On-Demand Cooperation MAC Protocols with Optimal Diversity-Multiplexing Tradeoff

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***Abstract*—This paper presents access protocols with optimal Diversity-Multiplexing Tradeoff (DMT) performance in the context of IEEE 802.11-based mesh networks. The protocols are characterized by two main features: on-demand cooperation and selection of the best relay terminal. The on-demand characteristic refers to the ability of a destination terminal to ask for cooperation when it fails in decoding the message transmitted by a source terminal. This approach allows maximization of the spatial multiplexing gain. The selection of the best relay terminal allows maximization of the diversity order. Hence, the optimal DMT curve is achieved with these protocols.**

I. Introduction

Cooperative communications provide an interesting alternative to Multiple Input Multiple Output (MIMO) techniques when wireless systems cannot support multiple antenna terminals. In a cooperative scenario, a source terminal S sends data to a destination terminal D. One or several relay terminals help the transmission by receiving the signal transmitted by S and forwarding the signal toward D (see Figure 1). The two majors relaying schemes in cooperative protocols are Amplify-and-Forward (AF) and Decode-and-Forward (DF). In AF scenarios [1], the signal received by a relay terminal is amplified and forwarded toward D. In DF scenarios [2], the signal is decoded, re-encoded, and forwarded. A relaying scheme can be fixed, i.e. always on, or selective, i.e. activated when the quality of the channel between the source and the relay, is good enough. Spatial diversity is the main advantage provided by cooperative transmissions whereas their main limitation lies in the additional bandwidth consumption needed for both relay selection and relay transmission[1].

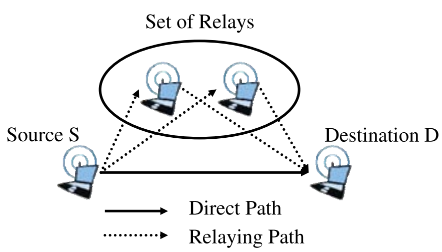

Fig. 1. Cooperation scenario with two relay terminals.

Several cooperative transmission techniques have been proposed in order to both maximize the spatial diversity and minimize the bandwidth consumption [1], [3]–[5]. To compare the cooperation techniques, performance is described in terms of Diversity-Multiplexing Tradeoff (DMT) [6]. This criterion has been first developed in the context of MIMO techniques. 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 $d(r)$ if the spectral efficiency R scales like $r \log_2 SNR$, and the outage probability decays like $1/SNR^{d(r)}$. In the context of cooperative transmissions, the spatial multiplexing gain can be thought as the spectral efficiency of the cooperative transmission, normalized by the spectral efficiency of a direct transmission. When a single relay terminal is involved in a cooperation scenario, the optimal DMT curve is $d^*(r) = 2(1-r)$ for $0 \leq r \leq 1$. In [7], optimal DMT curves have been also established when no feedback to the transmitting terminal is allowed. The optimal DMT curve can be obtained using on-demand relaying (see Figure 3). In an on-demand relaying scenario [2], the relay terminal is transmitting only when D fails in decoding the data transmitted by S. So D is asking for cooperation with a signaling frame. The DMT is optimal but the diversity gain is limited to a factor of two. When $(m-1)$ relay terminals are involved in a cooperative scenario, a diversity order of m can be achieved [3] but this improvement is counterbalanced by increased bandwidth consumption due to the multiple relay transmissions, $(m-1)$ time-slots for $(m-1)$ relay terminals. This approach has been improved using space-time codes (STCs) [3]. Because the $(m-1)$ relay terminals are all using a single time slot instead of $(m-1)$ time slots, this approach consumes less bandwidth than the previous one. A similar approach consists in implementing a selection of the best relay terminal [8]. Here also, when $(m-1)$ terminals are available, a single additional time-slot is required for the cooperation (one for the best relay terminal). But, here also, even if the spatial diversity order is m, the spatial multiplexing gain r is still limited by a factor of $1/2$. This approach has been recently improved by using on-demand relaying in an AF scenario [9].

