Two-way Communication for IEEE 802.11n WLANs Using Decode and Forward Relays

Marc Kuhn, Azadeh Ettefagh, Ingmar Hammerström, Armin Wittneben
Communication Technology Laboratory, ETH Zurich
Sternwartstrasse 7, 8092 Zurich, Switzerland
{kuhn, ettefagh, hammerstroem, wittneben}@nari.ee.ethz.ch

***Abstract* - In this paper we investigate the integration of two-way decode-and-forward (2W DF) relaying in IEEE 802.11n WLANs. Two-way DF relaying is a signaling scheme recently proposed in [2] for half-duplex relays. We compare this scheme to conventional DF relaying in two scenarios, either the Access Point acts as a DF relay ("two-way AP") or a station. After analyzing capacity and coverage in the considered scenarios at the 5 GHz band, we conclude that 2W DF relaying is able to increase the spectral efficiency and to reduce the delay of a two hop link in an 802.11n WLAN, while the communication range is smaller than in the case of a conventional DF relaying scheme.**

I. Introduction

The current draft of the IEEE 802.11n standard [1] specifies MAC and PHY for a high throughput WLAN; data rates of several hundreds Mbit/s will be available. Relaying is important in WLANs for several reasons, e.g. to provide additional coverage by multi-hop connections or to connect WLAN stations (STAs) served by the same access point (AP) using the legacy IEEE 802.11 standard [3]. According to this standard all connections between STAs in the same basic service set are not directly between both STAs, but using the AP as relay. Conventional decode-and-forward (DF) relaying with half-duplex relays (cf. [7]) suffers from a reduced spectral efficiency because of the pre-log factor ½. The authors in [2] propose a signaling scheme that avoids the pre-log factor ½: Two-way relaying. In this paper we investigate the integration of two-way relaying in 802.11n WLANs. In the following we review some details of the upcoming IEEE 802.11n standard and compare conventional DF relaying to Two-way DF relaying.

WLAN 802.11n: Details that are important for our investigations are summarized in the following paragraph: The PHY is based on MIMO OFDM in the 2.4 GHz and 5 GHz band operating in 20 MHz bandwidth; operation in 40 MHz bandwidth is optional. For an 802.11n Access Point (AP) it is mandatory to support one and two spatial streams for 20 MHz bandwidth, one spatial stream for an 802.11n STA; the support of 3–4 spatial streams in 20 MHz mode and of 1–4 spatial streams in 40 MHz mode is optional. Other optional features include transmit beamforming and space-time block codes (STBC) or hybrid STBC/ Spatial Multiplexing (SM). Channel State Information at the Transmitter (CSIT) is required for transmit beamforming, while it is not needed for STBC and SM. When SM is used without CSIT, interference between spatial streams has to be cancelled at the receiver.

Conventional two-hop communication using half-duplex DF relays: Fig. 1 shows an example for such a relaying scheme. Two wireless nodes A and B are communicating via a half-duplex DF relay. In the following we assume, that there is no direct communication possible between A and B. In the first time slot A transmits to the relay, then the relay transmits to B; in the third time slot, B transmits to the relay, then the relay sends the data to A. Hence, four time slots are necessary to deliver the data from A to B and vice versa – the achievable rate suffers from the use of four time slots, and delay is introduced. Such schemes are used to increase the coverage or to reduce the overall transmit power.

Two-way DF relaying according to [2]: In the first time slot both nodes A and B transmit their symbols to the relay simultaneously and in the same bandwidth (cf. Fig. 2). The relay decodes both streams and retransmits the received signal (i.e. the sum of the symbols of A and B) in the second time slot to A and B.

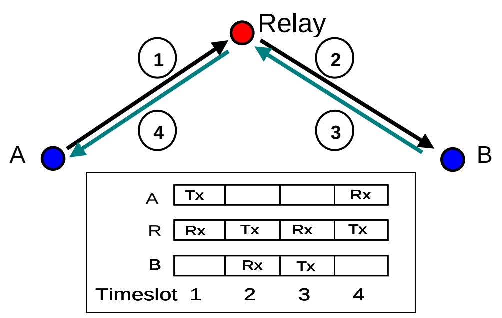

Fig. 1. Conventional DF relaying using half-duplex relays.

