Comparison of Distributed and Co-located Antenna Diversity Schemes for the Coverage Improvement of VoWLAN Systems

Azadeh Ettefagh[1], Marc Kuhn[1], Barry Cheetham[2], Armin Wittneben[1]
[1]Swiss Federal Institute of Technology (ETH) Zurich, Communication Technology Laboratory, CH-8092 Zurich, Switzerland; Email: {ettefagh, kuhn, wittneben}@nari.ee.ethz.ch
[2]University of Manchester, Dept. of Computer Science, Oxford Rd, Manchester, UK

***Abstract*—This paper concerns the coverage range of a high quality voice over wireless local area network (VoWLAN) system based on the IEEE 802.11a standard. Techniques for enhancing the coverage range of each access point (AP) using co-located and distributed antenna diversity schemes are proposed and it is shown that the number of required APs and therefore the infrastructure cost may thus be reduced. Comparisons are made between the coverage range of the 802.11a and that of DECT (Digital Enhanced Cordless Telecommunication), and simulations and channel measurements devised for predicting the effect of diversity techniques on the range of APs are described. The results of two different measurement campaigns are presented, one with co-located antennas and the other with locally distributed antennas. The coverage enhancement gained within these scenarios by employing diversity techniques is thus deduced.**

I. INTRODUCTION

NOWADAYS the use of VoWLAN is of great interest because WLAN technology is widespread and VoWLAN allows to merge two wireless networks, the cordless telephony network and the WLAN. But the coverage area served by a WLAN AP is in general smaller than that of a cellular or DECT base-station (BS). To provide coverage over a given area, for example in an office building, WLANs need more APs and this requirement can increase the infrastructure costs considerably. This paper is concerned with the provision of high quality VoWLAN systems based on IEEE 802.11a [1] with the adoption of extension 802.11e to guarantee the required quality of service (QoS) [2]. We consider that voice packets will be transferred in contention-free periods using HCF Control Channel Access (HCCA) and there will be no interference between different Stations (STAs). WLAN systems are optimised for data and the requirements for high quality VoWLAN impose different criteria which must be met by specially adapted techniques (e.g. consider seamless handover of an ongoing call between two APs). Usually a delay is not critical for data traffic, but for high quality telephony only small delays are acceptable. Whilst, for data traffic, dead spots within the coverage area and the requirement for damaged data packets to be retransmitted can be acceptable, for voice traffic, full coverage is crucial since a call can be dropped when the first outage is encountered. Due to the additional delay that is introduced Automatic Repeat Request (ARQ) methods are problematic for voice traffic and we do not consider them in this paper.

Theoretically there are different possibilities for optimising the coverage range of an AP in a WLAN system. Diversity techniques increase not only the diversity degree (protection against fading) but also the coverage range. Without ARQ methods we do not benefit from time diversity gained by ARQ thus we have to introduce other diversity techniques; in this paper we concentrate on antenna diversity schemes because they are compliant to the considered WLAN standards and are proper for the VoWLAN systems with low delay requirements. Coverage enhancement can also be achieved by relaying and by increasing the transmit power. Regulations and standards limit the scope for increasing the transmit power. However, multi-user diversity gain achieved through scheduling techniques can improve the spectral efficiency and QoS and consequently enhance the coverage range from the user's point of view [3]. The following sections explore how the coverage range may be expanded by applying diversity techniques having different antenna distributions.

Using measurements made in a particular environment, we will compare 802.11a's coverage range with the range of DECT. Diversity techniques for increasing the coverage will be suggested and examined through the use of a channel measurement campaign. Both line-of-sight (LoS) and non-line-of-sight (NLoS) within different scenarios: i.e. co-located and locally distributed antennas, will be considered.

II. SYSTEMS OVERVIEW

We consider DECT as the specification of a professional high quality wireless telephone system and its coverage range as a basis for comparison with VoWLAN systems based on IEEE 802.11a. DECT can provide high quality interactive voice communication over a wide area with BSs accessible at distances of up to 100m in an indoor environment [4].

