The 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'06)

ON THE RANGE PERFORMANCE OF DECODE-AND-FORWARD RELAYS IN IEEE 802.11 WLANS

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

ABSTRACT

We consider a wireless local area network (WLAN) in the 5 GHz band. The coverage is one of the main challenges in high-frequency wireless systems and we focus on enhancing the coverage range of such a system by relaying. So far no relaying functions are defined in IEEE 802.11 medium access control (MAC). We introduce three simple MAC schemes for multihop communications and classify them based on delay, simplicity, capacity and application. We also point out the deficiency of the actual standard regarding multihop connections. We study the outage behaviour of a single input single output (SISO) two-hop link and improve it by developing a multiple input multiple output (MIMO) system. We investigate the tradeoff between coverage range and number of relays in a two-dimensional scenario. We also discuss the tradeoffs between having relays instead of adding more access points (APs) to the system and give an estimation of the number of required APs/relays to fully cover an area. In other words we show how much range one can gain from *decode-and-forward* (DF) relaying in a WLAN scenario.

I. INTRODUCTION

Recently with fast growth of wireless communications WLANs are given a lot of attention. It is expected that future wireless communication systems will operate even beyond 5 GHz. Moving towards higher frequencies leads to larger path loss and as a result smaller coverage area. Besides, providing full coverage is problematic due to the random nature of wireless channels and shadowing. Coverage is one of the main challenges in future wireless communication systems. The problem is usually more critical for real-time traffic applications as for these types of services full coverage would be necessary as, for example, in cellular telephony networks. Even small dead spots are not acceptable since a call may be dropped when the first outage event is encountered. For these applications in addition to full coverage seamless handover is required which implies having enough overlaps between ranges of neighbouring APs. In [1] the relatively poor coverage range of an IEEE 802.11a [2] AP compared to the range of digital enhanced cordless telecommunications (DECT) handset is shown. The coverage enhancement for a single-hop link in a voice over WLAN (VoWLAN) by space diversity techniques using co-located and locally-distributed antennas is also shown in [1].

Cooperative relaying has become a major subject in the WLAN research literature [3]. Applying relaying schemes one can enhance the outage probability performance [4] and as a result increase the coverage range of a system. In [5] some advantages and applications of relaying for future wireless systems are discussed and it is shown that relays can extend the coverage of an AP significantly especially in highly obstructed areas. The authors of [6] propose a relayed wireless access network based on legacy IEEE 802.11 which carries real-time packets. They focus on packet transmission delay and packet rate rather than the range itself. In this paper we focus on relaying in a 5 GHz WLAN in a frequency-selective fading environment. Cooperative relaying in frequency selective channels are far less studied so far. In [7] the authors derive capacities of orthogonal frequency division multiplexing (OFDM) and OFDMA systems having multiple source and relay nodes and a single destination node. In [8] a jointly optimised power allocation over subchannels in space and frequency domain at source and relay to maximize the instantaneous capacity is presented. The authors consider MIMO systems with nonregenerative relays, i.e. a*mplify-and-forward* (AF) relays. Here we consider uniform power over all subcarriers as in the current WLAN standards. The results can be further improved by allocating optimised power over subchannels. In [9] we showed that DF relaying outperforms AF in the considered VoWLAN scenario. A DF relay decodes the received data from the AP and after re-encoding sends it to the destination while an AF relay amplifies what it has received from the AP and forwards it to the destination without having any knowledge about the content of the data. In this paper we consider only DF relays due to their better performance and easier deployment.

The main focus of this paper is to evaluate the coverage range of an IEEE 802.11a WLAN system and enhance this range by DF relaying and space diversity techniques. At first, to show the feasibility of relaying in a WLAN system, we introduce three different MAC schemes and classify them based on delay, simplicity, capacity and application. Then the system model and simulation results evaluating the performance of DF relays in both SISO and MIMO wireless systems are studied. We consider a two-dimensional scenario and estimate the range enhancement in a WLAN by adding more relays or APs.