In this paper, we propose DMT optimal protocols. The two major features of the protocols are: on-demand cooperation and selection of a best relay terminal. Cooperation is activated only when needed, i.e. only when the destination terminal fails in decoding the source message. This feature allows maximization of the spatial multiplexing gain. Moreover, when a cooperative communication is necessary, only the best relay

[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.

terminal participates in the communication. This approach allows the maximization of the diversity gain. We show that these On-demand relaying protocols with selection of the Best relay terminal (OB) provide an optimal performance in terms of DMT. These cooperative protocols have been designed in the context of IEEE 802.11-based mesh networks. Though restricted to this standard in this paper, we believe that our proposals can also be applied to other wireless systems such as wireless sensor networks, broadband wireless networks, and broadcast wireless systems.

In section II, the OB protocols are described in details. Section III presents the DMT analysis of the protocols. In particular, two options for the OB protocols are presented: protocols with a fixed AF scheme and protocols with a selective DF scheme. We conclude in section IV.

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

A. System model

We consider a slow Rayleigh fading channel model following [2]. Our analysis focuses on the case of slow fading, to capture scenarios in which delay constraints are on the order of the channel coherence time. A half duplex constraint is imposed across each relay terminal, i.e., it cannot transmit and listen simultaneously. Moreover, transmissions are multiplexed in time, they use the same frequency band. Let h_{ij} be the channel gain between a transmitting terminal i and a receiving terminal j. The channel gain h_{ij} captures the effects of path-loss, shadowing, and Rayleigh fading. We consider scenarios in which each fading coefficient h_{ij} is accurately measured by the receiver j, but not known to the transmitter i. We also assume that the channel gain h_{ij} is identical to the channel gain h_{ji}. This assumption is relevant since both channels are using the same frequency band. Statistically, channel gains h_{ij} between any two pair of terminals i and j are modeled as i.i.d circularly symmetric complex Gaussian random variables with zero mean and equal variance σ^2. Let P be the power transmitted by each terminal and σ_w^2 be the variance of the AWGN (Additive White Gaussian Noise) in the wireless channel. We define $SNR = P/\sigma_w^2$ to be the effective signal-to-noise ratio.

We also restrict our study to a single source-destination pair. It is assumed that $(m-1)$ wireless terminals are situated in the range of these two terminals. These terminals are available for implementing a cooperative transmission and they are not participating to another transmission. However, these $(m-1)$ terminals are also likely to cause collisions 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. In any case, if a terminal should interfere with the cooperative transmission, the proposed OB protocols are implementing classical error recovery mechanisms.

B. Protocol Description

The implementation of cooperative MAC (Medium Access Control) protocols in the context of IEEE 802.11-based networks can be modeled by four main tasks: activation of the cooperative transmission mode, collection of cooperation information (CoI), relay selection, and notification of the terminals [10]. In the following, we review these four tasks.

Moreover, we assume that the classical operating mode consists in the transmission of a data frame by the source terminal S and the transmission of an acknowledgment frame by the destination terminal D in case of successful decoding[2]. This scenario corresponds to the direct transmission mode, compared to the cooperative mode which is considered next.

1) Cooperation Mode Activation: We consider that terminals are always in a cooperative mode, i.e. the cooperation mode is always activated. How to turn the cooperation mode on and off on a terminal is left for further study. Moreover, the activation of the relay selection at a given terminal R_i, $1 \leq i \leq (m-1)$ is reactive, i.e. based on the reception of signaling MAC frames. When the source terminal S sends its data frame, every terminal R_i in the range of S stores this frame. This event triggers the relay selection process at the relay candidates. A terminal R_i stores effectively the data frame when R_i is implementing the cooperation functionality and R_i is not already involved in another cooperative transmission. When terminal D succeeds in decoding the data frame, terminal D sends an acknowledgment frame (ACK). When D fails in decoding the source message, D sends a short signaling frame (CFC for Claim For Cooperation) [11], [12]. The CFC frame works like a negative acknowledgment frame. When the CFC frame is lost, the protocol implements a classical error recovery mechanism. When the source terminal does not receive an acknowledgment before a timeout, it usually retransmits the frame until it receives an acknowledgment or exceeds a predefined number of re-transmissions. Note that the timeout should be delayed to take into account possible cooperative transmissions. When a terminal R_i stores the source message, it waits for either an ACK frame or a CFC frame. If any of these two frames is not received within a given time-slot, the source message is discarded at terminal R_i. Hence, only terminals that have received both the data frame and the CFC frame trigger the relay selection process[3].