The WLAN equipment for IEEE 802.11a operates in frequency bands close to 5.2 GHz while the DECT equipment uses frequencies in the range 1.88 to 1.9 GHz. For the same path loss exponent this results in power loss that is several times larger for the WLAN equipment than for DECT over the same distance. Consequently a smaller coverage area is obtained for each AP and so higher infrastructure costs may be incurred. DECT uses a 'single carrier' Gaussian minimum (frequency) shift keying (GMSK) modulation scheme [5], whereas the IEEE802.11a WLAN is based on a 'multi-carrier' Orthogonal Frequency Division Multiplexing (OFDM) scheme with effectively 64 sub-carriers, 48 of which carry data [1]. The modulation on each OFDM sub-carrier depends on the required bit-rate and may be selected from a number of possibilities (e.g. BPSK which is used for the lowest bit-rates of 6 and 9 Mbit/s [1]). The many advantages of OFDM include its robustness to the effects of frequency selective fading arising from multi-path propagation that is unavoidable in most settings of WLANs [6]. In contrast to the DECT the IEEE802.11a standard also includes 'forward error correction' (FEC) coding to give packets some degree of protection against bit-errors at the radio receiver.

III. COVERAGE MEASUREMENTS

In order to compare the indoor coverage range of a WLAN based on 802.11a with that of a DECT system a measurement campaign has been carried out in an old office building. The building is a typical office environment with long corridors, in our case, 38m long, and middle-sized rooms. Two devices were used; a standalone AP and a CardBus WLAN card in a laptop computer. Both devices are off-the-shelf but a specialist test program was used to perform the measurements. Using the test software we were able to send packets at each of the data rates. A plan of the arena is shown in Fig. 1. We began the measurements in room 110 (the room in the left side of the plan) where the AP was located and continued towards the other side of the corridor until we received no signal; see [7] for more details. The measurements of Frame Error Rate (FER) show that a threshold was reached, after which the FER quickly increased, so resulting in a rapid transition from working to not working. This effect is largely due to the FEC. Based on the discussion of packet loss concealment in [7] we defined successful coverage to exist when the FER was 5% or less (more than 5% FER seems definitively too high for high QoS restrictions). Fig. 1 shows the distribution of successful coverage area as estimated by comparing practical measurements of FER with the 5% threshold. Fig. 2 shows Received Signal Strength Indication (RSSI) measurements for the same scenario. The RSSI measurements are values in the range 0 to 60 which have no units and represent the received field strength relative to other RSSI measurements by the same test equipment.

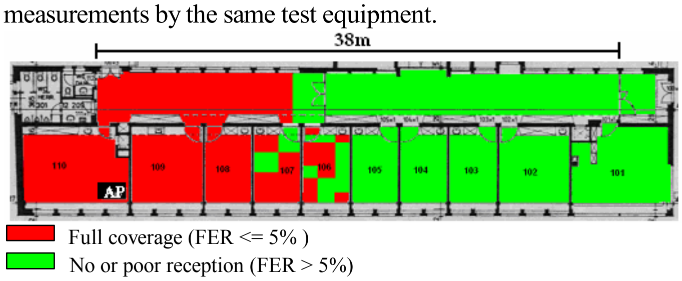

Fig. 1. 802.11a coverage range

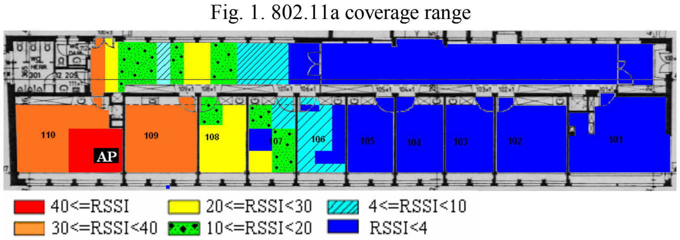

Fig. 2. Map of RSSI

These measurements were obtained for the lowest available bit-rate, i.e. 6 Mb/s. This will give the widest coverage. As expected, full coverage has been obtained in the area close to the AP, but propagation down the corridor shows some unusual fluctuations. This can be mainly due to the reflections from the copper layer on the corridor's roof. The same measurement campaign has been performed using DECT handsets, locating the DECT BS in the same place as the AP in the previous measurement. This time we had full coverage for the entire floor. One should note that AP in WLAN systems is equivalent to the BS in DECT.

