events $I_{AF}^{(i)} \leq R/2$ for $1 \leq i \leq (N-1)$, we have that

$$p_{AF}^{out}(SNR, r) = \Pr[I_{SD} \leq R] \times \Pr\left[\bigcup_{i=1}^{N-1}\left(I_{AF}^{(i)} \leq \frac{R}{2}\right)\right].$$

According to the results in [17], we have that

$$\lim_{SNR\to\infty} -\frac{\log[p_{AF}^{out}(SNR, r)]}{\log SNR} \leq \left(m_{SD} + \sum_{i=1}^{N-1} m_i\right)(1-r)$$

where m_{SD} is the shape parameter of the Nakagami-m random variable $|h_{SD}|$ and

$$m_i = \min\{m_{SR_i}, m_{R_iD}\} \tag{6}$$

where m_{SR_i} and m_{R_iD} denote the shape parameters of the random variables $|h_{SR_i}|$ and $|h_{R_iD}|$, respectively. So, the diversity curve $d_{AF}(r)$ can be lower-bounded as follows

$$d_{AF}(r) \geq \left(m_{SD} + \sum_{i=1}^{N-1} m_i\right)(1-r). \tag{7}$$

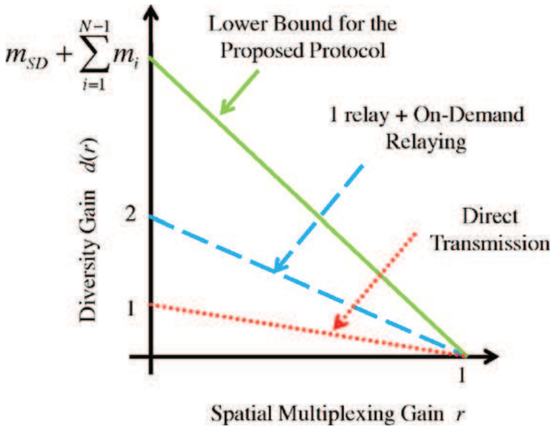

Fig. 6. DMT curves of three protocols: the proposed protocol, the direct transmission, and the on-demand cooperation with one relay terminal [6]. For the special case of Rayleigh fading, $m_{SD}+\sum_{i=1}^{N-1} m_i = N$.

Eq. (7) gives the lower bound of the DMT performance (see Fig. 6). For the special case of Rayleigh fading, i.e $m_{SD} = m_i = 1$ for $1 \le i \le (N-1)$, we have that $d_{\mathrm{AF}}(r) = N(1-r)$. So, when there are $(N-1)$ candidates, the proposed protocol achieves the optimal DMT curve. The data rate of the overall transmission scales like the data rate of a direct transmission, even in presence of a cooperative relaying. Note, however, that the signaling overheard does not appear in (7) because the DMT analysis is just providing a rough estimate of the achieved multiplexing gain r, not a precise value. This results is consistent with the one obtained with other DMT analyzes of on-demand cooperation techniques [6]. Moreover the diversity order of our proposal scales like the diversity order of a transmission scheme with N receiving antennas installed on the destination terminal. It is clear that a lower outage probability could be obtained if N signals were received by the destination terminal instead of one signal from the best relay terminal. However, receiving this single signal provides enough energy to achieve a diversity order of N.

3.2. DMT analysis for a selective DF transmission scheme

The same base-band-equivalent, discrete-time channel model is used as in Section 3.1. The first two received signals are defined in (1) and (2). When terminal D succeeds in decoding the data frame from S, no signal is transmitted by the best relay B. Otherwise, terminal B sends a new signal using a selective DF scheme, i.e. if and only if it has been able to decode the source message. The event that a relay R_i 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 relay R_i, I_{SR_i}, lies above the spectral efficiency R [2,10]. In that case, it can be considered that the estimation of signal $x(n)$, denoted $\hat{x}(n)$, is error free. Hence, during the second time slot, D is receiving a signal from B

