Relaying to Enhance the Coverage Range of a Voice over WLAN System

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ABSTRACT

We consider a high-quality voice over Wireless Local Area Network (WLAN) system and we are interested in enhancing the coverage range of such a system by relaying while complying with Quality of Service (QoS) requirements. We show that in contrast to data networks we cannot gain from multihop communications with large number of hops so we consider the network under a two-hop traffic pattern. We distinguish two scenarios: single-antenna and multiple-antenna case. In the first scenario all nodes, i.e. Access Point (AP), Station (STA) and relay are equipped with a single antenna and *Amplify-and-Forward* (AF) and *Decode-and-Forward* (DF) relaying schemes are applied. In the second case we consider a two-hop Multiple Input Multiple Output (MIMO) system and diversity techniques are applied to enhance the range of the AP. In both scenarios only one relay assists the communication between the AP and the STA. Since WLANs are optimised for data we need to consider different aspects of QoS restrictions for a Voice over WLAN (VoWLAN) system. We point out such differences and provide appropriate solutions wherever applicable. The coverage range of the two-hop link for such a system is investigated and compared with that of cordless digital phones as well as single-hop link. We show the feasibility of relaying in a WLAN system by introducing three simple Medium Access Control (MAC) protocols for it. We focus on one of these schemes which is appropriate for VoWLAN. This new scheme is based on IEEE 802.11e standard and easy to implement while QoS features are guaranteed.

1. INTRODUCTION

Recently with fast growth of wireless communications WLANs are given a lot of attention. The use of VoWLAN is of great interest as WLAN technology is widespread. This allows us to merge wireless data networks with cordless phones, which reduces the infrastructure and maintenance costs. 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 covered area. Coverage is one of the main challenges in future communication systems. WLANs in general are optimised for data traffic while real-time traffic systems need to be taken care of differently. Most real-time traffic applications are even more problematic 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 for example a call can be dropped when the first outage is encountered. In addition to full coverage they require seamless handover which implies having enough overlaps between ranges of neighbouring APs. Furthermore we cannot benefit from temporal diversity techniques like Automatic Repeat Request (ARQ) due to delay restriction. Fig.1 depicts outage probability, as defined in section 3, versus distance between source and destination for a system based on Digital Enhanced Cordless Telecommunications (DECT) [1] and a WLAN based on IEEE 802.11a operating in the 5 GHz band [2] in Non Line-of-Sight (NLoS) conditions. For 802.11a we plotted the outage probability using channel models with different degrees of frequency diversity ranging from one (single-tap channel) to infinity i.e. Additive White Gaussian Noise (AWGN) channel. As it is seen in our interest region, i.e. outage probability of 1%, the coverage range of the VoWLAN is poor compared to that of DECT and not only diversity but also array gain is required to enhance this range considerably. We chose DECT as a reference since it is optimised for voice traffic and at the same time provides large covered range. One should note that the range highly depends on the environment but nevertheless the plot shows comparative range of these two systems.

In [3] the coverage enhancement for a single-hop link in a VoWLAN by space diversity techniques is studied using collocated and locally-distributed antennas. Cooperative relaying has become a major subject in the WLAN research literatures [4],[5]. Applying relaying schemes one can enhance the outage probability performance [5] and as a result increase the coverage range of a system. In [6] some advantages and applications of relaying as well as performance evaluation of applying fixed relays 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. In contrast to data networks we cannot benefit from multihop scenarios with a large number

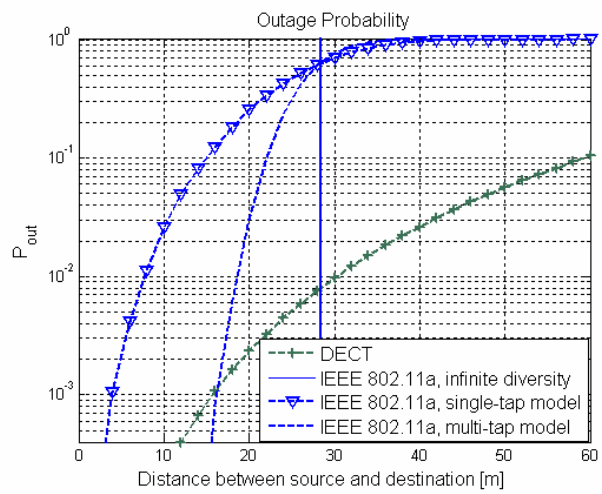

Fig. 1. Outage probability for a system based on IEEE 802.11a and DECT.