II. SIMPLE MAC SCHEMES FOR RELAYING

In this section we introduce three different MAC schemes for relaying in an IEEE 802.11 WLAN. MAC aspects for multihop communications have been considered in different research works. In [10] authors evaluate the performance of multihop ad hoc WLANs by simulation. They consider the legacy IEEE 802.11 MAC with distributed coordination function (DCF) and show that due to lack of coordination and other restrictions the results do not seem promising for real-time applications. In [6] a MAC scheme is introduced for relayed wireless access networks based on the legacy IEEE 802.11, where each relay supports *dual channels*, i.e. two separate frequency channels, consisting of one *HOME* channel to communicate with the stations within its coverage range and one *RELAY* channel to forward or download AP's traffic. European telecommunications standards institute (ETSI) also defined a MAC scheme for DECT wireless relay station (WRS) in [11]. Our schemes are based on the latest WLAN MAC standard i.e. IEEE 802.11e [12]. In each beacon interval there is a contention free period (CFP) followed by a contention period (CP). We assume a basic beacon period of T ms. In CFP the hybrid coordinator (HC) allocates timeslots to terminals by a polling mechanism which is defined in the hybrid coordination function (HCF) controlled channel access (HCCA) while in CP terminals contend to get the channel according to enhanced distributed channel access (EDCA). At first we assume a two-hop link. The decoding and encoding time in the relays are neglected.

A. *The First MAC Scheme*

In the first scheme which is the simplest case the relay communicates with the AP during the CFP and it communicates with the STAs during the CP. The relay operates at the same frequency as the AP and can be simply a station (STA). A two-hop link based on this scheme adds no considerable delay to the system as long as the relay can access to the channel during the CP, i.e. the data is delivered from AP to STA in the same beacon interval. This scheme is standard compliant but it is not desirable for real-time traffic services since there is always a certain probability that the relay cannot get the channel especially when there are many STAs trying to access the channel in the CP. This probability can be decreased by assigning higher priority to the relay or increasing number of possible relays for each STA but it is not diminished completely. The latter way is practical when there are enough relay nodes around the STA, e.g. when each STA can relay the data stream for another STA. Fig. 1 shows an example for the first MAC scheme. In this example STA_1 communicates with the AP via the relay and STA_2 in the first beacon interval communicates directly with the AP while in the second beacon interval it is not able to communicate directly and sets up its communication link via the relay.

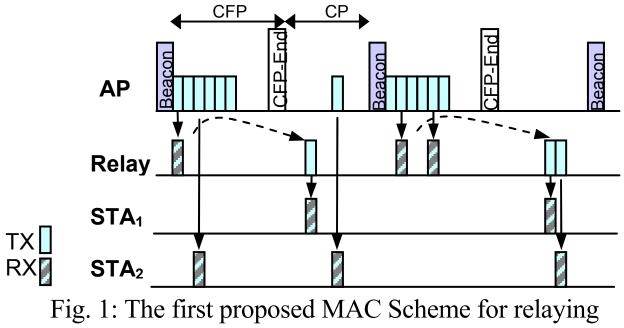

Fig. 1: The first proposed MAC Scheme for relaying

B. *The Second MAC Scheme*

In the second scheme during the CFP the HC allocates two timeslots (in M-hop case M timeslots) to the relay per each STA connected via it. In the first timeslot the relay communicates with the AP and in the second one it communicates with the STA. In other words in the second timeslot a quasi direct link is set up between relay and STA. The direct link is not as it is defined in the standard IEEE 802.11e. In the actual version of the standard the AP needs to communicate with both nodes in order to set up the direct link between them but in our scenario it is assumed that the STA is not in the communication range of the AP and that's why it is connected via a relay. Here again the relay can be a STA and it operates at the same frequency as the AP. As a result the AP has to be silent when the relay is transmitting or receiving. Due to allocating double timeslots per each STA connected via a relay, the capacity of the AP in HCCA in terms of number of connected STAs is reduced while there is no considerable additional delay because of the two-hop link. Fig. 2 shows the second MAC scheme for the same situation as the one in Fig. 1.