2) CoI Collection: Once the relay selection process has been triggered at terminal R_i, CoI is collected. With the source message (resp. the CFC frame), terminal R_i estimates the channel gain h_{SR_i} (resp. h_{R_iD}) between S (resp. D) and R_i.

3) Relay Selection Algorithm: A terminal R_i is selected as a relay terminal when it implements the cooperation functionality, it successfully received the data frame and the CFC frame, and it does not participate to any other cooperative transmission [8], [13].

[2]When D fails in decoding the data frame, S retransmits its message according to a given timeout.

[3]Terminals that just receive either an ACK frame or a CFC frame ignore the signaling frame.

4) Relay Notification: Once relevant terminals have selected themselves as candidates for best relay terminal, they enter a final competition step. The objective of this step consists in both completing the selection process and notifying the result of the selection to the participating terminals: source terminal S, destination terminal D, and any other relay terminal. Several approaches have been proposed to implement this notification step [8], [13]. We choose the one proposed in [8]. The best relay terminal will be the one that will notify its presence first. A timer T_i is associated to each terminal R_i. The timer T_i is inversely proportional to a channel metric which depends on the CoI. As soon as the timer expires, the terminal transmits a short duration signaling frame. Two relay candidates may be both within the range of the source and destination, but not within the range of each other. So the destination also transmits a short duration signaling frame. Hence, when a collision occurs, terminal D does not transmit any signaling frame, and cooperation is aborted. When the notification step is completed, the best relay terminal sends a copy of the data frame using either a fixed AF or a selective DF forwarding scheme. The destination receives the signal from the best relay terminal. Several combination schemes with the source message are possible: a maximum ratio combiner at the signal level or a code combining scheme at the bit level [14]. When D succeeds in decoding the data frame, D sends an ACK frame (see Figure 2). Otherwise, D remains silent and the timeout at the source terminal triggers a re-transmission.

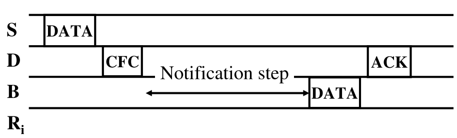

Fig. 2. Frame exchange sequence in the OB protocols using the basic IEEE 802.11 access method (S is the source terminal, D is the destination terminal, B is the best relay terminal, and R_i is a relay candidate).

5) Remarks: We give here some additional comments on the protocol design:

- RTS/CTS optional access method: Several cooperative MAC protocols rely on the exchange of modified Request-to-Send (RTS) and Clear-to-Send (CTS) signaling frames [13], [15], [16]. If CTS frames transmitted by the destination terminal D can be modified, we can infer that channel state information is available at the transmitter. Hence, the source can actually choose not to transmit when it cannot support a given spectral efficiency R. This gives rise to new cooperative protocols, the study of which is left for future work.
- NAV modification: The Network Allocation Vector (NAV) values at each terminal should be increased according to the new frame scheduling, just like the timeout at the source terminal. This should avoid unnecessary soundings by neighboring terminals.
- Error recovery mechanism: A timeout is used at the source terminal to avoid blocking states in the OB protocols. 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.

III. DMT Analysis of the On-Demand Cooperative Protocols

In this section, we study the DMT curve of OB protocols. We split the study in two cases according to the forwarding scheme used at the best relay terminal: fixed AF and selective DF.

Just like in [8], we assume that there is no collision among relay terminals. In [8], the probability of having a collision between relay terminals was computed but the probability was not taken into account while analyzing the DMT of the proposed protocols. This detailed performance analysis is left for future work.

A. DMT Analysis for On-Demand Fixed Amplify-and-Forward Relaying with Selection of the Best Relay Terminal

We develop the DMT curve of a protocol based on the On-demand fixed Amplify-and-forward relaying with selection of the Best relay terminal, denoted OAB protocol. We characterize our channel models using the system model described in the previous section, and a time-division notation; frequency-division counterparts to this model are straightforward. We use a base-band-equivalent, discrete-time channel model for the continuous-time channel. Three discrete time received signals are defined in the following. Here, $y_{ij}(n)$ denotes the signal received by terminal j and transmitted by terminal i. During a first time-slot, D and the best relay terminal B are receiving signals from S