of hops due to the extra delay each hop adds to the system. In this paper we focus on relaying in a VoWLAN with frequency-selective fading. Cooperative relaying for real-time traffic systems as well as in frequency-selective channels are far less studied so far. Authors of [7] proposed a relayed wireless access network based on legacy IEEE 802.11 which carries real-time packets. Their system supports multi-frequency relaying and could handle both constant and variable rate real-time traffic efficiently. They focused on packet transmission delay and packet rate rather than the range itself. In [8] authors derived capacities of Orthogonal Frequency Division Multiplexing (OFDM) and OFDMA systems having multiple source and relay nodes and a single destination node. In [9] a jointly optimised power allocation over sub-channels in space and frequency domain at source and relay to maximize the instantaneous capacity is presented. The authors consider MIMO systems with nonregenerative, i.e. AF relaying. Here we consider uniform power over all subcarriers as in WLAN standards. The results can be further improved by allocating optimised power over sub-channels.

The main focus of this paper is to evaluate the coverage range of a high quality VoWLAN system and enhance this range by relaying and space diversity techniques. To show the feasibility of relaying in a WLAN system we introduce three different MAC schemes. We also investigate delay performance for multihop case and compare AF and DF relaying especially from QoS aspects. Also tradeoffs between adding relays into the system instead of simply increasing the number of APs are discussed. Then the system model and simulation results evaluating the performance of AF and DF relays in both SISO and MIMO wireless systems are studied.

2. SIMPLE MAC SCHEMES FOR RELAYING

In this section we introduce three different MAC schemes for relaying to show the feasibility of relaying. 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 results do not seem promising for real-time applications.

In [7] a MAC scheme is introduced for relayed wireless access networks based on IEEE 802.11 in which relays support dual channel, i.e. one HOME channel to communicate with the AP and one RELAY channel to forward/download traffic to/from the AP. European Telecommunications Standards Institute (ETSI) also defined a MAC scheme for DECT Wireless Relay Station (WRS) in [11].

Our schemes are based on IEEE 802.11e [12]. In each beacon interval there is a Contention Free Period (CFP) followed by a Contention Period (CP). In CFP Hybrid Coordinator (HC) allocates time slots to relays/STAs by a polling mechanism which is defined in Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA) while in CP relays/STAs content to get the channel according to

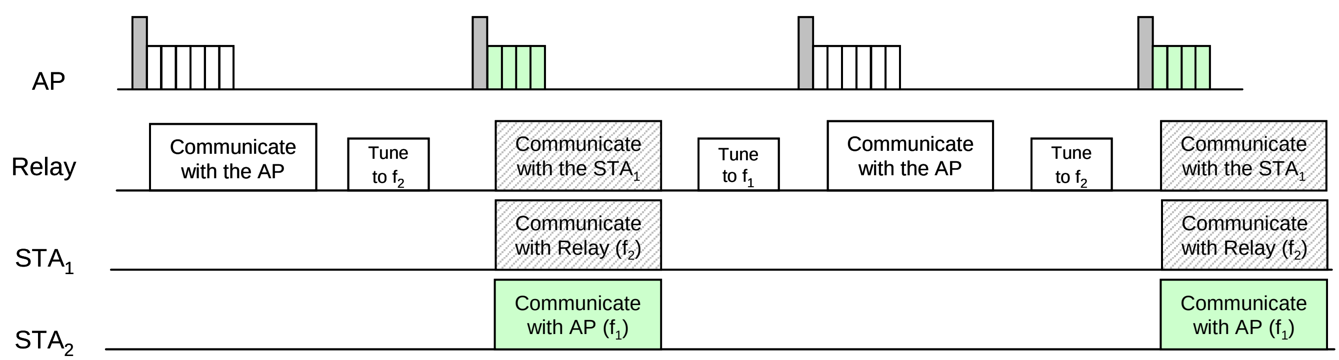

Fig. 2. The third proposed MAC scheme for relaying

Enhanced Distributed Channel Access (EDCA). In the first scheme which is the simplest case relay communicates with the AP during the CFP and it communicates with the STAs during CP. A two-hop link based on this scheme adds no considerable delay to the system as long as relay can access to the channel during the CP. This scheme is standard compliant but it is not desirable for real-time traffics since there is always certain probability that 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 but it is not diminished completely.

In the second scheme during the CFP two time slots are allocated to each relay per each STA connected via the relay by the HC. In the first time slot relay communicates with the AP and in the second one it communicates with the STA. In another words in the second time slot 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 since in the actual version of standard the AP needs to communicate with both nodes in order to setup the direct link between them but in our scenario it is assumed that STA is not in the range of the AP and that's why it is connected via a relay. This scheme reduces the capacity of the AP but can guarantee the delay requirement in the system. In the first two schemes AP and relays operate at the same frequency.