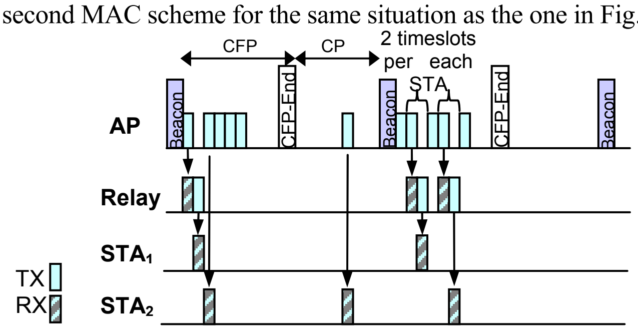

Fig. 2: The second proposed MAC scheme for relaying

C. *The Third MAC Scheme*

In the following we introduce the third scheme. In [13] this scheme is used for supporting seamless handover in a single-hop WLAN. Here we show that it can also be used for relaying in a WLAN system. We assume a basic beacon period of T ms. However for each associated STA/relay packets are only transmitted every second beacon. This results in a frame period of $2T$ ms and allows the STAs /relays to use the rest of the frame period for frequency tuning, communicating with other nodes and when necessary for handover.

For example in order to support N_u users half the connections are assigned to the even and the other half to the odd beacons. We assume that similar to a STA a relay is also served by the AP in either even or odd beacon. As an example suppose that in the first beacon interval the relay communicates with the AP at frequency f_1 afterwards it tunes to another frequency f_2 and in the second beacon interval it communicates with its associated STAs at f_2. During this beacon interval the AP does not need to be silent and can communicate with other STAs or relays at f_1. Each frequency tuning can take 1.5-2 ms and to receive the beacons on time the tuning has to be done more than 2 ms before each target beacon transmission time. We consider that STAs which are communicating with the AP via a relay, are served by the relay all in odd or even beacon intervals. In this case the maximum number of connections (consisting of both relays and STAs) supported by the AP remains the same as in the single-hop case, i.e. N_u and each relay can support up to $N_u/2$ STAs. In this scheme each relay operates at a different frequency from adjacent APs but due to the large number of available channels in IEEE 802.11a the frequency planning in most cases can be done easily. We assume that each relay is located almost on the border of the AP's coverage area so each frequency can be reused at a minimum distance of three hops to avoid interference. Fig. 3 shows an example situation for the third introduced MAC scheme in which STA_1 communicates with the AP via a relay while STA_2 communicates directly. It is assumed that the relay has the same functionality as the AP though it is not connected to the backbone. Data transmissions among relay and STAs are also performed during CFPs in which timeslots are assigned to a certain STA by the relay. All real-time transmissions are performed in CFPs and are fully controlled by the HC so this scheme is appropriate for real-time traffic services. Nevertheless there is an additional delay of one beacon interval compared to previous introduced MAC schemes.