As a second set-up we located the WLAN AP at the beginning of corridor and IEEE 802.11a LoS measurements have been carried out. In this case we had full coverage in the whole corridor.

IV. SIMULATION RESULTS

In order to have some idea of the performance bounds of our measurement system we carried out a theoretical analysis to assess the performance of traditional DECT, and an IEEE 802.11a WLAN. To devise a representative simulation, a channel model was applied in a scenario similar to that described in section III; i.e. a corridor of length about 38m. Rayleigh fading was considered with amplitude scaled according to path loss in equation 1.

$$PL(d)[dB] = \overline{PL}(d_0) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) \quad (1)$$

In equation (1), PL(d) denotes path loss at distance d between transmitter and receiver, d_0 reference distance which is equal to 1m, and γ path loss exponent which is 3 for NLoS and 2 for LoS. In table 1 the main parameters used in the simulations are presented. Values of transmit power are given according to the regulations for Switzerland.

Table 1 main simulation parameters

	DECT	IEEE 802.11a
Carrier frequency	1.9 GHz	5.2 GHz
Transmit power	250 mW	60 mW
Channel bandwidth	1.728 MHz	20 MHz
Outage rate	1.152 Mbit/s	3 Mbit/s

In the previous measurements, we obtained full coverage for LoS with distances up to 40m. We focus on the NLoS scenario in this section. For 802.11a we use a NLoS indoor channel model from [8] with RMS delay spread of 100 ns. This model has been recommended for HiperLAN/2 but due to the similarity of the PHY layers in HiperLAN2 and IEEE 802.11a we have employed this model. The model consists of an 18-tap delay line. The general tap-delay line model assumed for a time-invariant channel is given by equation 2 where $h(\tau)$ is the channel impulse response and α_n , φ_n and τ_n for $n = 0$ to $N - 1$ are respectively the amplitudes, Doppler phase shifts and delays of the assumed N resolvable multi-path components. For DECT a single-tap model has been considered since in contrast to 802.11a DECT is not able to achieve a frequency diversity gain. For a fair comparison between DECT with a single-tap model and 802.11a with an 18-tap channel model, the average energy of the 18 taps for 802.11a is kept the same as that of the one tap for DECT.

$$h(\tau) = \sum_{n=0}^{N-1} \alpha_n e^{-j\varphi_n} \delta(\tau - \tau_n) \quad (2)$$

According to [9] the coverage ψ of a cell can be defined as follows:

$$\Psi = 1 - P_{out}^{cell} \quad (3)$$

where P_{out}^{cell} is the outage probability calculated as the proportion of the area within the cell that does not meet its minimum power requirement P_{min} .Using this definition we employ the outage probability as a parameter which indicates the coverage. In Fig. 3 the outage probability for both systems are plotted. This outage probability is defined according to equation 4 with R_{out} as the outage rate and C as the capacity of the system. Since capacity changes logarithmically with the SNR (Signal to Noise Ratio) this definition matches to the definition in equation 3.

$$P_{out} = \Pr(C < R_{out}) \quad (4)$$

For DECT, the data rate and consequently R_{out} is 1.152 Mbit/s [5] and for 802.11a at its lowest bit-rate i.e. 6 Mbit/s with the coding rate of ½, the outage rate is about 3 Mbit/s.