Now 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 VoWLAN system. To guarantee the QoS voice packets are delivered during CFPs while all signalling data are transferred during CPs. We assume a basic beacon period of 10.24 ms i.e. 10 times of a Time Unit in IEEE 802.11. However for each associated STA voice packets are only transmitted every second beacon. This results in a frame period of 20.48 ms and allows STAs to use rest of the frame period for frequency tuning, communicating with relays and when necessary for handover. Assuming data rate of 6 Mbit/s and a voice payload of 164 bytes with MAC frame size of 192 bytes results in a frame duration of 592µs for duplex channel including Short Interframe Space (SIFS). Eq.1 is applied to calculate the frame duration for a single channel before adding SIFS [14].

$$\text{Frame duration}\,[\mu s] = 20 + 4 \times \text{ceil}\left(\left(22 + 8 \times \text{MAC\_frame\_size [bytes]}\right) / \left(4 \times \text{data\_rate [Mbit/s]}\right)\right) \quad (1)$$

Note that frame period and other parameters are calculated for voice packets transmitted over 802.11a WLAN. This formula considered OFDM symbol with length of 4µs, 16µs preamble, 4µs signal field, 6 tail bits and 16 service bits in the physical layer (PHY) payload. Whenever the last OFDM symbol is not filled it is padded with zeros. More details about these parameters can be found in [2] and [14].

In order to support 20 voice users half the connections are assigned to the even and half to the odd beacons. As a result a CFP of 5.92 ms is required in each beacon interval. We assume that similar to a STA a relay is also served by the AP in either even or odd beacon. For example if in the first beacon interval relay communicates with the AP at frequency f_1 afterwards it switches to another frequency e.g. 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 beacon arrival time. As long as STAs which are communicating with the AP via a relay, served by the relay all in odd or even beacon intervals, maximum number of connections supported by the AP remains the same as single-hop case, i.e. 20. In this case each relay can support up to 10 STAs.

In this scheme each relay operates at different frequency from adjacent AP's 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 AP's coverage area so each frequency can be reused at minimum distance of three-hops to avoid the interference. Fig. 2 shows the introduced MAC scheme. We assumed that relay has the same functionality as the AP though it is not connected to the backbone. Voice transmissions among relay and STAs are also performed during CFPs in which time slots are assigned to certain STA by the relay. In general in moderate or low loaded systems by using relays instead of increasing number of APs flexibility will be increased and infrastructure cost will be reduced. At the same time delay will be increased and the capacity will be reduced. Flexibility can be further improved by replacing fixed relays with mobile STAs in such a way that each STA can relay the packets for a neighbour user when this user is not in the range of an AP. Since for high-quality voice we need to guarantee the minimum delay and resiliency of the system in this paper we only consider fixed relays, i.e. dedicated relays which are portable but do not move. From now on we consider the third scheme and evaluate the delay performance of this MAC scenario. One should note that the proposed scheme is only one of the possible ways. As it was mentioned relaying in the CP is also possible but it is not as reliable as the last scheme introduced here.

2.1. Delay Performance of DF and AF Relaying

To estimate the delay in a multihop system we assume the third MAC scheme as explained in the previous section and a PHY layer as defined in IEEE 802.11a, i.e. OFDM in which Forward Error Correction (FEC) coding is performed over different subcarriers. Each OFDM symbol lasts 4µs and contains 64 subcarriers from those 52 are non-zero. In this paper we consider DF and AF relaying. In the former case relay decodes the received data from AP and after encoding sends it to the destination. In AF case, relay amplifies what is received from the AP and forwards it to the destination without having knowledge about the contents of the data. Here only half-duplex relays are considered so receiving and transmitting simultaneously is not possible. We assume that there exist one AP as source, one STA as destination and in between M relays which form a multihop communication link with M+1 hops.

First DF case is considered. In this scheme relay 1 can start decoding the data after receiving the first OFDM symbol from the AP but due to the MAC scheme it cannot start transmitting it before waiting for the second beacon interval i.e. T ms. In between it can switch to another frequency. After waiting about T ms relay 1 can access to the channel and retransmits the voice packets to the relay 2. Again relay 2 cannot start transmitting immediately rather it has to wait for upcoming beacon interval. The same will happen to all relays so a voice packet will take about MT ms more until it is received by the destination. Here we neglected the propagation time which is a reasonable assumption for indoor wireless environments.