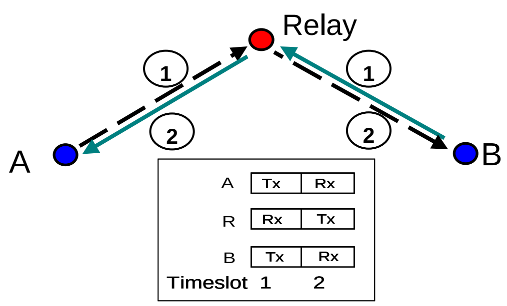

Fig. 2. Two-way DF relaying using half-duplex relays.

Since nodes A and B know their own transmitted symbols they can subtract the back-propagating self-interference prior to decoding [2], assuming CSI at the receiver and reciprocity of all involved channels. 2W DF relaying increases the spectral efficiency by avoiding the pre-log factor ½ of the conventional scheme [2].

Contribution of this work: We identify the required modifications to enable 2W DF relaying in 802.11n WLANs and analyze the 1%-outage capacity and the coverage of such WLANs.

II. Two-way Relaying in 802.11n

In the first time slot both nodes A and B have to start the transmission simultaneously and the relay has to be able to decode both interfering transmissions. The current MAC layer of an IEEE 802.11 WLAN allows only one STA to have a transmit opportunity at a given time [1], [3], [4]. Therefore the MAC layer has to be modified to enable 2W DF relaying. In the second time slot the relay forwards the sum of the two transmissions to A and B; both nodes A and B have to be able to cancel the self-interference by subtracting their own transmitted symbols.

In the following we consider two different scenarios for 2W DF relaying in an 802.11n WLAN and discuss extensions to the current IEEE 802.11 MAC layer to enable 2W DF relaying.

Scenario (1) “Two-way AP”: Two stations STA1 and STA2 in the same basic service set are communicating via an AP (see Fig. 3), i.e. the AP acts as a relay – in the legacy 802.11 MAC [3] this is the only setup for a communication between two STAs associated to the same AP; in 802.11e also a Direct Link Setup (DLS) between both STAs is possible, cf. [4]. There are advantages to use 2W DF relaying instead of the DLS; e.g. is it obvious that in a WLAN the STAs are in the communication range of the AP, while they are not necessarily in the range of each other.

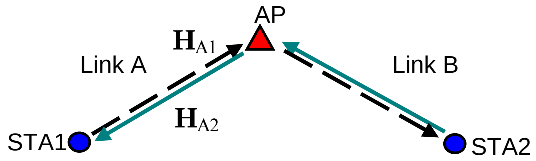

Fig. 3. Scenario (1).

Scenario (2) “Two-way DF relay STA”: STA2 is exchanging data packets with the AP. Because the distance between AP and STA2 is too large, or because the channel between the nodes is in a deep fade, a relay has to be used. This relay is either a dedicated relay (mounted intentionally at a certain place to extend the range of the AP by the use of a two hop transmission) or an idle station STA1 that is assisting the communication.

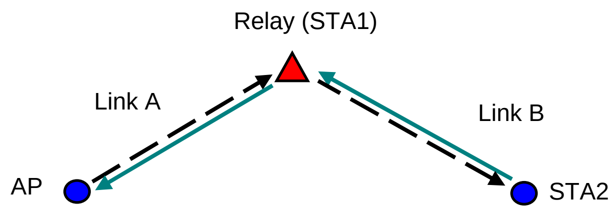

Fig. 4. Scenario (2).

The MAC layer in the draft of the IEEE 802.11n standard [1] is based on the MAC layer defined in the legacy 802.11 and the 802.11e standard, but it also describes extensions to enable higher data rates. Two different types of coordination functions are defined: a decentralized CSMA/CA approach for a contention period (DCF and EDCA) and a centralized polling (PCF and HCCA) in a contention-free period.