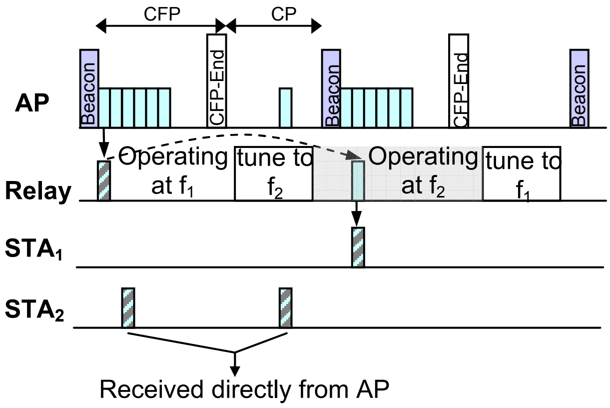

Fig. 3: The third proposed MAC scheme for relaying

D. Extension to multihop links with more than two hops

Now we extend the system to a multihop link with more than two hops. This results in a delay increment. For example for a three-hop link in the first scenario an additional delay of one beacon interval is expected when the second relay cannot access the channel in the CP of the beacon interval in which it received the packets from the first relay. In the second MAC scheme as long as all intermediate relays can be scheduled in the CFP of the first beacon interval there is no additional delay. In this way a small delay is guaranteed but the maximum number of connections is reduced significantly. For example assume that in a single-hop case the AP allocates one time-slot to each associated terminal and supports maximum 10 direct connections during CFP of each beacon interval. Then the capacity is dropped to at most four connections when three STAs are served by the relays in a three-hop scenario and one free time-slot is left which can only be used for a direct communication. However the delay is almost as large as the single-hop case. In the third MAC scheme a packet takes about $(M-1)T$ more until it is received by the destination via M hops. In all cases we neglected the propagation time which is a reasonable assumption for indoor wireless environments.

Generally in addition to extra delay there is also a problem with the HCCA in multihop scenarios. The problem is similar to what we mentioned in the second MAC scheme, i.e. in the actual IEEE 802.11e AP cannot set up direct links among the nodes which are not in its coverage range. As a result relays cannot be simple STAs and must have at least the AP's scheduling capability similar to the third MAC scheme. To solve this problem we assume that in the first MAC scheme HCCA is not used at all or only used in the first hop and communication among relays and STAs in other hops are performed based on EDCA. In the second MAC scheme an extension to the standard is assumed, i.e. in a M-hop link, M timeslots are allocated to the first relay (the relay which is communicating directly with the AP) per each STA connected via this relay. Of course for a certain beacon interval and a fixed number of STAs this assumption restricts the maximum possible number of hops.

III. Outage Behaviour

Now a WLAN system is considered with one AP, one STA and in the general case N half-duplex DF relays which are uniformly distributed on a disk-shaped area. Relays are portable but do not move. We consider different locations for the STA with different distances from the AP but all on the same line (one-dimensional scenario) and at each place select a relay among all N relays according to its location. The link from AP to relay is defined as uplink and from relay to STA as downlink. We assume perfect channel state information (CSI) at the receivers and no CSI at the transmitters. We also assume that no direct communication is possible between the AP and the STA which is a reasonable assumption for coverage investigations.

The outage probability is calculated based on a minimum signal to noise ratio (SNR), i.e. SNR_{thr} required to achieve a certain bit error rate (BER). Without loss of generality we consider voice packets and we choose BER of 10^{-3} as the maximum acceptable BER in our system [14] and from that by taking into account the forward error correction (FEC) coding we calculate a threshold SNR and a threshold rate. The same calculation can be carried out for data packets considering a different maximum acceptable BER. It is assumed that an outage occurs whenever $C < R_{thr}$ and when the probability of outage is equal or smaller than 1% we have full coverage.

$$C = \sum_{k=1}^{N_{sub}} B_k \log_2(1 + SNR_k) \qquad (1)$$

in which

$$SNR_k = \frac{P_T}{N_0 B_k} \left| H_k \right|^2 \qquad (2)$$

and C is the capacity per hop, P_T the transmit power, N_0 noise power density, B_k bandwidth of each OFDM subcarrier, H_k k-th subchannel coefficient and N_{sub} number of subcarriers. In the two-hop link with a DF relay (without direct link) an outage occurs whenever any of the hops is in outage. A Non-Line-of-Sight (NLoS) two-hop link in which the AP transmits the packets to the relay in the first timeslot and the relay retransmits them to the STA during the second time interval is considered. For both hops a frequency-selective fading channel model is used according to ETSI channel model B recommended for HiperLAN/2 [15] including path loss. In order to model practical scenario main parameters, e.g. bandwidth, noise figure etc. are taken from standard IEEE 802.11a. Transmit power is set according to local regulations. The same transmit power for AP and relay is considered. Table 1 shows the simulation parameters. We assume H_{sr} as channel coefficients of the uplink and H_{rd} channel coefficients of the downlink. Fig. 4 shows the simulation results obtained for the

Table 1: Simulation parameters.

