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DMT Optimal Cooperative MAC Protocols in Wireless Mesh Networks with Minimized Signaling Overhead

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ABSTRACT

In this paper, a cooperative protocol is proposed for wireless mesh networks. Two features are implemented: on-demand cooperation and selection of the best relay. First, cooperation is activated by a destination terminal when it fails in decoding the message from a source terminal. Second, a selection of the best relay is performed when cooperation is needed. The robustness of wireless links are increased while the resource consumption is minimized. The selection of the best relay is performed by a splitting algorithm, ensuring a fast selection process, the duration of which is now fully characterized. Only terminals that improve the direct link participate in the relay selection and inefficient cooperation is avoided. The proposed protocol is demonstrated to achieve an optimal diversity-multiplexing trade-off. This study focuses on Nakagami- m wireless channel models to encompass a variety of fading models in the context of wireless mesh networks.

Keywords: Channel Models, Cooperative Protocol, Fading Models, Links, Wireless Mesh Networks

INTRODUCTION

One of the major properties of wireless mesh networks (WMNs) consists in the possibility of breaking long distances into a series of shorter hops. Apart from increasing the signal quality of the links, the mesh architecture allows the cooperative forwarding of data packets through intermediate terminals in the network. Cooperative communications provide an interesting contribution in this context. More precisely, they enable data transmission between

two terminals through an alternate path when the direct wireless link is experiencing a deep fade. Cooperative communications can be envisioned at several network layers. 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. 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)

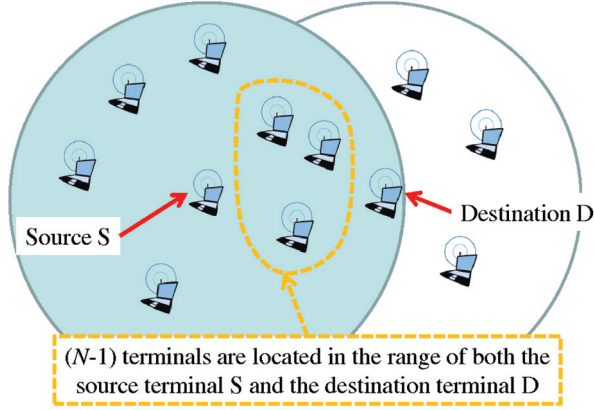
layer. At the PHY layer, cooperative communications increase the wireless link reliability. In a cooperative scenario, a source terminal S sends data to a destination terminal D through a direct path. One or several relay terminals help the transmission by receiving the source message and forwarding it to D through a relaying path (Figure 1). Hence the direct path is rendered more robust (Laneman & Wornell, 2000, 2003; Sendorais, Erkip, & Aazhang, 2003; Hunter & Nosratinia, 2006). However, this comes at the price of bandwidth consumption so that the system operates at diminished capacity¹. One common way to compare cooperative transmission techniques is to compute the diversity-multiplexing tradeoff (DMT) (Zheng & Tse, 2002). The DMT analysis of a transmission scheme yields the diversity gain $d(r)$ achievable for a spatial multiplexing gain r . The diversity gain helps in quantifying the robustness of the S-D link and the multiplexing gain gives an hint on the capacity of the link. Both indicators should be maximized in order to get an optimal DMT curve. When $(N - 1)$ relay candidates are involved in a cooperative scenario, the optimal DMT curve $d(r)$ is achievable by protocols that implement both on-demand relaying and a selection of the best relay (Bletsas, Khisti, & Win, 2008; Escrig, 2010): $d(r) = N(1 - r)$ for $0 \leq r \leq 1$. In an on-demand relaying scenario (Laneman, Tse, & Wornell, 2004; Gomez, Alonso-Zarate, Verikoukis, Perez-Neira, & Alonso, 2007), 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 (Bletsas, Khisti, Reed, & Lippman, 2006). 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 tradeoff between link robustness and bandwidth consumption is reached. This optimal tradeoff has been demonstrated by computing the DMT

curve of the transmission scheme. 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 Laneman et al. (2003), 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 the design of cooperative MAC protocols.