In *Scenario (1) “Two-way AP”* we assume the use of HCCA or PCF (cf. Fig. 5). The AP polls both STAs at the same time. The STAs transmit simultaneously in the following time slot, i.e. the first time slot of the 2W DF relaying. A modification of the current 802.11 MAC is necessary to poll two STAs simultaneously. In the following time slot the AP retransmits the sum of both transmissions. The whole 2W DF relaying is done in the contention-free period; the contention period is not used in Scenario (1).

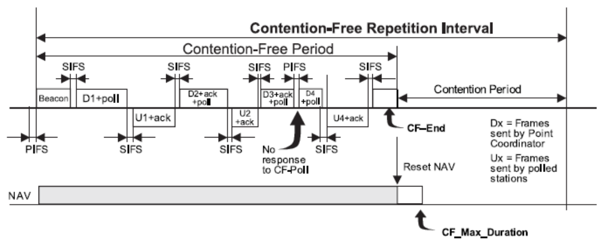

Fig. 5. Example of PCF transfer (Figure 62 in [3]).

In *Scenario (2) “Two-way DF relay STA”* the relay is not able to control the polling in the contention-free period, because the AP is the polling master not the relay. Therefore we assume a contention period under control of EDCA or DCF for this scenario. But due to the CSMA/CA protocol in the contention period a simultaneous transmission of the AP and the STA2 in one single time slot is not possible. Hence we propose that the AP and STA2 transmit in two different time slots to the relay. The relay (STA1) transmits the sum of both messages in the third time slot. In this case the communication is similar to the approach proposed in [8]. Because three time slots are used the spectral efficiency is higher than in the conventional relaying scheme, where 4 time slots are used, but lower than in Scenario (1).

III. System Model

We use a frequency-selective block fading MIMO channel model. In the following we describe the system model for Scenario (1) (cf. Fig 3), i.e. STA1 and STA2 are the two nodes A and B in Fig. 1 and Fig. 2 that communicate using the AP as a relay. The system model for Scenario (2) follows accordingly.

N, M, and R are the number of antennas at the two sources (i.e. STA1 and STA2 in Scenario (1)) and at the relay (the AP in Scenario (1)), respectively; the AP and the STAs are using the transmit power P, which is limited by the 802.11n standard, N_0 denotes the noise power density. The matrix I is the identity matrix and $*$ is the hermitian transposition operator. $\mathbf{H}_{A1}$ and $\mathbf{H}_{A2}$ denote the MIMO channel matrices for one OFDM subcarrier of link A (for Scenario (1) between STA1 and AP, cf. Fig. 3) in the first and second time slot, respectively. $\mathbf{H}_{B1}$ and $\mathbf{H}_{B2}$ are the respective MIMO matrices for link B. We also assume that the channels are reciprocal, and that they remain the same during the first and second time slot.

The achievable instantaneous rates per OFDM subcarrier for Scenario (1) **"Two-way AP"** are derived in the following. The maximum rate of STA1 for link A in the first time slot is given by:

$$R_{A1} = C\left(\frac{P}{N_0}\mathbf{H}_{A1}\right) \quad (1)$$

Respectively, for STA2 on link B in the first time slot follows:

$$R_{B1} = C\left(\frac{P}{N_0}\mathbf{H}_{B1}\right) \quad (2)$$

In the second time slot the rates for the AP transmitting on link A and link B are given by

$$R_{A2} = C\left(\frac{\beta P}{N_0}\mathbf{H}_{A2}\right) \quad (3)$$

and

$$R_{B2} = C\left(\frac{P\cdot(1-\beta)}{N_0}\mathbf{H}_{B2}\right), \quad (4)$$

where βP is the average transmit power used by the relay in the second time slot in the direction relay $\rightarrow$ STA1, and (1-β)P the relay average transmit power for the reverse direction, i.e. relay $\rightarrow$ STA2 in the second time slot ($0 \leq \beta \leq 1$). We assume that the back-propagating self-interference is cancelled successfully prior to decoding. In the equations above

$$C\left(\frac{P}{N_0},\mathbf{H}\right) = \log_2\left(\det\left(I_{N_R} + \frac{P}{N_T N_0}\mathbf{H}\mathbf{H}^*\right)\right) \quad (5)$$

is the capacity for the MIMO system with channel matrix $\mathbf{H}$, N_T and N_R are the number of antennas at the transmitter and receiver, respectively.