Now we consider AF case; generally AF relaying may perform faster than DF since it does not need to decode the packets but here it is again MAC scheme that determines the delay. We assume that each AF relay is able to decode at least the beacon and is synchronized with the AP. In this condition delay performance will be the same as that of DF. Due to the delay restrictions from now on we consider only two-hop links.

3. SYSTEM MODEL AND SIMULATION RESULTS

We consider a WLAN system with one AP, one STA and in the general case N half-duplex relays which are uniformly distributed on a disk-shaped area. We consider different locations for the STA with different distances from the AP and at each place select a relay among all N relays according to its location. The system topology is plotted in Fig. 3. The link from AP to relay is defined as uplink and from relay to STA as downlink. We consider fixed relays in order to fulfil QoS requirements.

A two-hop communication link in which the AP transmits the packets to the relay in the first time slot and relay retransmits them to the STA during the second time interval is considered. We assume perfect Channel State Information (CSI) at receivers and no CSI at transmitters. We also assume there is no direct link between AP and STA which is a reasonable assumption for coverage investigations. A frequency-selective fading channel model is used according to ETSI channel model B recommended for HiperLAN/2 [15]. In order to model a 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. Both AF and DF relaying are studied.

The outage probability is calculated based on minimum

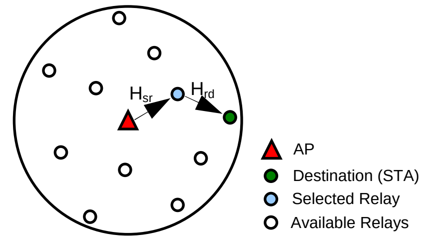

Fig. 3. System Topology

Signal to Noise Ratio (SNR), i.e. SNR_{thr} required to achieve a certain Bit Error Rate (BER). As we focus on voice we choose BER of 1e-3 as the maximum acceptable BER in our system [16] and from that by taking into account the Forward Error Correction (FEC) coding we calculate threshold SNR and threshold rate. We assume that an outage occurs when

$$C < R_{thr} \text{ with } \quad C = \sum_{k=1}^{N} B_k \cdot \log_2(1 + SNR_k) \qquad (2)$$

in which

$$SNR_k = \frac{P_T}{N_0 B_k} \left| H_k \right|^2 \qquad (3)$$

and C is the capacity per hop, P_T is the transmit power, N_0 noise power density, B_k bandwidth of each subcarrier, H_k k-th sub-channel coefficient and N number of subcarriers which in our case is equal to 52. Capacity equations for two-hop links with AF and DF relay can be found in [5]. Fig. 4 shows the simulation result obtained for the Single Input Single Output (SISO) case when the user selects the relay which has the shortest poorest link, i.e. the relay which has the $\min_j \left\{ \max \left\{ d_{sr_j}, d_{rd_j} \right\} \right\}$, j=1:N and the optimal case when the relay is exactly in the middle the imaginary line between AP and STA. d_{sr} is distance between AP and jth relay and d_{rd} distance between jth relay and the STA. Direct link is plotted just as a reference. Same outage probability on both uplink and downlink has been

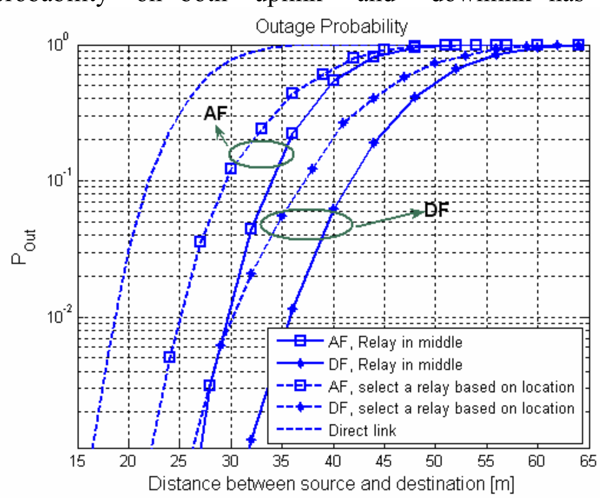

Fig. 4. Outage probability for AF and DF relaying in SISO case

considered. The result shows considerable range enhancement for DF and AF relaying compared to the case where no relay is used. It is also seen that DF relaying outperforms AF regarding outage probability. The reason is noise propagation in AF case. On the other hand AF relaying may lead to lower complexity transceivers. It is important to note that we assume in DF case relay can decode the received data from the AP perfectly whenever $C > R_{thr}$.