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

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

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

The noise $w_{ij}(n)$ and the symbols $x(n)$ have been defined in the previous subsection. The same power constraint is also imposed at both the source and the relay: $E[|x(n)|^2] \le P$. The source and the relay are assumed to transmit orthogonally on half of the time-slots. A perfect synchronization is assumed at the block, carrier, and symbol level. The diversity gain $d_{\mathrm{DF}}(r)$ of the protocol is defined by

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

The probability $p_{\mathrm{DF}}^{\mathrm{out}}(SNR, r)$ is the outage probability for a signal to noise ratio SNR and a spatial multiplexing gain r. For high SNR values, we use (3). When $(N-1)$ terminals are available, the protocol is in outage if all the $(N-1)$ candidates fail in improving the direct transmission

$$p_{\mathrm{DF}}^{\mathrm{out}}(SNR, r) = \Pr[I_{SD} \le R] \times \Pr\left[\bigcup_{i=1}^{N-1}\left(I_{\mathrm{DF}}^{(i)} \le \frac{R}{2}\right) | I_{SD} \le R\right] \quad (8)$$

where $I_{\mathrm{DF}}^{(i)}$ is the mutual information of the relayed transmission using a selective DF cooperation scheme at terminal R_i and implementing frame dropping at the destination terminal

$$I_{\mathrm{DF}}^{(i)} = \begin{cases} \frac{1}{2}\log_2(1 + SNR|h_{SD}|^2), & \text{if } I_{SR_i} \le R \\ \frac{1}{2}\log_2(1 + SNR|h_{R_iD}|^2), & \text{if } I_{SR_i} > R \end{cases} \quad (9)$$

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 in (4). The probability $p_{\mathrm{DF}}^{\mathrm{out}}(SNR, r)$ can be expressed as the sum of $2^{(N-1)}$ terms

$$p_{\mathrm{DF}}^{\mathrm{out}}(SNR, r) = \sum_{j=1}^{2^{(N-1)}} P_j = \sum_{j=1}^{2^{(N-1)}} P_j^E \prod_{i=1}^{N-1} \Pr[\epsilon_j^{(i)}] \quad (10)$$

where

$$P_j^E = \Pr[I_{SD} \le R] \times \Pr\left\{\bigcup_{i=1}^{N-1}\left[I_{\mathrm{DF}}^{(i)} \le \frac{R}{2}\middle| (\epsilon_j^{(i)}, I_{SD} \le R)\right]\right\}.$$

The event $\epsilon_j^{(i)}$ equals the event $I_{SR_i} \le R$ or $I_{SR_i} > R$ according to the value of index j, $1 \le j \le 2^{(N-1)}$. The probability P_j in (10) is constituted with N components. The first component P_j^E is the probability denoted in (8) where each value of $I_{\mathrm{DF}}^{(i)}$ is conditioned to the value of I_{SR_i}. The $(N-1)$ last terms in the product exhibit the probabilities that the I_{SR_i} are above or beyond the threshold R, for $1 \le i \le (N-1)$. According to [18], we have that

$$\lim_{SNR\to\infty} \frac{\log[P_j]}{\log(SNR)} \ge \left(m_{SD} + \sum_{i=1}^{N-1} m_i\right)(r-1)$$

where m_i has been defined in (6). So, we have that

$$\lim_{SNR\to\infty} -\frac{\log[p_{\mathrm{DF}}^{\mathrm{out}}(SNR, r)]}{\log(SNR)} \leq \left(m_{SD} + \sum_{i=1}^{v-1} m_i\right)(1-r).$$

Hence, the diversity curve $d_{\mathrm{DF}}(r)$ of the protocol is lower bounded by the following expression

$$d_{\mathrm{DF}}(r) \geq \left(m_{SD} + \sum_{i=1}^{N-1} m_i\right)(1-r). \quad (11)$$

Eq. (11) gives the lower bound on the DMT performance of the protocol using the selective DF transmission scheme. When $m_{SD} = m_i = 1$ for $1 \leq i \leq (N-1)$ (Rayleigh fading), we have that $d_{\mathrm{DF}}(r) = N(1-r)$.