Parameters	IEEE 802.11a WLAN
Transmit Power	60 mW
Path Loss Exponent	3.5
Noise Figure	10 dB
Implementation Margin	5 dB
Carrier Frequency	5.2 GHz
Carrier Spacing	20 MHz

SISO case when the relay is exactly in the middle of the virtual line that links AP to STA, i.e. the optimal case when a relay is selected based on its physical location. The same probability for outage occurrence on both uplink and downlink is considered by assuming the same outage rate and channel model for both links. The result shows considerable range enhancement for DF relaying compared to the case where no relay is used. It is important to note that we assume the DF relay can decode the received data from the AP perfectly whenever $C \geq R_{thr}$. One should also note that relay selection can play an important role in the scenarios in which many relays are available around a certain node, e.g. when each STA can be used as a relay for another STA. In such a scenario a relay which has the best channel, i.e. a relay with $\max\left\{\min\left\{\sum_{k=1}^{N_{sub}}\left|H_{sr_{j_k}}\right|^2, \sum_{k=1}^{N_{sub}}\left|H_{rd_{j_k}}\right|^2\right\}\right\}$, $j=1{:}N$ may be selected.

Now we increase the number of antennas in each node to two. Primarily we perform receive antenna selection at relay and STA as the simplest space diversity scheme which adds no delay to the system. Then we apply receive antenna selection at relay and maximum ratio combining (MRC) at the STA as a technique which provides us with the maximum array gain. Since for coverage enhancement low-SNR regions are our main concern and in order to have an IEEE 802.11a standard compliant system we do not consider spatial multiplexing techniques. Simulation results for both MIMO techniques when the relay is located in the middle of the virtual line that links AP to STA are also plotted in Fig. 4. The results show that even by applying simple antenna selection one can increase the range several meters further in comparison with the SISO scenario. The range has been further improved by performing MRC at the receiver. The direct link with a single antenna at each node is also depicted as reference.

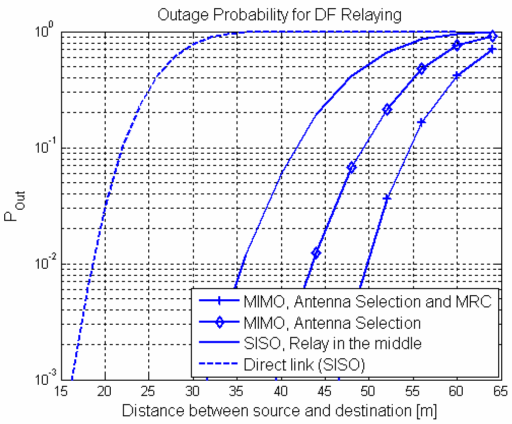

Fig. 4: Outage probability

Finding a better location for the relay can further enhance the range. So far the same probability of outage occurrence on both uplink and downlink has been considered. As a specific case for WLANs a fixed location for the relay can be chosen to guarantee a good connection to the AP. For this case the uplink's outage is diminished and does not limit the performance of the two-hop link.

IV. Coverage Investigations

In order to have a more realistic model we extend our scenario to a two-dimensional scenario. We consider a SISO WLAN system with one AP and one DF relay. The AP is located at the centre with (0,0) coordination. The relay is located on the virtual horizontal line which passes through the AP. The capacity C at each point of the area is calculated while the relay is getting far away from the AP. To calculate the capacity it is assumed that whenever the STA is closer to the relay than AP and the relay can connect to the AP, it communicates via relay while no direct link exists otherwise the STA connects to the AP directly. We define the angle of coverage α as the central angle of a circular sector which is fully covered by AP and relay when the radius of the circle is equal or smaller than the range d. As we show there is a tradeoff between number of relays and corresponding coverage angle. A smaller coverage angle results in a larger coverage range but requires more relays [16]. In order to fully cover a circular area with radius of d, $N_r = \lceil 360° / \alpha \rceil$ relays are required. Fig. 5 shows the coverage range of a certain scenario explained in the following with a coverage angle of 60°. This angle determines the size of the circle sector supported by one specific relay. Fig. 6 shows the coverage angle versus coverage range d when the relay has different distances from the AP. It is seen that a maximum range of 29 m at coverage angle of 60° is reached when the relay is located at 16m distance from the AP. If the relay gets closer or farther from the AP the range is decreased. In this case to fully cover a disk-shaped area, i.e. coverage angle of 360° with radius of 29 m, one AP and six relays are required in such a way that the relays are placed uniformly around the AP and all have a distance of 16m from AP. Fig. 5 shows this scenario. Repeating the simulation this time without any relay at least six APs are needed to fully cover, i.e. α=360°, the same