The selection process in Bletsas et al. (2008) and Escrig (2010) 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 (Bletsas et al., 2006; Gomez et al., 2007). More generally, the optimization of the selection has not been included in the design of the cooperative protocols (Azgin, Altunbasak, & AlRegib, 2005; Liu, Tao, Narayanan, Korakis, & Panwar, 2007a). This issue has been addressed through splitting algorithms (Qin & Berry, 2004; Shah, Mehta, & Yim, 2010). 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 wireless link between two terminals. The use of cooperative communications in this context allows to avoid the need to re-establish a whole route when one link is temporarily dropped. We start with the cooperative MAC protocols developed in (Bletsas et al., 2008; Escrig, 2010). They all

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



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 can find the best relay terminal, on average, within at most 2.507 slots even for an infinite number of relay candidates (Qin & Berry, 2004; Shah et al., 2010). Collision between relay candidates are not avoided but the contention time is fully characterized.
- *Pre-selection of the relay terminals:* the efficiency of the selection process is guaranteed. Only terminals that are able to improve the direct transmission are pre-selected. The pre-selection is implemented by adding a condition on the relaying scheme. More precisely, the relay terminal should retransmit only when the relayed path has a mutual information greater than a given threshold (Chou, Yang, & Wang, 2007). Otherwise, the source terminal retransmits its message. Inefficient cooperation is now avoided.

In this paper, Nakagami- m fading channels are considered in order to encompass a variety of fading models followed in the context

of WMNs. Classical Rayleigh fading model corresponds to the case $m = 1$ while the Rice fading model corresponds to the case $m = (m + 1)^2 / (2m + 1) > 1$ where m is the Ricean 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 particular, we show the optimality of the DMT when the relaying scheme is based on either a fixed amplify-and-forward (AF) method or a selective decode-and-forward (DF) method.

ON-DEMAND RELAYING WITH SELECTION OF THE BEST RELAY TERMINAL

System Model

We consider a slow Nakagami- m fading channel model. A half duplex constraint is imposed across each relay terminal, i.e. it cannot transmit and listen simultaneously. Transmissions

are multiplexed in time, they use the same frequency band. Each channel gain h_{ij} is accurately measured by the receiver j , but not known to the transmitter i . Moreover, 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 gain $|h_{ij}|$ 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 m_{ij} ($m_{ij} > 0$). So, the probability density function $f_{|h_{ij}|^2}(x; m_{ij}, \theta_{ij})$ of the random variable $|h_{ij}|^2$ is:

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

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

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

The cumulative distribution function (CDF) of $|h_{ij}|^2$, denoted $F_{|h_{ij}|^2}(x; m_{ij}, \theta_{ij})$, is the regularized gamma function:

$$F_{|h_{ij}|^2}(x; m_{ij}, \theta_{ij}) = \frac{\gamma(m_{ij}, \frac{x}{\theta_{ij}})}{\Gamma(m_{ij})}$$

where $\gamma(m_{ij}, \frac{x}{\theta_{ij}})$ is the lower incomplete gamma function such that:

$$\gamma(s, x) = \int_0^x t^{s-1} \exp(-t) dt$$

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. 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. Clearly, the best spatial diversity gain is no more 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 address this tradeoff 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.

Protocol Description

Cooperation Mode Activation. the cooperation mode is activated at terminal R_i , $1 \leq i \leq (N - 1)$, upon reception of a data frame from any source terminal S. This triggers the relay selection process at the relay candidates. The data frame is stored when R_i is implementing the cooperation functionality and R_i is not already involved in any other transmis-

sion. When terminal D succeeds in decoding the data frame, it sends an acknowledgment frame (ACK). Otherwise, terminal D discards the data frame and sends a call for cooperation (CFC) (Gomez et al., 2007). This saves processing time without sacrificing the optimality of the DMT. Note that the data frame from S contains an additional control field on the source address. Hence, when the checksum on the entire frame is wrong and the checksum on the source address is good, the destination terminal is able to send a CFC with the source address. When the CFC frame is lost, the protocol implements classical error recovery mechanisms². 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 process³. Moreover, only terminals that improve the direct path are allowed to compete for best relay terminal. To decide whether a terminal R_i is pre-selected or not, a suitability metric u_i is used: the mutual information of the cooperative link between the source and the destination. More precisely, the suitability metric of R_i is defined in (5) (resp. in (12)) when a fixed AF (resp. a selective DF) transmission scheme is used. This metric is also used in the splitting algorithm in order to evaluate the relay candidates. So the best terminal is the one that can achieve the best link capacity. 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 . Note that the computation of the mutual information in (5) and in (12) requires the knowledge of the channel

gains h_{SR_i} and h_{R_iD} . These gains are estimated at terminal R_i using the signals corresponding to the data frame and the CFC frame respectively. Note also that the criterion can be simplified when using a selective DF transmission scheme. Indeed, choosing the best $I_{DF}^{(i)}$ in (12) is equivalent to choosing the best $|h_{R_iD}|^2$ coefficient.