Considering the outage probability of 5% employed during measurements, the 802.11a signal can be received at a maximum distance of 17m while around 36m can be achieved for DECT. It is important to note that although 802.11a's model benefits from frequency diversity, which DECT does not, due to the smaller outage rate and lower frequency range, DECT has a lower outage probability for $P_{out} < 4\times10^{-3}$ which is the interested region. In Fig. 3 it is seen that 802.11a outage probability has a deeper slope. This is due to the frequency diversity achieved from FEC coding across OFDM sub-carriers. But frequency diversity alone does not improve the coverage range of WLAN sufficiently and we need to apply other diversity techniques to increase the range. It is clear that in addition to diversity gain we also need array gain in order to get closer to the range of DECT. We have considered a MISO (Multiple Input Single Output) and SIMO (Single Input Multiple Output) instead of a SISO (Single Input Single Output) system and applied two effective schemes; antenna selection as a low complexity diversity method and beamforming as a technique which leads to the upper bounds of diversity gain [10].

In selection diversity the stream with highest SINR (Signal to Interference and Noise Ratio) in the whole frequency band is selected and in beamforming we adapt the weights for each transmit (TX beamforming) or receive antenna (RX beamforming) in such a way that the SNR at receiver is maximized. We assume perfect channel knowledge in the receiver in both the SIMO and the MISO case. In addition, for the MISO case we need to know the channel in the transmitter too, i.e. feedback from the receiver to the transmitter is required. This feedback is usually available in WLAN systems. The MISO structure for the downlink (AP to the mobile STA) and SIMO for the uplink (STA to AP) can be easily implemented since only the number of antennas in the AP is increased. Results are shown in Fig. 4 where plots using these schemes are compared with the SISO case. In this paper we consider uncorrelated antennas in the simulation and therefore the outage curves are lower bounds of outage in practice.

Applying RX beamforming we achieve not only diversity gain but also array gain [11]. These results show the possibility of a maximum of 16m range improvement with 4 antennas RX beamforming and 4m with 4 antennas TX beamforming for achieving 5% outage. By comparing these results with the outage probability of DECT (Fig. 3) we see that with RX beamforming

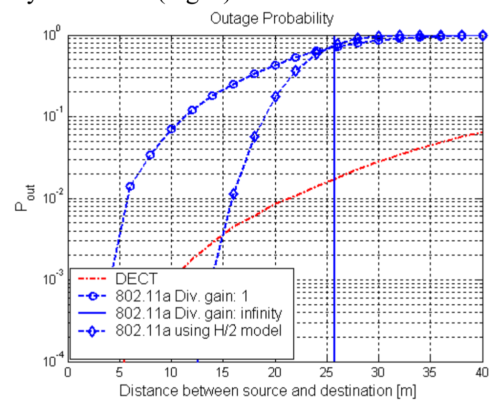

Fig. 3. Simulated outage probability

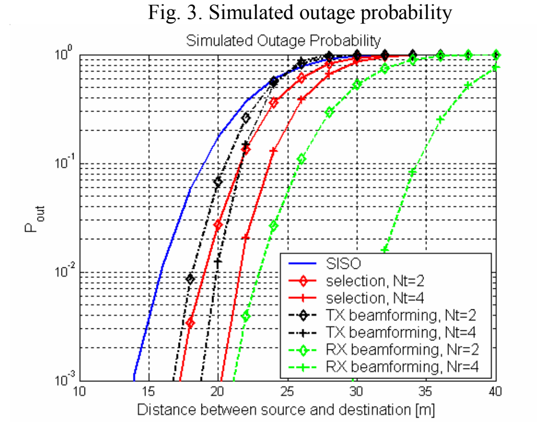

Fig.4. NLoS outage probability using diversity techniques

the achievable range of 802.11a is very close to the DECT's range for outage of 5%. One should note that with respect to our assumption of only one antenna in the STA we can benefit from RX beamforming only in uplink and due to the reciprocity of a voice system we are limited to downlink; i.e. maximum gain we can achieve is the gain from TX diversity.