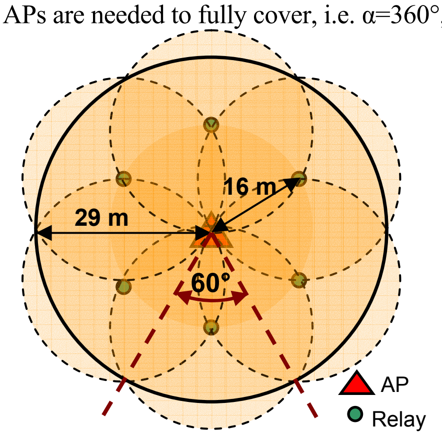

Fig. 5: Coverage range of the introduced scenario with 6 relays and 1 AP

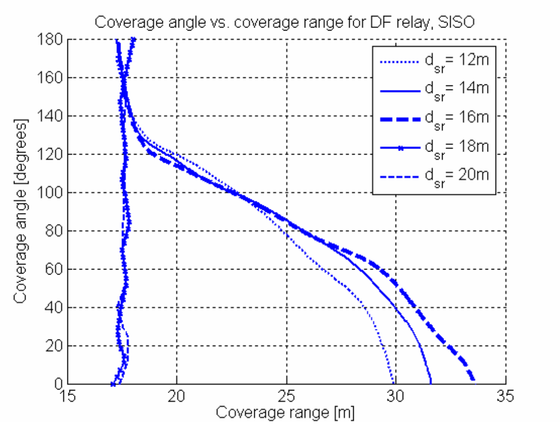

Fig. 6: Coverage angle for an AP and a DF relay

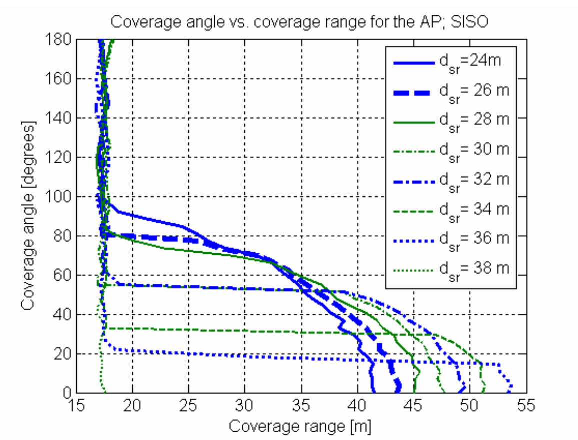

Fig. 7: Coverage angle for two neighbouring APs

area. One AP again is located at the centre and five other APs are located on a virtual circle around it with distance of d_{sr} =26 m from the AP which is positioned at the centre (Fig. 7). Obviously a much larger range can be achieved with less APs if a smaller coverage angle would be acceptable, e.g. to fully support an area with a coverage angle of 50° and length of 40 m two APs are enough. It is important to note that in indoor scenarios shape of the rooms, location and type of the walls and furniture can change the desired coverage area significantly. For example to fully cover a long narrow corridor it is not necessary to consider a coverage angle of 360°. Nevertheless our simulation is realistic for general scenarios and fair comparisons between adding more relays or APs can be performed based on that. In the considered scenario it is reasonable to employ relays as long as six relays are less expensive than five APs and/or flexibility in the system is favoured.

In general in moderate or low loaded systems by using relays instead of increasing the number of APs, flexibility is increased and infrastructure cost is reduced. At the same time the delay is increased and the capacity is reduced. The flexibility is further improved in scenarios with mobile STAs where instead of dedicated relays each STA can relay packets for a neighbouring user when this user is not in the communication range of an AP. This is realistic for data but for real-time traffic services for which we need to guarantee the minimum delay and resiliency of the system further considerations are required.