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

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

for $n = 1, 2, ..., T_M/2$, 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

$$y_{BD}(n) = h_{BD}[\beta y_{SB}(n)] + w_{BD}(n) \tag{3}$$

for $n = T_M/2 + 1, ..., T_M$. The noise $w_{ij}(n)$ between transmitting terminal i and receiving terminal j are all assumed to be i.i.d. circularly symmetric complex Gaussian with zero mean and variance σ_w^2. Symbols transmitted by the source terminal S are denoted $x(n)$. For simplicity, we impose the same power constraint at both the source and the relay: $E[|x(n)|^2] \leq P$ and $E[|\beta y_{SB}(n)|^2] \leq P$. We implement a fixed AF cooperation scheme. So the normalization factor β must satisfy $\beta^2 = P/(|h_{SB}|^2 P + \sigma_w^2)$. We assume that the source and the relay each transmit orthogonally on half of the time-slots. We also consider that a perfect synchronization is provided at the block, carrier, and symbol level. We define the diversity order $d_{OAB}(r)$ of the OAB protocol by

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

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

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

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

$$R = r\log_2 SNR \tag{4}$$

The outage probability $p^{out}_{OAB}(SNR, r)$ is given by

$$p^{out}_{OAB}(SNR, r) = \Pr[I_{OAB} \le R]$$

Here, I_{OAB} denotes the mutual information of the OAB protocol. The OAB protocol operates at spectral efficiency R when the direct transmission is successful, and operates at spectral efficiency $R/2$ when the best relay terminal must amplify and forward the source message. For given values of SNR and R, the outage probability $p^{out}_{OAB}(SNR, r)$ is defined by

$$\begin{aligned} p^{out}_{OAB}(SNR, r) &= \Pr[I_D \le R]\Pr[I_{AB} \le R/2 | I_D \le R] \\ &= \Pr[I_{AB} \le R/2] \end{aligned} \tag{5}$$

where I_D and I_{AB} are the mutual information of a direct transmission and the mutual information of a fixed amplify-and-forward relaying scheme implementing the selection of the best relay terminal. The mutual information I_D is given by

$$I_D = \log_2(1 + SNR|h_{SD}|^2) \tag{6}$$

and the mutual information I_{AB} is given by

$$\begin{aligned} I_{AB} = \frac{1}{2}\log_2[1 &+ SNR|h_{SD}|^2 \\ &+ f(SNR|h_{SB}|^2, SNR|h_{BD}|^2)] \end{aligned} \tag{7}$$

where

$$f(x, y) = \frac{xy}{x + y + 1} \tag{8}$$

The second equality in (5) follows from the fact that the event $I_D \le R$ is included in the event $I_{AB} \le R/2$. Using (4) and (7), for large values of SNR, we have that

$$\begin{aligned} &p^{out}_{OAB}(SNR, r) \\ &\quad= \Pr[1 + SNR|h_{SD}|^2 \\ &\qquad +f(SNR|h_{SB}|^2, SNR|h_{BD}|^2) \le SNR^r] \\ &\quad\le \Pr[SNR|h_{SD}|^2 \le SNR^r, \\ &\qquad f(SNR|h_{SB}|^2, SNR|h_{BD}|^2) \le SNR^r] \end{aligned}$$

since $SNR|h_{SD}|^2$, $f(SNR|h_{SB}|^2, SNR|h_{BD}|^2)$, and SNR^r are all positive numbers. Moreover, we have that

$$\begin{aligned} &p^{out}_{OAB}(SNR, r) \\ &\quad\le \Pr[|h_{SD}|^2 \le SNR^{r-1}] \\ &\quad\times \Pr[f(SNR|h_{SB}|^2, SNR|h_{BD}|^2) \le SNR^r] \end{aligned}$$

since $|h_{SD}|^2$, $|h_{SB}|^2$, and $|h_{BD}|^2$ are uncorrelated variables. We now study the two terms on the right side of the above expression, for high SNR values. From Lemma 2 in [8], we have that

$$\lim_{SNR\to\infty} \frac{\log\{\Pr[|h_{SD}|^2 \le SNR^{r-1}]\}}{\log(SNR)} = r - 1 \tag{9}$$

because $|h_{SD}|^2$ is an exponential random variable with parameter σ^2. For the second term, we first adapt the result of Lemma 4 in [8]

$$\Pr[f(\rho a, \rho b) \le \rho^r] \le \Pr[\min(a, b) \le \rho^{r-1} + \sqrt{\rho^{r-2}(\rho^r + 1)}] \tag{10}$$