4. Simulation results

The simulation results focus on the splitting algorithm. Simulation results showing the diversity order of the transmission scheme can be found in [9] for the case of Rayleigh fading channels. Note that the results on the diversity order are independent of the selection process. Figs. 7 and 8 plot the average and standard deviation of number of slots N_{slot} required to select the best relay as a function of N, the number of possible relays for N going from 2 to 30 (see Fig. 7) and for N going from 30 to 100 (see Fig. 8). The results have been obtained through extensive MATLAB simulations using a Monte-Carlo approach. One hundred thousand simulations have been run for each value of N. The channel gains $|h_{ij}|$ are distributed according to a Nakagami-m distribution with equal shape parameter $m = 1$ (Rayleigh fading) and equal scale parameter θ. The selection of the best relay using a splitting algorithm is performed within 2.46 slots on average as long as the number of possible relays is greater than 30. Otherwise, the mean value of slots is lower. The standard deviation is 1.70 for N greater than 30. These results are consistent with the ones obtained in [19]. The slot duration includes two transmissions, one by the relay candidates and another one by the destination, and necessary gaps, as required, between these two transmissions. In IEEE 802.11-based networks, the duration of a slot may exceed 100 µs [20]. So the duration of the selection should not exceed 250 µs on average. Note however that the duration of the selection process has a standard deviation. Typically, the standard deviation is on the order of 2 slots. Comparatively, the other studies consider that some information exchange is needed to process the selection but the amount of bandwidth dedicated to this task is not computed [21]. In [10], the protocol requires a contention period during which relay candidates may contend for access to the channel and two time slots to notify the selection of the best relay: one by the best relay and another one by the destination. The notification by the destination terminal is used to address the issues of hidden relays. Each relay candidate triggers a timer, the expiration of which triggers the transmission of a flag. The average duration of a timer can be made as small as 200 µs. When the duration of the notification, 100 µs in IEEE 802.11-based systems, is added to the average duration of the timers, the result

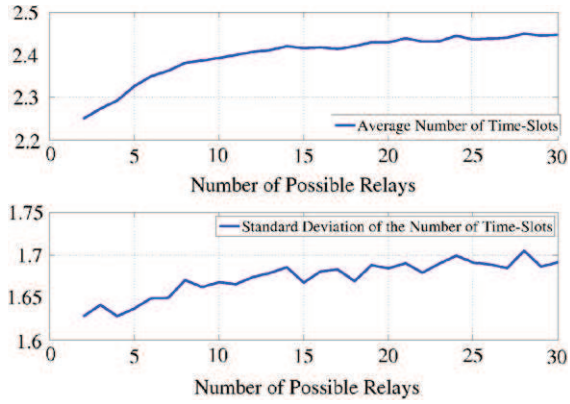

Fig. 7. Duration of the selection process (expressed in number of time-slots) as a function of the number of relay terminals N: average number (top) and standard deviation (bottom).

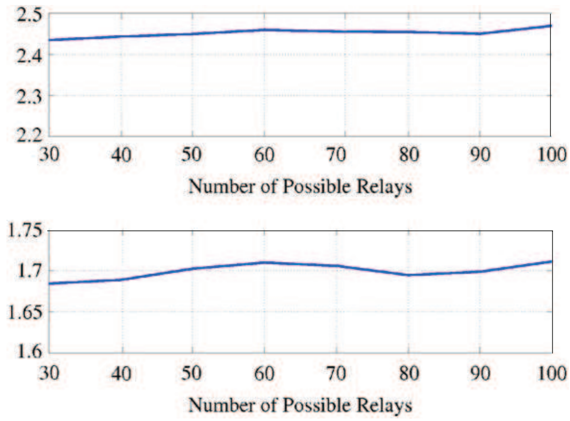

Fig. 8. Duration of the selection process (expressed in number of time-slots) as a function of the number of relay terminals N: average number (top) and standard deviation (bottom).

is similar to the one proposed in this paper. However, the approach may not succeed because of the collisions between relays candidates. In [15], a selection based on a similar approach is performed. Actually, the selection algorithm uses busy tones rather than timers but the same conclusion can be drawn. In [22,16], the selection process is proactive in the sense that the source terminal already knows the most appropriate relay terminal for its transmission toward a specific destination terminal when cooperation is needed. The selection is performed by overhearing frames from possible relays. Quantifying the resources needed to perform the selection may be done by measuring the amount of time required to collect the channel state information about the possible relays. This corresponds to an awake time, the duration of which should be minimized. On the other hand, these protocols also need to transmit one or two signaling frames, so the overhead is comparable to the one induced by the proposed approach.