V. Conclusion

In this paper we considered a 5 GHz WLAN with multihop links. So far no relaying/forwarding functions are defined in the IEEE 802.11 MAC. We introduced three simple MAC schemes based on IEEE 802.11e for relaying and compared them based on data packet delay and capacity of the AP. We also discussed their compliance with the standard and provided solutions to solve incompatibility wherever applicable.

We studied the coverage enhancement for a WLAN having SISO and MIMO two-hop links with a DF relay. We benefit from frequency diversity gained by coding over different frequency subcarriers as it is defined in IEEE 802.11a as well as space diversity achieved by MIMO diversity techniques. The outage probabilities showed that coverage range can be considerably improved by relaying and space diversity techniques. Our coverage investigations showed that we need at least six APs to fully cover a disk-shaped area with radius of 29 m under NLoS conditions. The number of required AP can be reduced to one by deploying six relays. This not only reduces the cost but also improves the flexibility of the system.

References

[1] A. Ettefagh, M. Kuhn, B. M. G. Cheetham, and A. Wittneben, “Comparison of Distributed and Co-located Antenna Diversity Schemes for the Coverage Improvement of VoWLAN Systems,” PIMRC, Sept. 2005.

[2] IEEE Standard 802.11a, “High-speed physical layer in the 5 GHZ band,” 1999.

[3] P. Gupta and P.R. Kumar, “The capacity of wireless networks,” *IEEE Trans. Information Theory*, vol. 46, pp. 388-404, Mar. 2000.

[4] J.N. Lanemann, D.N.C. Tse and G.W. Wornell , “Cooperative diversity in wireless networks: efficient protocols and outage behaviour,” *IEEE Trans. Information Theory,* vol. 50, pp. 3062-3080, Dec. 2004.

[5] N. Esseling, B.H. Walke and R. Pabst, “Performance evaluation of a fixed relay concept for next generation wireless systems,” in Proc. PIMRC, vol. 2, pp 744-751, Sept. 2004.

[6] D. Zhao and T.D. Todd, “Real-time traffic support in relayed wireless access networks using IEEE 802.11,” *IEEE Wireless Communications Magazine*, vol. 11, pp. 32-39, Apr. 2004

[7] G. Li and H. Liu, “On the capacity of the broadband relay networks,” in Proc. Asilomar Conf. Signals, Systems and Computers vol. 2, pp. 1318-1322, Nov. 2004.

[8] I. Hammerstroem and A. Wittneben, “Joint power allocation for nonregenerative MIMO-OFDM relay links,” ICASSP, May 2006.

[9] A. Ettefagh, M. Kuhn and A. Wittneben, “Relaying to enhance the coverage range of a Voice over WLAN system,” *International ITG / IEEE Workshop on Smart Antennas*, Mar. 2006.

[10] F. Eshghi, A.K. Elhakeem and Y.R. Shayan, “Performance evaluation of multihop ad hoc WLANs,” *IEEE Communications Magazine*, vol. 43, pp. 107-115, Mar. 2005.

[11] ETSI standard, ETSI EN 300 700 “Digital Enhanced Cordless Telecommunications (DECT); Wireless Relay Station (WRS),” 2000.

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

[13] M. Kuhn, A. Ettefagh, M. Kuhn, A. Lunn, B. M. G. Cheetham, and M. Spegel, “Professional Quality Voice over WLAN,” in Proc VTC Fall, vol. 4, pp. 2601-2605, Sept. 2004.

[14] Recommendation ITU-R M.1225, Guidelines for evaluation of radio transmission techniques for IMT-2000, 1997.

[15] 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

[16] J. Zhao, I. Hammerstroem, M. Kuhn, A. Wittneben and M. Herdin, “Coverage analysis for cellular systems with multiple antennas using decode-and-forward relays,” submitted for publication to Globecome 2006.