The rate of the multiple access channel in the first time slot is given by:

$$R_{MA} = C\left(\frac{P}{N_0}, \mathbf{H}_{A1}, \mathbf{H}_{B1}\right) = \log_2\left(\det\left(I_R + \frac{P}{N\,N_0}\mathbf{H}_{A1}\mathbf{H}_{A1}^* + \frac{P}{M\,N_0}\mathbf{H}_{B1}\mathbf{H}_{B1}^*\right)\right) \quad (6)$$

We derive the maximum rate R_1 that can be used by STA1 in the first time slot for the two hop communication assisted by the DF relay as

$$R_1 = \min\left\{R_{A1}\ ,\ R_{B2}\ ,\ \frac{1}{2}R_{MA}\right\}, \quad (7)$$

where the factor ½ in front of R_{MA} in this equation assures that R_1 is always in the rate region of the two-user MIMO multiple access channel. Note that this allocation is not optimal with respect to the sum rate, but it provides a fair situation for both users in a scenario where the data traffic is symmetric in both directions.

Accordingly the maximum rate for STA2 in the first time slot is given by

$$R_2 = \min\left\{R_{B1}\ ,\ R_{A2}\ ,\ \frac{1}{2}R_{MA}\right\} \quad (8)$$

The AP decodes the data of STA1 and STA2 and forwards it in the second time slot to the respective destinations. Therefore, the two hop data rate R_A^{2W} for STA1 $\rightarrow$ STA2 is given by

$R_A^{2W} = \frac{1}{2}R_1$ and vice versa $R_B^{2W} = \frac{1}{2}R_2$.

The sum rate follows to:

$$R_{SUM} = \frac{1}{2}\left(R_1 + R_2\right) \quad (9)$$

For the *conventional two-hop communication using DF relays* we assume that both time slots are used to transmit the data of only one STA; therefore we find the two hop rate per OFDM subcarrier

$$R_A^{1W} = \frac{1}{2}\min\left\{R_{A1}\ ,\ R_3\right\} \quad (10)$$

if STA1 is transmitting to STA2 via the AP ,with

$$R_3 = C\left(\frac{P_S}{N_0}\mathbf{H}_{B2}\right) \quad (11)$$

and in the case that STA2 uses both time slots to send its data to STA1

$$R_B^{1W} = \frac{1}{2}\min\left\{R_{B1}\ ,\ R_4\right\} \quad (12)$$

with

$$R_4 = C\left(\frac{P_S}{N_0}\mathbf{H}_{A2}\right) \quad (13)$$

.

All rates in this section are derived per one OFDM subcarrier. For the simulation results presented in the following section, the rates of all non-zero OFDM subcarriers are added up.

A. Power distribution

The factor β in the equations (3) and (4) controls the power allocation of the relay in the second time slot. For β = ½ the AP distributes the power equally to both destinations STA1 and STA2; in asymmetric situations, e.g. when the channel to one STA shows a stronger attenuation because of a larger distance or a deep fading, the factor β can be used to strengthen the weaker channel by taking power away from the stronger channel; in a WLAN there is a sum power constraint for any node. To enable a successful cancellation of the self-interference at the two STAs, the power distribution factor β has to be known to both STAs. A power allocation for SISO Two-way relaying that is optimal with respect to the sum rate is derived in [2].