Splitting algorithm. consider a time-slotted system 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 goal is to select the terminal with the highest metric. The metrics are continuous and i.i.d. with complementary CDF (CCDF) denoted by $F_c(u) = \Pr[u_i > u]$. Therefore, the $F_c(\cdot)$ is monotonically decreasing and invertible. The algorithm is specified using three variables $H_L(k)$, $H_H(k)$, and $H_{\min}(k)$ (Qin & Berry, 2004). $H_L(k)$ and $H_H(k)$ are the lower and upper metric thresholds, respectively, such that a terminal R_i transmits at time slot k if and only if its metric u_i satisfies $H_L(k) < u_i < H_H(k)$. $H_{\min}(k)$ tracks the largest value of the metric known up to slot k above which the best metric surely lies.

Initialization: in the first slot ($k = 1$), the parameters are initialized as follows: $H_L(1) = F_c^{-1}(1 / N_r)$, $H_H(1) = \infty$, and $H_{\min}(1) = 0$. The parameter N_r denotes the number of possible relays and should be set to $(N - 1)$. So, each terminal should know the value of N_r . When this value is not known at each terminal, it can be overestimated by the number of terminals in the range of D.

Terminal D generally knows this number through upper layer protocols.

Transmission rule: at the beginning of each slot, each terminal locally decides to transmit if and only if its metric lies between $H_L(k)$ and $H_H(k)$.

Feedback generation: at the end of each slot, the destination terminal broadcasts to all terminals a two-bit feedback: (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: let

$$split(a, b) = F_c^{-1}(F_c(a) / 2 + F_c(b) / 2)$$

be the split function. Then, depending on the feedback, the following possibilities occur:

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

A selective DF transmission scheme is considered in order to illustrate the operation of the splitting algorithm in Figures 2 through 4. The suitability metric u_i for terminal R_i is defined in (12). It can be noted that the channel coefficient $|h_{R_i D}|^2$ between terminal R_i and the destination terminal D can be used directly as the suitability metric. The channel gain $|h_{R_i D}|$

is a random variable with a Nakagami- m distribution with parameter $m = 1$ (Rayleigh distributed variable) such that the variable $|h_{R_i D}|^2$ is exponentially distributed. We assume that the random variable $|h_{R_i D}|^2$ has a variance unity.

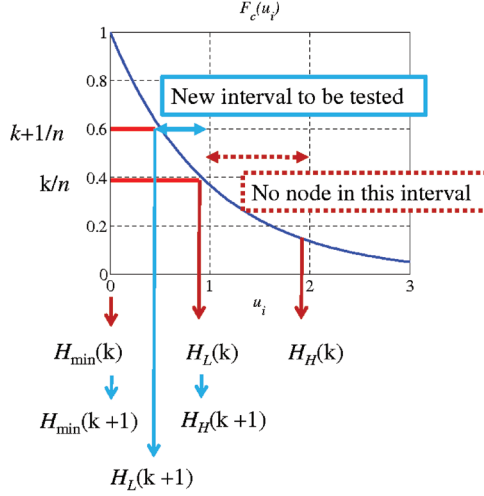
Termination: The algorithm terminates when the outcome is a success (1).

Data transmission. when the destination terminal sends its last feedback, the best relay terminal sends a copy of the data frame using either a fixed AF forwarding scheme or a selective DF forwarding scheme. The destination receives the signal from the best relay terminal. When D succeeds in decoding the data frame, D sends an ACK frame (Figure 5). Otherwise, D remains silent and the timeout at the source terminal triggers a re-transmission. In section II.B of (Escrig, 2010) additional design constraints are given in order to implement this cooperative protocol in an IEEE 802.11-based network.

DMT Analysis of the On-Demand Cooperative Protocol

In this section, the DMT curve of the proposed protocol is studied. The DMT analysis focusses on the transmission part of the protocol, i.e. on the PHY layer. Indeed, DMT analyses do not take into account signaling overhead such as the one due to relay selection. Similarly, the relay selection has not been taken into account in the DMT analysis of Laneman et al. (2003) and the overhead required to distribute space-time codes to relay terminals has not been taken into account in the DMT analysis in Laneman et al. (2004). 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 Li et al. (2009).

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



DMT Analysis for a Fixed AF Transmission Scheme

The channel models are characterized using the system model described in the previous section, and a time-division notation; frequency-division counterparts to this model are straightforward. A base-band-equivalent, discrete-time channel model is used 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:

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

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

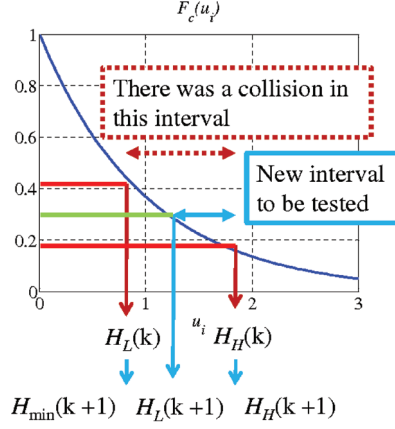
for $n = 1, 2, \dots, T_M/2$, where T_M denotes the duration of time-slots reserved for each message. When terminal D succeeds in decoding the data frame from S, no signal is transmitted by the best relay terminal B. Otherwise, B