Thus, we have that

$$\begin{aligned} &\Pr[f(SNR|h_{SB}|^2, SNR|h_{BD}|^2) \le SNR^r] \\ &\le \Pr[\min(|h_{SB}|^2, |h_{BD}|^2) \le SNR^{r-1} \\ &\quad + \sqrt{SNR^{r-2}(SNR^r + 1)}] \end{aligned}$$

The random variable $\min(|h_{SB}|^2, |h_{BD}|^2)$ is an exponential variable with parameter $2\sigma^2$ because $|h_{SB}|^2$ and $|h_{BD}|^2$ are two i.i.d. exponential random variables with equal parameter σ^2. Moreover, $\min(|h_{SB}|^2, |h_{BD}|^2)$ is the maximum value in a set of $(m - 1)$ exponential random variables. We now use Lemma 2 in [8] and the fact that $\sqrt{SNR^{r-2}(SNR^r + 1)} \to SNR^{r-1}$ as $SNR \to +\infty$. So, we have that

$$\begin{aligned} \lim_{SNR\to\infty} &\frac{\log\{\Pr[f(SNR|h_{SB}|^2, SNR|h_{BD}|^2) \le SNR^r]\}}{\log SNR} \\ &= (m - 1)(r - 1) \end{aligned} \tag{11}$$

Now, with (9) and (11), we have that

$$\lim_{SNR\to\infty} -\frac{\log[p^{out}_{OAB}(SNR, r)]}{\log SNR} = m(1 - r)$$

Hence, the diversity curve $d_{OAB}(r)$, i.e. the DMT of the OAB protocol, is

$$d_{OAB}(r) = m(1 - r) \tag{12}$$

Hence, when $(m - 1)$ relay terminals are involved, the OAB protocol achieves the optimal DMT curve reaching the two extremes points $d^*(0) = m$ and $d^*(1) = 0$ (see Figure 3). Note that the only information provided by the DMT curve is 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 and the notification step, does not appear in (12) because the DMT analysis is based on a rough estimate of the achieved multiplexing gain r, not a precise value.

We end up this analysis with a last remark. The DMT analysis has been made considering a spectral efficiency R. Note that the effective spectral efficiency is rather $\overline{R}$,

$$\overline{R} = R \times \Pr[I_D > R] + \frac{R}{2} \times \Pr[I_D \le R] \tag{13}$$

Equation (13) follows from the fact that the OAB protocol operates at spectral efficiency R when the direct transmission is successful, and operates at spectral efficiency $R/2$ when a

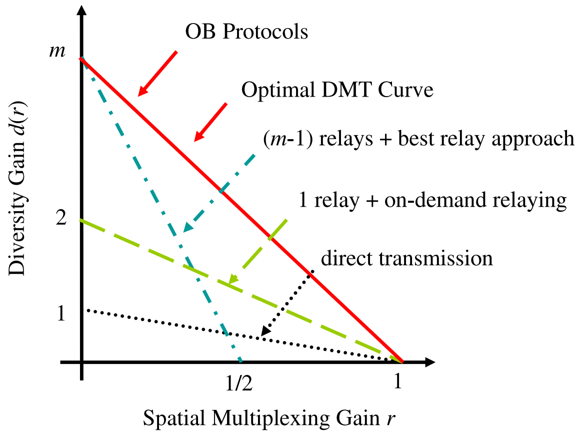

Fig. 3. DMT curves of the OB protocols, the direct transmission, and other cooperation schemes (best relay approach with $(m-1)$ relays, on-demand relaying with one relay).

cooperative transmission is needed. Using the definition of I_D in (6), we have that

$$\overline{R} = \frac{R}{2}[1+\exp(-\frac{1}{\sigma^2}\frac{2^R-1}{SNR})]$$

Here also, $\overline{R}$ cannot be reported on DMT curves since the spatial multiplexing gain r only reports that the data rate scales like R, without giving a precise value.