IV. Simulation Results

We assume no CSIT at the nodes A and B, DF relaying, no direct path between source and destination, i.e. all communication is done via the relay. We use an indoor NLOS frequency-selective block fading channel model according to the ETSI channel model B recommended for HiperLAN/2 [5], [6], including path loss. All the spatial channels between transmit and receive antennas are fading independently. The transmit power is set according to local regulations. Table 1 shows the simulation parameters.

Table 1. Simulation parameters.

Parameters	IEEE 802.11n WLAN
Maximum transmit power AP, STA1, STA2	60 mW
Path Loss Exponent α	3.5
Noise Figure	10 dB
Implementation Margin	5 dB
Carrier Frequency	5.2 GHz
Bandwidth	20 MHz
# of non-zero OFDM subcarriers	52

Scenario (1) 2W AP relaying: If the relay is able to decode the symbols from both nodes transmitting in time slot 1, it retransmits in time slot 2 a linear combination of the two messages in different spatial streams as defined in [1].

We evaluate the achievable rates of 2W DF relaying and the conventional DF relaying by Monte Carlo simulations. Based on these rates we calculate the outage probabilities of the two schemes for a minimum QoS requirement: We define an outage rate R_{out} for both two hop data rates R_A^{2W} and R_B^{2W}; e.g., if R_A^{2W} is below R_{out} there is an outage event for the two hop channel STA1 $\rightarrow$ STA2.

For the simulations, the distance d_1 between STA1 and AP is chosen to be d_1=20m, d_2 varies between 10m and 50m. Fig. 6 shows the 1%-outage rates for Scenario (1) for the case β= ½. The AP uses R=4 antennas, the STAs have N=M=2 each; in our case the AP is able to decode four spatial streams; hence both STAs can use two spatial streams. We compare the rates to those of the *conventional DF relaying scheme* assuming that only one STA can use both time slots for its two-hop communication.

In two hops, the sum rate of the 2W DF relaying scheme (i.e. the sum of the 1%-outage rates for the two STAs according to equation (9), denoted "2W Sum Rate" in Fig. 6) is always higher than the two hop 1%-outage rate of one STA using the conventional scheme ("1W Rate" in Fig. 6); this means, the 2W DF relaying scheme shows a higher spectral efficiency. In the case of 2W DF relaying, for d_2 > 20m the 1%-outage rate of STA1 (STA1 → STA2: "2W Rate STA1") is lower than "2W Rate STA2". For increasing d_2 both are limited by the hop between the AP and STA2. For "2W Rate STA2" the first hop is a 2x4 MIMO link from STA2 to the AP using the transmit power P, whereas for "2W Rate STA1" the second hop is a 4x2 MIMO link from the AP to STA2 using only P/2 with a lower receive array and diversity gain.

To determine the coverage range of the system we define a two hop outage rate R_{out} = 1b/s/Hz. The conventional DF scheme "1W STA1" shows a lower outage probability compared to "2W STA1" for a given distance d_2, cf. Fig. 7. This is again mainly due to the fact, that for 2W DF relaying the AP has only half the power for each link in time slot 2, whereas in the conventional scheme the AP has the full power P for the first link in time slot 2 and again P for the second link in time slot 4. However, "2W STA2" and "1W STA2" show the same performance: For increasing d_2 both are limited by the hop from STA2 to the AP, where both transmit with the full power P.

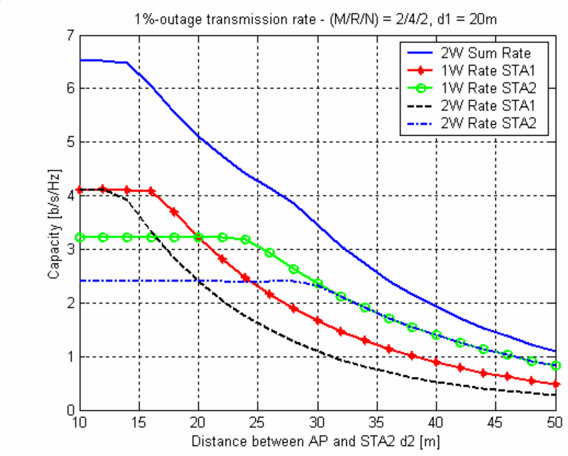

Fig. 6. Two hop 1%-outage rates for Scenario (1), β= ½.