The impact of the channel parameters on the number of time-slots N_{slot} is presented in the next figures. Fig. 9 presents the average and the standard deviation of N_{slot} as a function of N, for different logarithmically spaced values of θ, from 0.01 to 100. Recall that the channel gains are i.i.d.

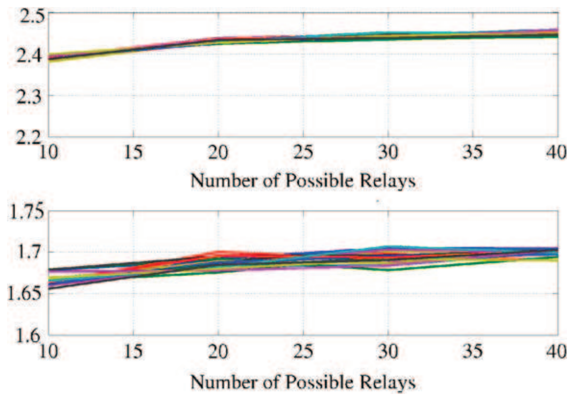

Fig. 9. Duration of the selection process (expressed in number of time-slots) as a function of the number of relay terminals N: average number (top) and standard deviation (bottom) for different values of the scale parameter.

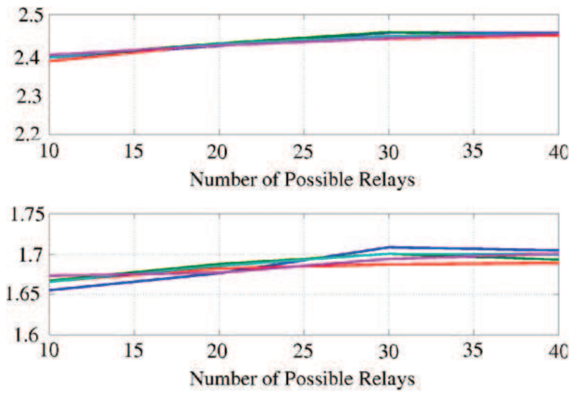

Fig. 10. Duration of the selection process (expressed in number of time-slots) as a function of the number of relay terminals N: average number (top) and standard deviation (bottom) for different values of the shape parameter.

random variables with a Nakagami-m distribution with equal shape parameter m and equal scale parameter θ. The shape parameter is set to 1 (Rayleigh fading). Similarly, Fig. 10 presents the average and the standard deviation of N_{slot} as a function of N for ten linearly spaced values of m, from 1 to 10 and a scale parameter θ set to 1. The results in Figs. 9 and 10 show that the number of time-slots N_{slot} does not depend on the channel parameters m and θ.

5. Conclusion

A cooperative MAC protocol has been presented in this paper. Two basic features are characterizing this protocol: on-demand cooperation and relaying by a single terminal. Two additional features have been implemented. First, terminals are pre-selected, i.e. they are considered as relay candidates when they are able to improve the mutual information of the direct transmission. Hence, efficient cooperation is guaranteed. Second, it has been proved that there is no need to keep the source message at the destination terminal in order to achieve an optimal spatial diversity gain. So there is no need to combine the source signal with the signal from the best relay. A splitting algorithm has been implemented in order to select the best relay terminal. This provides a fast means to select a terminal even when the number of relay candidates tends toward infinity. Simulation results have shown that a relay terminal could be selected within 2.4 time-slots on average. Moreover, this result does not depend on channel statistics, i.e. the scale and shape parameters of the Nakagami-m distributed channel gains.

The splitting algorithm should now be evaluated on non-identically distributed channel gains to support more realistic transmission scenarios. Moreover, the duration of the selection process can be reduced if there was a means to include the number of terminals involved in a collision in the threshold computation. This work is currently in progress.

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