Now we increase the number of antennas in each node to two. Primarily we perform antenna selection at AP, relay and STA as the simplest space diversity scheme which adds no delay to the system. Then we apply antenna selection at AP and 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 a standard compliant system we do not consider spatial multiplexing techniques. Simulation results are plotted in Fig. 5 for DF and in Fig. 6 for AF relaying. Note that in both figures relay is located in the middle of the imaginary line that links AP and the STA i.e. the optimal case when relay is selected based on its physical location. The results show that even by applying simple antenna selection one can increase the range several meters further in compare to SISO scenario. Direct link with single antenna at each node is also depicted as reference. The range has been further improved performing MRC at the receiver. Again due to noise propagation AF does not perform as well as DF relaying. Hitherto we consider both AF and DF relaying but in WLANs it is reasonable to use DF relay due to the better performance and easier deployment.

The range can be further enhanced by finding a better place for relay or better selection criteria. So far same probability of outage on both uplink and downlink has been considered. As a specific case for WLANs one can assume a fixed location for the relay where it always has good

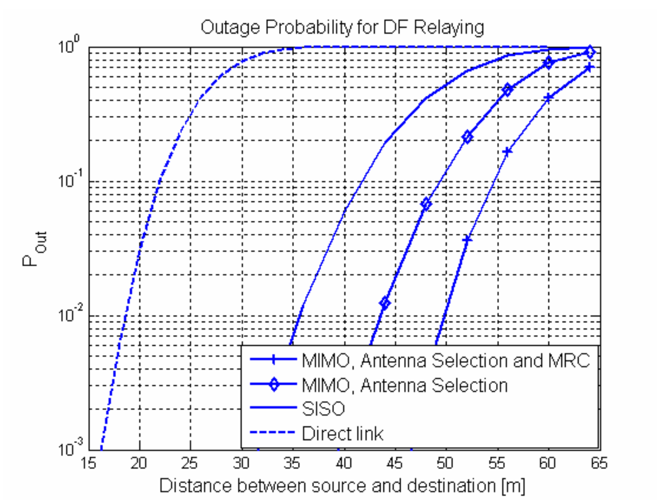

Fig. 5 Outage Probability for DF in MIMO case with two antennas per each node

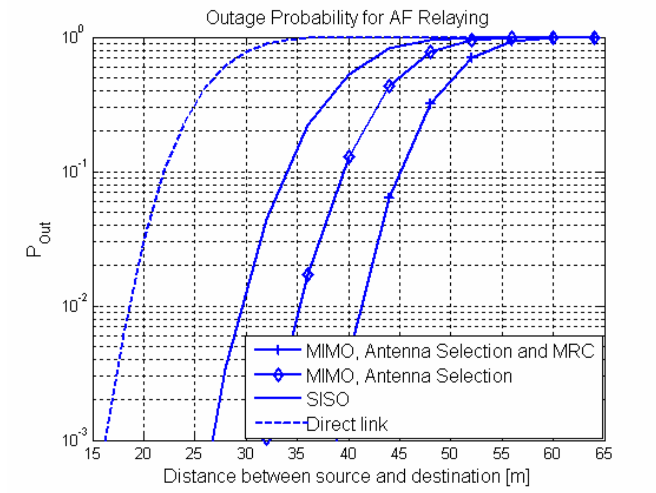

Fig. 6 Outage Probability for AF in MIMO case with two antennas per each node

connection to the AP. For this case the uplink's outage is diminished and does not limit the performance of two-hop communication link.

In this paper a relay is selected based on its physical location but selection can be performed based on both instantaneous CSI and 2nd order CSI. This can enhance the range more, especially 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. As mentioned before in this paper we only consider dedicated relays to avoid large delays.

4. CONCLUSION

In this paper we studied the coverage enhancement for a high-quality VoWLAN having SISO and MIMO two-hop communication links. We also introduced three simple MAC schemes for relaying from those one which is proper for voice transmission was explained in more detail. This scheme is standard compliant except for transmitting over every second beacon interval and easy to implement. The proposed MAC scheme is based on IEEE 802.11e and transmitting over every other synchronized beacon intervals in such a way that delay requirement is fulfilled. Although multihop communications with more than two hops can increase the range further, due to high quality requirements we could not gain from it. In this paper only two-hop links were considered. 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 results showed that coverage range can be considerably improved by relaying. Adding one more antenna to each node and applying space diversity techniques enhanced this range additionally. It was also shown that the DF outperforms AF in our scenario. In general it is reasonable to use a DF rather than AF relay in WLANs as long as only one relay assists the communication between STA and AP, and the relay is able to decode the signal perfectly. We can gain more from AF relays in multiple-relay scenarios where it is possible to coherently combine signals received from different AF relays at the STAs. Studies on multiple-relay scenarios are underway.

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