All the plots which have been shown in this section are for the NLoS case. Running the simulation for LoS with the path loss exponent of 2 we had no outage for the distance range of 40m. This matches our coverage measurement in section III.

V. CHANNEL MEASUREMENTS WITH CO-LOCATED ANTENNAS

To examine the simulation results, adjust model parameters and compare the different scenarios channel measurements in the same location have been carried out. Five independent wireless nodes (RACooN lab) [12] which can transmit and receive signals in the operation band of 5.1GHz to 5.9GHz and are synchronized via a Rubidium clock are used. A SIMO system with four co-located antennas as receivers and one mobile node as the transmitter has been set up. In order to have less correlation between antennas and benefit from space diversity, receive antennas are located with a distance of a wavelength, about 5.7cm, apart from each other.

During these measurements the channel transfer functions were identified directly and we calculate the channel impulse response (IR) and capacity from the transfer function.

Again we concentrate on NLoS. Fig. 5 shows an example of one of the transfer functions and IRs of the channels between each of the receive antennas and the transmitter. Fig. 6 depicts locations where measurements have been performed along the corridor and it also shows the coverage enhancement obtained by applying RX beamforming. The range was increased from 12.4m to 21.5m. Note that we defined the border of outage from the first location with the capacity below the outage rate in spite of the fact that some locations with further distance might be not in outage. This is true since we emphasize the voice service where a call could drop at the first outage event. The capacity increase due to the RX beamforming compared to the SISO case has been shown as a number of bars above each location.

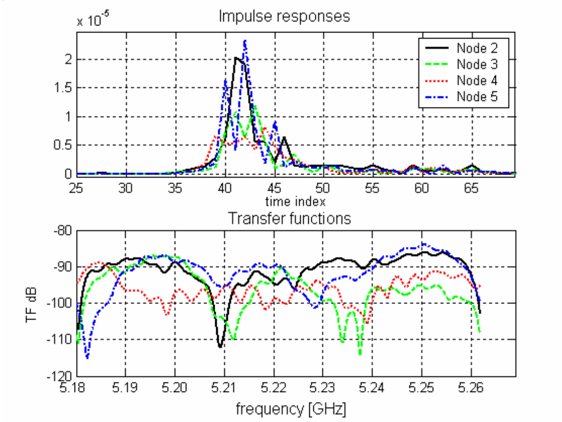

Fig. 5. IR and Transfer function in NLoS case and d=12.5m

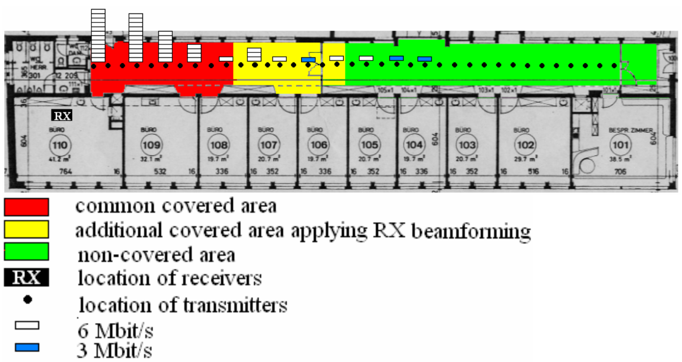

Fig. 6. Coverage performance applying the RX beamforming in a 1x4 system with co-located antennas

Each white bar represents 6 Mbit/s capacity enhancement and the blue bar 3 Mbit/s. It is obvious that in order to achieve the coverage performance we should be able to apply these techniques in both directions: uplink and downlink. This results in a MIMO (Multiple Input Multiple Output) system. Many of GSM and UMTS mobile phones have already been equipped with two antennas in the handsets and considering carrier frequency at 5.2 GHz antenna size and distance of half a wavelength are small, about 2.9cm; and a MIMO system with two antennas in the handset and 4 or more antennas in the AP can be easily implemented. Motivated by these considerations we decided for the next measurements to assume two antennas in the STA which leads to a MIMO system. In the following section we are going to investigate the effect of the antenna spacing on the coverage; therefore we introduce locally distributed antennas.