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, 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 a 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:

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



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

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:

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

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

$$R = r \times \log_2 SNR \quad (3)$$

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:

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

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

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

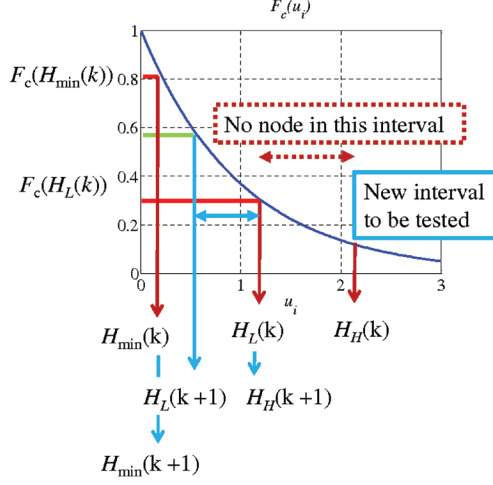
and $I_{AF}^{(i)}$ is the mutual information of the relayed transmission using a fixed AF cooperation scheme at terminal R_i and implementing frame dropping at the destination terminal:

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

where $f(x, y) = (xy) / (x + y + 1)$.

There is no $SNR |h_{SD}|^2$ term in $I_{AF}^{(i)}$ because the source message is now dropped at the destination terminal D when D fails in decoding the message from S. This saves the processing time required to combine the source signal and the relay signal, without sacrificing the optimality of the DMT. 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:

Figure 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



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

With (4), we have that:

$$\Pr[I_{SD} \leq R] = \Pr[|h_{SD}|^2 \leq SNR^{r-1}]$$

for high SNR values. The random variables h_{SR_i} and h_{R_iD} being mutually independent, for high SNR , we have that:

$$\begin{aligned} p_{AF}^{out}(SNR, r) &\leq \Pr[|h_{SD}|^2 \leq SNR^{r-1}] \\ &\times \prod_{i=1}^{N-1} \Pr\left[f\left(\begin{matrix} SNR |h_{SR_i}|^2 \\ SNR |h_{R_iD}|^2 \end{matrix}\right) \leq SNR^r\right] \end{aligned} \quad (6)$$

From Lemma 2 in (Bletsas et al., 2008), we have that:

$$\lim_{SNR \rightarrow \infty} \frac{\log\{\Pr[|h_{SD}|^2 \leq SNR^{r-1}]\}}{\log(SNR)} = m_{SD}(r-1) \quad (7)$$

when $|h_{SD}|$ is a Nakagami- m random variable with shape parameter m_{SD} .

The result of Lemma 4 in (Bletsas et al., 2006) is adapted for the other terms of (6):

$$\begin{aligned} \Pr[f(\rho a, \rho b) \leq \rho^r] \\ \leq \Pr[\min(a, b) \leq \rho^{r-1} + \sqrt{\rho^{r-2}(\rho^r + 1)}] \end{aligned}$$

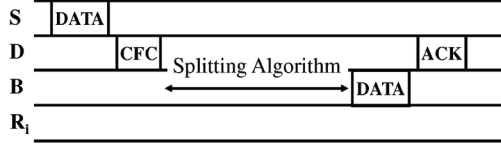
Thus, we have that:

$$\begin{aligned} \Pr[f(SNR |h_{SR_i}|^2, SNR |h_{R_iD}|^2) \leq SNR^r] \\ \leq \Pr\left[\begin{matrix} \min(|h_{SR_i}|^2, |h_{R_iD}|^2) \leq SNR^{r-1} \\ + \sqrt{SNR^{r-2}(SNR^r + 1)} \end{matrix}\right] \end{aligned} \quad (8)$$

From (8) and Lemma 4 in (Bletsas et al., 2008) and the fact that:

$$\sqrt{SNR^{r-2}(SNR^r + 1)} \rightarrow SNR^{r-1} \text{ as } SNR \rightarrow +\infty, \text{ we have that}$$

Figure 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).



$$\lim_{SNR \rightarrow \infty} \frac{\log\{\Pr[f(SNR | h_{SR_i}^2, SNR | h_{R_iD}^2) \leq SNR^r]\}}{\log(SNR)} \leq m_i(r-1) \quad (9)$$

where $|h_{SR_i}|$ and $|h_{R_iD}|$ are Nakagami- m random variables with shape parameter m_{SR_i} and m_{R_iD} respectively and:

$$m_i = \min\{m_{SR_i}, m_{R_iD}\} \quad (10)$$

Using (7) and (9) in (6), we have that:

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

Hence, the diversity curve $d_{AF}(r)$, i.e. the DMT performance of the protocol using a fixed AF transmission scheme, is:

$$d_{AF}(r) \geq (m_{SD} + \sum_{i=1}^{N-1} m_i)(1-r) \quad (11)$$

Equation (11) gives the lower bound of the DMT performance (Figure 6). Note that for the special case of Rayleigh fading, i.e. $m_{SD} = m_i = 1$ for $1 \leq i \leq (N-1)$, we have that $d_{AF}(r) = N(1-r)$. So, when there are $(N-1)$ potential relay terminals, the proposed protocol achieves the optimal DMT curve

reaching the two extreme points $d_{AF}(0) = N$ and $d_{AF}(1) = 0$. Note also that the only information provided by the DMT curve is that the data rate of the overall transmission scales like a direct transmission, even in presence of a cooperative relaying. In particular, the overhead induced by the additional signaling frames (CFC, splitting algorithm) does not appear in (11) because the DMT analysis is just providing a rough estimate of the achieved multiplexing gain r , not a precise value. In particular, the spatial multiplexing gain scales like 1. This result is consistent with the one obtained with other on-demand cooperation techniques (Laneman et al., 2004).

DMT Analysis for a Selective DF Transmission Scheme

The same base-band-equivalent, discrete-time channel model is used. 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 terminal B. Otherwise, the best relay 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 (Laneman et al., 2003; Bletsas et al., 2006). 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:

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

for $n = T_M / 2 + 1, \dots, T_M$, 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: $E[|x(n)|^2] \leq P$. 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 $d_{DF}(r)$ of the protocol is defined by:

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

The probability $p_{DF}^{out}(SNR, r)$ 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:

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

where $I_{DF}^{(i)}$ 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

$$I_{DF}^{(i)} = \begin{cases} \frac{1}{2} \log_2(1 + SNR | h_{SD} |^2), & \text{if } I_{SR_i} \leq R \\ \frac{1}{2} \log_2(1 + SNR | h_{R_iD} |^2), & \text{if } I_{SR_i} > R \end{cases} \quad (12)$$

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 $p_{DF}^{out}(SNR, r)$ can be expressed as the sum of $2^{(N-1)}$ terms:

$$p_{DF}^{out}(SNR, r) = \sum_{j=1}^{2^{(N-1)}} P_j = \sum_{j=1}^{2^{(N-1)}} P_j^E \prod_{i=1}^{N-1} \Pr[\varepsilon_j^{(i)}] \quad (13)$$

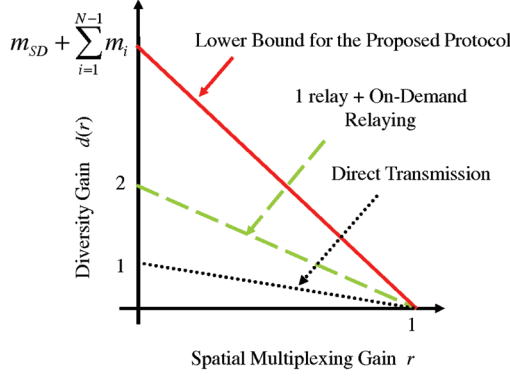
where:

$$P_j^E = \Pr[I_{SD} \leq R] \times \Pr\left\{\bigcup_{i=1}^{N-1} [I_{DF}^{(i)} \leq \frac{R}{2} \mid (\varepsilon_j^{(i)}, I_{SD} \leq R)]\right\}$$

The event $\varepsilon_j^{(i)}$ equals the event $I_{SR_i} \leq R$ or $I_{SR_i} > R$ according to the value of index j , $1 \leq j \leq 2^{(N-1)}$. The probability P_j in (13) is constituted with N components. The first component P_j^E is the probability denoted in (12) where each value of $I_{DF}^{(i)}$ 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 $1 \leq i \leq (N - 1)$. We assume that there are N_j passive relay terminals such that $\varepsilon_j^k = [I_{SR_k} \leq R]$ in P_j . We define the set K_j such that:

Figure 6. DMT curves of three protocols: the proposed protocol, the direct transmission, and the on-demand cooperation with one relay terminal. For the special case of Rayleigh fading,

$$m_{SD} + \sum_{i=1}^{N-1} m_i = N$$



$$K_j = \{k / \varepsilon_j^{(k)} = [I_{SR_k} \leq R], 1 \leq k \leq (N-1)\}$$

So, we have that:

with cardinality $|K_j| = N_j$. Thus, there are $(N-1) - N_j$ active relay terminals such that $\varepsilon_j^{(l)} = [I_{SR_l} > R]$ in P_j . We define the set L_j such that:

$$L_j = \{l / \varepsilon_j^{(l)} = [I_{SR_l} > R], 1 \leq l \leq (N-1)\}$$

$$\Pr[(I_{DF}^{(k)} \leq \frac{R}{2} | \varepsilon_j^{(k)}) | I_{SD} \leq R] = 1.$$

Moreover, we have that:

$$\begin{aligned} \Pr[\varepsilon_j^{(k)}] &= \Pr[I_{SR_k} \leq R] \\ &= \Pr[\log_2(1 + SNR | h_{SR_k} |^2) \leq R] \end{aligned}$$

For the $(N-1) - N_j$ active relay terminals, we have that:

with cardinality $|L_j| = (N-1) - N_j$. Note also that $0 \leq N_j \leq (N-1)$. So, we have that:

$$\begin{aligned} I_{DF}^{(l)} \leq \frac{R}{2} | \varepsilon_j^{(l)} &\Leftrightarrow I_{DF}^{(l)} \leq \frac{R}{2} | I_{SR_l} > R \\ &\Leftrightarrow \log_2(1 + SNR | h_{R_lD} |^2) \leq \frac{R}{2} \end{aligned}$$

$$P_j^E = \Pr[I_{SD} \leq R] \times \Pr\{\bigcup_{k \in K_j} [I_{DF}^{(k)} \leq \frac{R}{2} | (\varepsilon_j^{(k)}, I_{SD} \leq R)]\},$$

and:

$$\bigcup_{l \in L_j} [I_{DF}^{(l)} \leq \frac{R}{2} | (\varepsilon_j^{(l)}, I_{SD} \leq R)] \quad (14)$$

$$\Pr[\varepsilon_j^{(l)}] = \Pr[I_{SR_l} > R]$$

For the N_j passive relay terminals, we have that:

For high SNR values, we have a simpler expression for (14):

$$I_{DF}^{(k)} \leq \frac{R}{2} | \varepsilon_j^{(k)} \Leftrightarrow I_{DF}^{(k)} \leq \frac{R}{2} | I_{SR_k} \leq R \Leftrightarrow I_{SD} \leq R$$

$$\begin{aligned} P_j^E &= \Pr[\log_2(1 + SNR | h_{SD} |^2) \leq R] \\ &\times \Pr\{\bigcup_{l \in L_j} [\log_2(1 + SNR | h_{R_lD} |^2) \leq R]\} \end{aligned}$$

The $|h_{R,D}|^2$ random variables being mutually independent, we have that:

$$P_j^E = \Pr[|h_{SD}|^2 \leq SNR^{r-1}] \times \prod_{l \in L_j} \Pr[|h_{R,D}|^2 \leq SNR^{r-1}] \quad (15)$$

using (3). The random variables $|h_{SR_k}|^2$ and $|h_{R,D}|^2$ being mutually independent, we have that:

$$\prod_{i=1}^{N-1} \Pr[\varepsilon_j^{(i)}] \leq \prod_{k \in K_j} \Pr[|h_{SR_k}|^2 \leq SNR^{r-1}] \quad (16)$$

So, using (16), we have that:

$$P_j \leq \Pr[|h_{SD}|^2 \leq SNR^{r-1}] \times \prod_{l \in L_j} \Pr[|h_{R,D}|^2 \leq SNR^{r-1}] \times \prod_{k \in K_j} \Pr[|h_{SR_k}|^2 \leq SNR^{r-1}] \quad (17)$$

The random variables $|h_{SD}|^2$, $|h_{R,D}|^2$ for $l \in L_j$, and $|h_{SR_k}|^2$ for $k \in K_j$ are all gamma distributed variables. Let $|h|^2$ be one of these random variables, with shape parameter m . From Lemma 2 in (Bletsas et al., 2008), we have that:

$$\lim_{SNR \rightarrow \infty} \frac{\log\{\Pr[|h|^2 \leq SNR^{r-1}]\}}{\log(SNR)} = m(r-1) \quad (18)$$

So, using (18) in (17), we have that:

$$\lim_{SNR \rightarrow \infty} \frac{\log[P_j]}{\log(SNR)} = (m_{SD} + \sum_{k \in K_j} m_{SR_k} + \sum_{l \in L_j} m_{R,D})(r-1)$$

for every j , $1 \leq j \leq 2^{(N-1)}$, where m_{ij} is the shape parameter of the random variable $|h_{ij}|^2$. So, we have that:

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

where m_i has been defined in (10). So, we have that:

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

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

$$d_{DF}(r) \geq (m_{SD} + \sum_{i=1}^{N-1} m_i)(1-r) \quad (19)$$

Equation (19) gives the lower bound on the DMT performance of the protocol using the selective DF transmission scheme. Note again that for the special case of Rayleigh fading, i.e $m_{SD} = m_i = 1$ for $1 \leq i \leq (N-1)$, we have that $d_{DF}(r) = N(1-r)$.