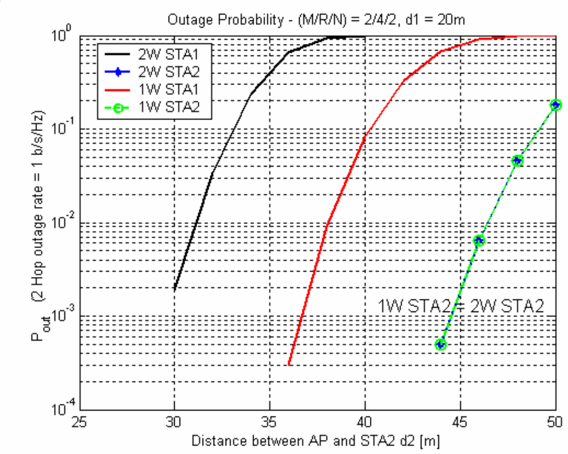

Fig. 7. Outage probabilities for Scenario (1), β= ½, outage rate: 1 b/s/Hz.

Because the coverage is determined by the weaker connection between the two STAs, an efficient power allocation at the relay is able to improve the performance significantly, particularly in situations, in which the distances d_1 and d_2 can differ strongly (e.g. "2W STA1" and "2W STA2" in Fig. 7).

For Scenario (2) "Two-way DF relay STA" the outage probabilities are similar to those found for Scenario (1). The only difference is, that in Scenario (2) there is no multiple access channel in the first phase of the 2W DF relaying scheme because there are two different time slots used. Whereas the results for the two hop 1%-outage rates are different; due to the use of three time slots the sum rate is only about 2/3 of the sum rate for Scenario (1)., i.e. the spectral efficiency is decreased for Scenario (2).

A. Power distribution

In contrast to the investigations in [2], we analyze the coverage of the Two-way relaying scheme based on outage probabilities. The coverage is determined by the performance of the weaker link, therefore the optimal power distribution leads to the same two hop rates R_A^{2W} and R_B^{2W} for the case of the same outage rate R_{out} for both two hop communications; in other words we need to find the factor β which fulfils the following equality:

$$R_A^{2W} \overset{!}{=} R_B^{2W} \quad (14)$$

Considering this equation with the assumption of equal transmit power in all OFDM sub-carriers, we calculate the factor β which indicates the fraction of transmit power allocated to link A in the second time slot. Assuming that the relay knows the second-order statistics of the channels, from equation. (14) two values for β are achieved for the 2x4x2 MIMO system; from those results the one which is between 0 and 1 is shown in the following equation:

$$\beta = \frac{d_2^{\alpha}}{d_2^{\alpha} + d_1^{\alpha}} \quad (15)$$

where α denotes the path loss exponent.

Repeating the simulation using the new β for the same case as the one described on the previous page we get the results shown in Fig. 8 and 9. As it is seen in Fig. 8 the sum rate is almost the same as the rate for β=0.5 while the outage curve of STA1 is improved in Fig. 9. The price for this improvement is a smaller rate for STA2. This is acceptable since we aim to improve the path with the largest outage probability which belongs to STA1. In comparison to Fig. 7 there is only a small difference left in Fig. 9 between the outage probabilities of the 2W DF MIMO relaying compared to the conventional DF MIMO relaying "1W STA1"; "1W STA1" determines the coverage performance of the conventional scheme.