VI. CHANNEL MEASUREMENTS WITH LOCALLY DISTRIBUTED ANTENNAS

In these measurements a 2x4 MIMO system with locally distributed antennas has been considered. TX nodes were the mobile nodes and the distance between the TX antennas was about 19λ (110cm) where λ is the wavelength. Each of the RX antennas was located in the edge of a rectangular trolley. Distance between RX antennas was in one direction 10λ (57cm) and in the other direction about 19λ (110cm). Again channel measurements have been performed using RACooN nodes and in the same location as previous measurements.

To compare the new results to the results of the previous section we first consider a SIMO system (as we did in the case of co-located antennas) before we analyse the performance of the MIMO system. SIMO measurements have been performed along the corridor and RX beamforming has been applied. The range was increased from 12.4m to 23.8m. Again we defined the border of outage from the first location with the capacity below the outage rate. Comparing this result with co-located case the improvement of more than 2m is achieved by distributing the antennas. As we expected, the correlation between channels was reduced and we benefit more from space diversity and perform better against shadowing. In WLANs, TX/RX antennas are usually separated with a distance of at least λ/2 and it's favourable to keep this distance as large as feasible. The results for the 2x4 MIMO case with RX beamforming and selection between two transmit antennas have been shown in Fig. 7. This time the coverage range was increased from 12.4m to 31.8m which shows 8m improvement compared to the SIMO case and almost 19m enhancement compared to the SISO case.

In the simulations, so far a path loss exponent of 3 has been used for the NLoS model. By comparing the measurements and simulation results we can modify our channel model used in the simulation. Applying minimum mean squared error criterion to the measured and simulated SNR versus distance we obtain the path loss exponent of 3.3. Using the new parameter we achieve a model that conforms better to the real channel in our scenario compared to our previous model. Results from simulations with the new set of parameters are shown in Fig. 8 and Fig.9.

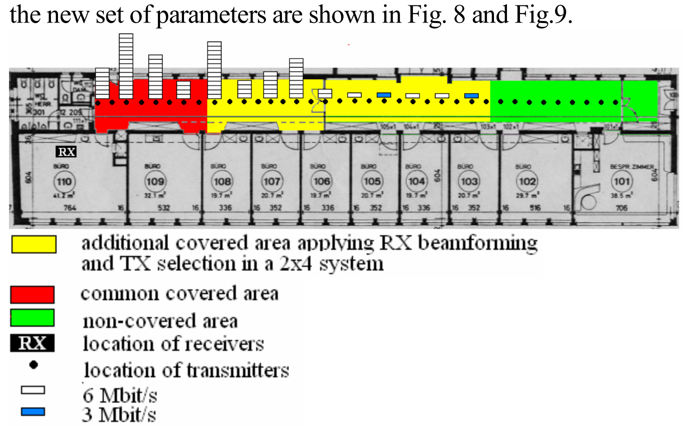

Fig. 7. Coverage performance applying diversity techniques in a 2x4 system with locally distributed antennas

The capacity C of the MIMO system [10] is calculated as follows:

$$C = \log_2 \det(\mathbf{I}_{M_R} + \frac{E_s}{M_T N_o} \mathbf{H}\mathbf{H}^H) \qquad (5)$$

In this equation M_T and M_R denote the number of antennas in the transmitter and receiver respectively, **H** is the channel matrix, E_s is the power of the transmit signal, N_0 is noise power and $\mathbf{I}_{MR}$ is the identity matrix with the dimension of M_R. Results for the 1x4 SIMO and 4x1 MISO are shown in Fig.8 and for the 2x4, 4x2 and 2x2 MIMO systems in Fig. 9. Results for the antenna selection in the 4x2 MIMO system is also depicted in Fig. 9. This selection is based on choosing the channel with the highest energy among all available channels and requires having channel knowledge both in the transmitter and the receiver. These results show that by applying diversity techniques we can increase the coverage range of each AP and consequently the number of required APs reduces.