SIMULATION RESULTS

The simulation results focus on the splitting algorithm. Simulation results showing the diversity order of the transmission scheme can be found in (Escrig, 2010) for the case of Rayleigh fading channels. These results are independent of the selection process. Figures 7 and 8 plot the number of slots required to select the best relay as a function of N the number of possible relays. Figure 8 plots the results for N going from 2 to 30 and Figure 7 plots the results for N going from 30 to 100. The results have been obtained through extensive MATLAB simulations using a Monte-Carlo approach. Ten

Figure 7. Duration of the selection process (expressed in number of time-slots) as a function of the number of relay terminals N (case of N greater than 30): average number (top) and standard deviation (bottom). The dashed line on each figure shows the mean value.

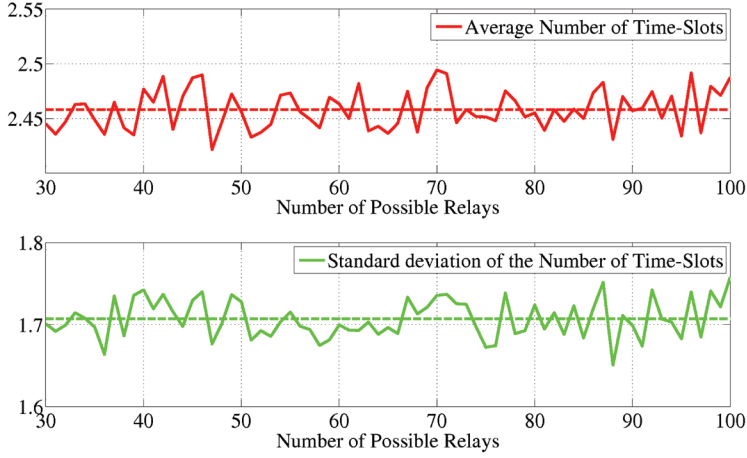
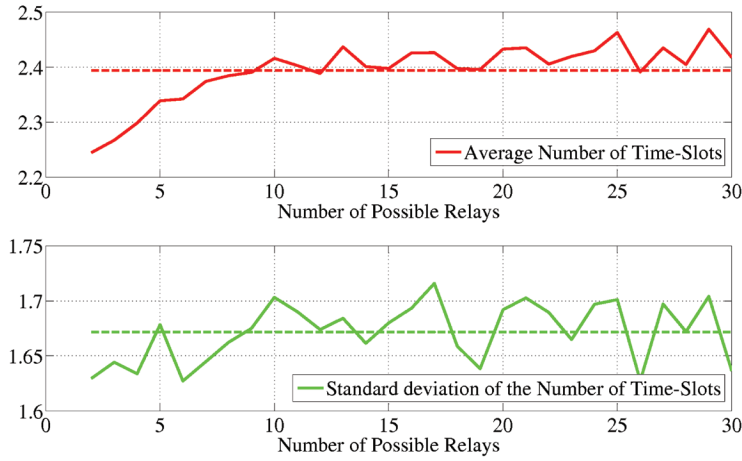


Figure 8. Duration of the selection process (expressed in number of time-slots) as a function of the number of relay terminals N (case of N lower than 30): average number (top) and standard deviation (bottom). The dashed line on each figure shows the mean value.



thousands simulations have been run for each value of N . 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 (Shah, Mehta, & Yim, 2009).

The slot duration includes two transmissions, one by the relay candidates and the other by the destination, and necessary gaps, as required, between these two transmissions. In IEEE 802.11-based networks, the duration

Figure 9. Impact of terminal location on the performance of the splitting algorithm: source and destination terminals at the same place (left side), and source and destination terminals at the limit of their range (right side)