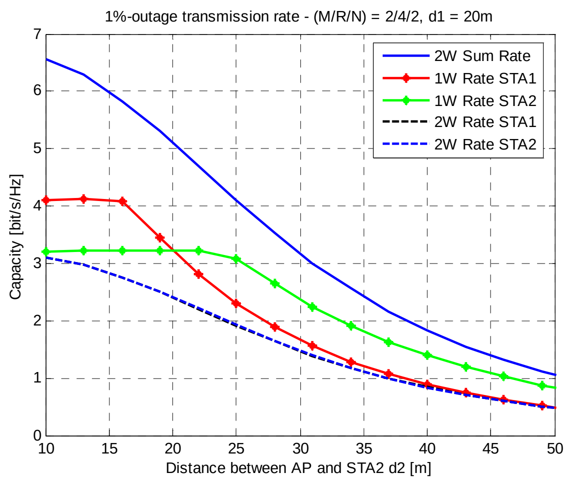

Fig. 8. Two hop 1%-outage rates for Scenario (1), β derived from equation (15).

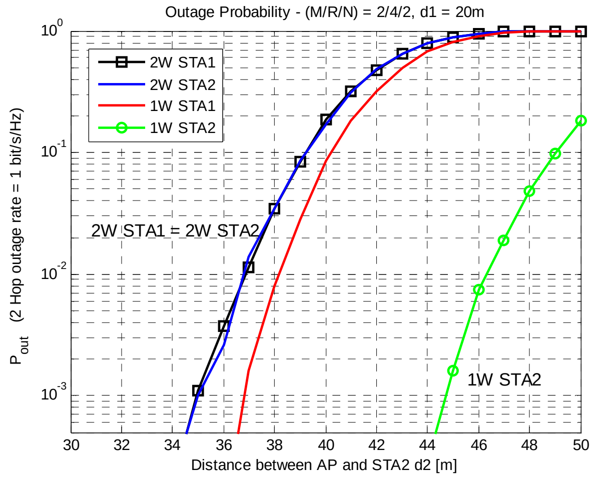

Fig. 9. Outage probabilities for Scenario (1), outage rate: 1 b/s/Hz, β derived from equation (15).

V. Conclusions

The Two-way DF relaying scheme is an interesting approach for high speed 802.11n WLANs to increase the coverage of a basic service set (Scenario (2)) and to improve the spectral efficiency if there is often symmetric traffic between the STAs associated to one AP, e.g. gaming or (video) telephony over WLAN, (Scenario (1)). For applications needing high data rates or for delay critical services, the 2W DF relaying scheme is better suited due to the higher spectral efficiency, but for coverage range extension the conventional scheme shows advantages as long as no power distribution is used, i.e. β = ½. With a power distribution at the relay in the second phase of the 2W DF relaying, the outage performance is only slightly lower compared to the conventional scheme.

References

[1] IEEE Draft Standard 802.11n/ D1.04, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Enhancements for Higher Throughput," September 2006.

[2] B. Rankov, A. Wittneben, "Spectral efficient signaling for half-duplex relay channels," *Proc. Asilomar Conference on Signals, Systems, and Computers 2005*, Pacific Grove, CA, Nov. 2005.

[3] IEEE Standard 802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications," 1999 Edition (ISO/IEC 8802-11:1999).

[4] IEEE Standard 802.11e, "Medium Access Control (MAC) Quality of Service (QoS) Enhancements," 2005.

[5] M. Debbah, J. Gil, P. Fernandes, J. Venes, F. Cardoso, G. Marques, L. M. Correia, FLOWS project "Final report on channel models," 2004. Online available: http://129.215.162.66/flows/main/outputs/list.htm

[6] Medbo, J. and Schramm, P., "Channel models for HIPERLAN/2 in different indoor scenarios," EP BRAN 3ERI085B, ETSI, Sophia Antipolis, France, Mar. 1998.

[7] N.J. Laneman, D.N. Tse, G.W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," IEEE Trans. Inform Theory, vol. 50, Dec. 2004.

[8] Y. Wu, P.A. Chou, S.-Y. Kung, "Information exchange in wireless networks with network coding and physical-layer broadcast," *Proc. of 39th Annual Conf. on Information Sciences and Systems (CISS)*, March 2005.