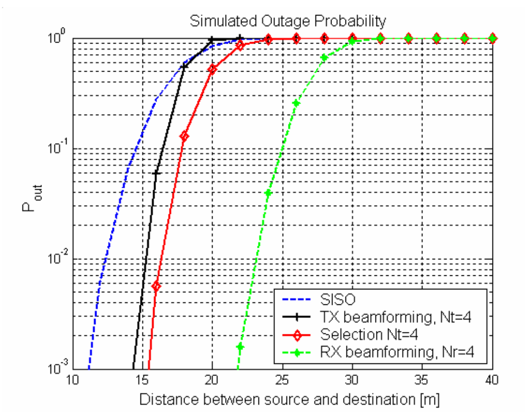

Fig. 8. NLoS outage probability with gamma of 3.3

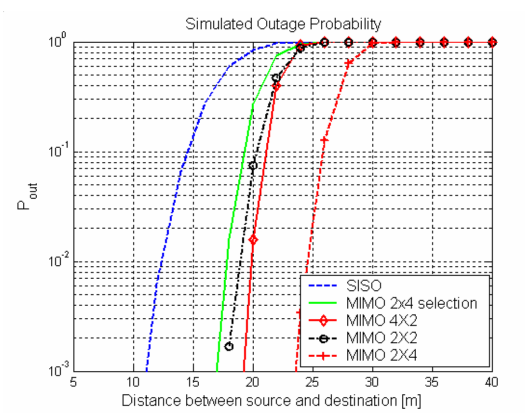

Fig. 9. NLoS outage probability for MIMO case with gamma of 3.3

VII. CONCLUSION

This paper has investigated the coverage range of a VoWLAN system based on IEEE 802.11a and techniques for the enhancement of this range. Restricting ourselves to VoWLAN we had to consider only the techniques that do not increase the delay in our system. We defined the border of outage from the first location with the capacity below the outage rate, in spite of the fact that some locations with further distance might be not in outage. This is true since the emphasis is on the voice service. Coverage measurements were made, and theoretical analysis carried out to investigate the performance bounds of the system. To verify our simulation results and adjust the model parameters, channel measurements have been performed. Two different measurement campaigns with co-located and distributed antennas were performed and results were compared. In order to increase the coverage range two schemes, i.e. antenna selection and beamforming, have been applied in a MISO and a SIMO system with co-located antennas and a 2x4 MIMO system with locally distributed antennas. In this paper we assume these techniques introduce no additional delay and thus are proper for VoWLAN systems.

We observed an increased coverage range for co-located antennas and a further increase for distributed antennas. Although these improvements depend on the environment and may change in other scenarios, they illustrate the coverage enhancement which can be achieved through the use of the applied techniques. Due to the reciprocity of the voice channel we can enhance the coverage using RX beamforming up to the observed range only if we can utilize these schemes in both the uplink and the downlink. This requires having a MIMO system instead of a MISO/SIMO. Today MIMO with 4 or more (perhaps distributed) antennas in the AP and 2 antennas in the mobile STA seems quite feasible. Being able to use selection and beamforming techniques our results show a huge improvement of the MIMO system compared to the MISO cases. It is important to note that we benefit from maximum frequency diversity available in HIPERLAN/2 channel model but usually there is not much frequency diversity available and we can gain even more from antenna diversity.

These results show that diversity techniques can increase the coverage range of each AP and as a result the number of required APs to cover an area is reduced. In our scenario in the SISO case we need at least 2 APs to cover the whole floor. This number can be reduced to one AP by employing diversity techniques which provide both diversity and array gain. This is reasonable if an AP equipped with diversity techniques is cheaper than two simple APs and in cases that problems with handover and frequency planning are expected.

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