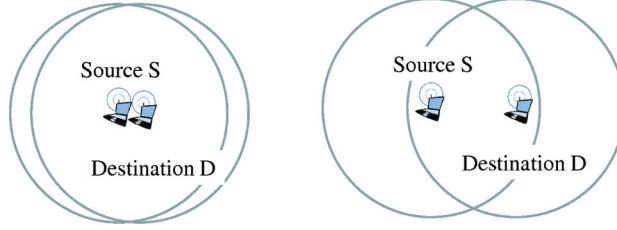
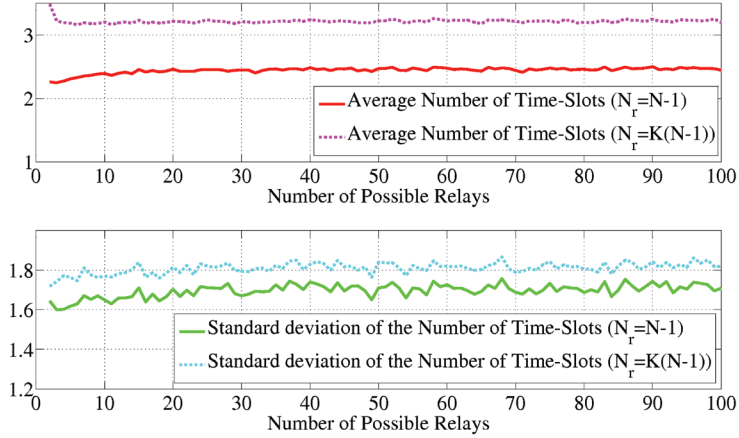


Figure 10. Duration of the selection process (expressed in number of time-slots) as a function of the number of relay terminals N : average number (top) and standard deviation (bottom). Solid lines correspond to $K = 1$ and dotted lines correspond to $K = 2\pi / (\pi - 2)$.



of a slot may exceed $100 \mu \text{ sec}$ (*Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, Tech. Rep. IEEE Std 802.11-2007, 2007*). So the duration of the selection should not exceed $250 \mu \text{ sec}$ 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 (Beres & Adve, 2008). In (Bletsas et al., 2006), 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 the other 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 $200 \mu \text{ sec}$. When the duration of the notification, $100 \mu \text{ sec}$ in IEEE 802.11-based systems, is added to the average duration of the timers, the result is similar to the one proposed in this paper. However, the approach may not succeed because of the collisions between relays candidates. In Chou et al. (2007), 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 Liu et al. (2007) and Li et al. (2009), the selection process is proactive in the sense that the source terminal already knows the most appropriate relay terminal for its transmission toward a particular 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.

In Figure 10, the impact of overestimating the number of possible relays on the mean duration of the selection algorithm is investigated. Assuming that the number of possible relays equals the number of terminals in the range of terminal D amounts to overestimating the number of possible relays by some factor K . In order to compute this factor, two extremes cases are considered (Figure 9). Terminals are assumed to be uniformly (though randomly) distributed over the network area. When the source terminal and the destination terminal are almost located at the same place, the number of possible relays equals the number of terminals in the range of D. The overestimation factor is one ($K = 1$). However when the source terminal and the destination terminal are located at the limit of their range, the ratio between the coverage area of D and the area of possible relays is greater than one ($K = \pi / (2\pi / 3 - \sqrt{3} / 2)$). This extreme case is the worst case, resulting in an overestimation factor K of 2.56. According to Figure 10, overestimating the number of relays increases both the mean duration of the selection process (from 2.46 to 3.21) and its standard deviation (from 1.70 to 1.81). Further studies should address this issue in order to

design efficient implementations of the splitting algorithm.

CONCLUSION

The purpose of the study is the design of a DMT optimal access protocol in the context of IEEE 802.11 mesh networks. The designed protocol has two basic features: on-demand cooperation and selection of the best relay terminal. Cooperation is activated on-demand, i.e. only when a destination terminal fails in decoding the message of a source terminal. This approach allows maximization of the spatial multiplexing gain, i.e. the capacity of the source-destination link. Moreover, when cooperation is needed, only the best relay terminal retransmits the source message. This allows maximization of the diversity order, i.e. the robustness of the link. Hence, an optimal DMT curve is achieved. Three features are added in order to guarantee both a fast and an efficient relay selection. Using a splitting algorithm, the time required to select a best relay terminal is fully characterized. Moreover, only terminals that can improve the direct transmission are pre-selected. So inefficient cooperation is now avoided. Finally, the destination terminal discards the source message when it fails to decode it. This saves processing time without sacrificing the optimality of the DMT. When $(N - 1)$ terminals are situated in the range of both a source terminal S and a destination terminal D, a diversity gain of N is provided while a spatial multiplexing gain of one is achieved when a Rayleigh fading channel is considered. Thus, the protocol implements a DMT optimal transmission scheme. The approach has been applied to both fixed AF and selective DF transmission schemes. Further studies should take signaling overhead into account in DMT analyses. Moreover an accurate estimation of the number of possible relays is required in order to minimize the duration of the selection process. The duration of the splitting algorithm has been shown to be dependent of this estimate. This work is currently in progress.

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