B. DMT Analysis for On-Demand Selective Decode and Forward Relaying with Selection of the Best Relay Terminal

We develop the DMT curve of a protocol based on the On-demand selective Decode-and-forward relaying with selection of the Best relay terminal, denoted ODB protocol. We use the same model described in the previous subsection. The scenario is divided in two time slots. During a first time-slot, D and the best relay terminal B are receiving signals from S according to (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 relay terminal sends a new signal using a selective DF scheme, i.e. if and only if the best relay has been able to decode the source message. So, during the second time slot, D is receiving a signal from B

$$y_{DB}(n) = \begin{cases} h_{BD}\hat{x}(n) + w_{BD}(n), & \text{if } I_{SB} > R \\ 0, & \text{if } I_{SB} \le R \end{cases} \quad (14)$$

where $\hat{x}(n)$ is the estimation of $x(n)$ at terminal B, and the mutual information I_{SB} is given by

$$I_{SB} = \log_2(1+SNR|h_{SB}|^2) \quad (15)$$

As in [3] and [8], the event that the relay has been able to decode the data transmitted by S with a spectral efficiency R is equivalent to event that the mutual information of the channel between S and the best relay B, I_{SB}, lies above the spectral efficiency R. The outage probability $p^{out}_{ODB}(SNR,r)$ of the ODB protocol is given by

$$p^{out}_{ODB}(SNR,r) = \Pr[I_{ODB} \le R]$$

Here, I_{ODB} denotes the mutual information of the ODB protocol. The ODB protocol operates at spectral efficiency R when the direct transmission is successful, and operates at spectral efficiency $R/2$ when the best relay terminal B must decode and forward the source message. The outage probability $p^{out}_{ODB}(SNR,r)$ is defined by

$$p^{out}_{ODB}(SNR,r) = \Pr[I_D \le R]\Pr[I_{DB} \le R/2 | I_D \le R] \quad (16)$$

where I_D is defined in (6). The mutual information of the selective DF scheme using the selection of the best relay terminal is denoted I_{DB}. The expression of the mutual information I_{DB} depends on the probability of the event $I_{SB} \le R$. So I_{SB} is given by

$$I_{DB} = \begin{cases} \frac{1}{2}\log_2(1+2SNR|h_{SD}|^2), & \text{if } I_{SB} \le R \\ \frac{1}{2}\log_2(1+SNR|h_{SD}|^2+SNR|h_{BD}|^2), & \text{if } I_{SB} > R \end{cases} \quad (17)$$

Given (16) and (17), the outage probability of the ODB protocol is given by

$$\begin{aligned} p^{out}_{ODB}(SNR,r) &= \Pr[I_D \le R] \\ &\times \Pr[I_{DB} \le R/2 | (I_{SB} \le R, I_D \le R)] \\ &\times \Pr[I_{SB} \le R] \\ &+ \Pr[I_D \le R] \\ &\times \Pr[I_{DB} \le R/2 | (I_{SB} > R, I_D \le R)] \\ &\times \Pr[I_{SB} > R] \end{aligned}$$

When $I_{SB} \le R$, from (6) and (17), we have that the event $I_D \le R$ is included in the event $I_{DB} \le R/2$. So, we have that

$$\begin{aligned} &\Pr[I_D \le R] \times \Pr[I_{DB} \le R/2 | (I_{SB} \le R, I_D \le R)] \\ &\qquad = \Pr[I_{DB} \le R/2 | I_{SB} \le R] \end{aligned} \quad (18)$$

The same observation can be done when $I_{SB} > R$ with a different expression for I_{DB}. Hence, we have that

$$\begin{aligned} &\Pr[I_D \le R] \times \Pr[I_{DB} \le R/2 | (I_{SB} > R, I_D \le R)] \\ &\qquad = \Pr[I_{DB} \le R/2 | I_{SB} > R] \end{aligned} \quad (19)$$

Using (18) and (19), we have that

$$\begin{aligned} p^{out}_{ODB}(SNR,r) &= \Pr[I_{DB} \le R/2 | I_{SB} \le R] \\ &\times \Pr[I_{SB} \le R] \\ &+ \Pr[I_{DB} \le R/2 | I_{SB} > R] \\ &\times \Pr[I_{SB} > R] \end{aligned} \quad (20)$$

Moreover, we give an upper bound on $p^{out}_{ODB}(SNR,r)$

$$\begin{aligned} p^{out}_{ODB}(SNR,r) &\le \Pr[I_{DB} \le R/2 | I_{SB} \le R]\Pr[I_{SB} \le R] \\ &+ \Pr[I_{DB} \le R/2 | I_{SB} > R] \end{aligned} \quad (21)$$

For high SNR values, using (15) and (17), we have that

$$\begin{aligned} \Pr[I_{DB} \le R/2 | I_{SB} \le R] &= \Pr[\log_2(1+2SNR|h_{SD}|^2) \le R] \\ &\le \Pr[2|h_{SD}|^2 \le SNR^{r-1}] \end{aligned} \quad (22)$$

$$\begin{aligned}\Pr[I_{SB} \le R] &= \Pr[\log_2(1+SNR|h_{SB}|^2) \le R)] \\ &\le \Pr[|h_{SB}|^2 \le SNR^{r-1}] \end{aligned} \quad (23)$$

$$\begin{aligned}&\Pr[I_{DB} \le R/2|I_{SB} > R] \\ &= \Pr[\log_2(1+SNR(|h_{SD}|^2+|h_{BD}|^2) \le R] \\ &\le \Pr[|h_{SD}|^2+|h_{BD}|^2 \le SNR^{r-1}] \\ &\le \Pr[|h_{SD}|^2 \le SNR^{r-1}] \\ &\times \Pr[|h_{BD}|^2 \le SNR^{r-1}] \end{aligned} \quad (24)$$

Thus, using (22), (23), and (24) in (21), we have that

$$\begin{aligned}p^{out}_{ODB}(SNR,r) &\le \Pr[2|h_{SD}|^2 \le SNR^{r-1}] \\ &\times \Pr[|h_{SB}|^2 \le SNR^{r-1}] \\ &+ \Pr[|h_{SD}|^2 \le SNR^{r-1}] \\ &\times \Pr[|h_{BD}|^2 \le SNR^{r-1}] \end{aligned} \quad (25)$$

From Lemma 2 in [8], we have that

$$\lim_{SNR\to\infty} \frac{\log\{\Pr[2|h_{SD}|^2 \le SNR^{r-1}]\}}{\log(SNR)} = r-1 \quad (26)$$

because $|h_{SD}|^2$ is an exponential variable. Given that $|h_{SB}|^2$ and $|h_{BD}|^2$ are also exponential variables, and the fact that both $|h_{SB}|^2$ and $|h_{BD}|^2$ are the maximum values of two sets of $(m-1)$ exponential variables, we have that

$$\lim_{SNR\to\infty} \frac{\log\{\Pr[|h_{SB}|^2 \le SNR^{r-1}]\}}{\log(SNR)} = (m-1)(r-1) \quad (27)$$

and

$$\lim_{SNR\to\infty} \frac{\log\{\Pr[|h_{BD}|^2 \le SNR^{r-1}]\}}{\log(SNR)} = (m-1)(r-1) \quad (28)$$

from Lemma 2 in [8]. Using (9), (26), (27), and (28) in (25), we conclude that

$$\lim_{SNR\to\infty} -\frac{\log[p^{out}_{ODB}(SNR,r)]}{\log SNR} = m(1-r)$$

Hence, the diversity curve $d_{ODB}(r)$, i.e. the DMT of the ODB protocol, is

$$d_{ODB}(r) = m(1-r)$$

Here also, when $(m-1)$ relay terminals are involved, the ODB protocol achieves the optimal DMT curve reaching the two extremes points $d^*(0) = m$ and $d^*(1) = 0$ (see Figure 3).

IV. Conclusion

The purpose of the study is the design of DMT optimal access protocols in the context of IEEE 802.11-based mesh networks. The designed protocol has two main features: on-demand cooperation and selection of the best relay terminal. When a destination terminal D fails in decoding the data message, D asks for cooperation with a signaling frame (on-demand approach). Terminals that have overheard the source message and the call from D, enter a competition step. The terminal with the best channel gain transmits a signaling frame first. This step concludes the selection of the best relay terminal. Then, this terminal sends a copy of the data message so D can transmits an acknowledgment frame when the combination of the two versions of the same data message has been successfully decoded. When $(m-1)$ terminals are situated in the range of both a source terminal S and a destination terminal D, a diversity gain of m is provided while a spatial multiplexing gain of one is achieved. Thus, the protocol implements a DMT optimal transmission scheme. This protocol can use either fixed AF or selective DF cooperation schemes.

Coding optimizations have not been addressed in the paper but they should be possible as soon as the relay terminals are allowed to demodulate and decode the source message. This is left for further study.

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