Coverage Enhancement for High-Quality Voice over WLAN Systems based on Diversity Techniques

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Abstract—**In this paper we consider the coverage range of a new system which is based on voice over WLAN (Wireless Local Area Network) and enhance this range using diversity techniques. This new system which has high Quality of Service (QoS) requirements has been developed within the WINDECT (Wireless local Area Network with Integration of Professional-Quality DECT Telephony) project [1]. Increasing coverage range per each Access Point (AP) reduces the number of required APs and as a result the infrastructure cost. Comparison between WINDECT's range and the range of DECT (Digital Enhanced Cordless Telecommunications) will be made and measurements and simulations applying diversity techniques to increase the range will be considered.**

I. Introduction

THE coverage range of WLAN APs is in general much smaller than that of cellular or DECT base stations. In order to have the same coverage, WLANs need more APs and this requirement can increase the infrastructure costs considerably. WINDECT as a WLAN system is no exception to this observation and suffers from small coverage range.

Currently available products for "voice over WLAN" are based on VoIP (Voice over IP) but they have some drawbacks such as high power consumption, poor (or most likely no) handover provisions between base stations and etc. In WINDECT we restrict ourselves to QoS requirements, for example very low delay (about 20ms) is allowed for voice service. Therefore we are not using VoIP in WINDECT.

Theoretically there are different possibilities for increasing the coverage range of an AP in a WLAN system. Diversity techniques increase not only the diversity degree but also the coverage range. Coverage enhancement can also be achieved by relaying and by increasing the transmit power. However relaying is probably not appropriate for WINDECT because of additional delay this would incur and allowed transmit power is restricted by the regulations and standards. In the following sections we will discover out how much the coverage range is expanded by applying diversity techniques.

In this paper we briefly review our new approach to voice over WLAN. This approach is based on an integration of the DECT standard and the current WLAN technologies and has been developed in the WINDECT project [1]. We mention some features of WINDECT with emphasis on its coverage range; using measurement results we will compare WINDECT'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.

II. System Overview

WINDECT is an integration of DECT and current WLAN technologies. The lower layers: Physical (PHY) and Medium Access Control (MAC) layers are based on WLAN standards IEEE 802.11a [2] and IEEE 802.11 [3] with extensions 802.11e (QoS) [4] and 802.11h (Spectrum and Power Management) [5]. Higher layers of WINDECT are defined according to the DECT standard [6]. Having this structure we can benefit from WLAN's wide bandwidth while DECT voice QoS is not impaired. As it is seen in Fig. 1 these layers are merged using a Protocol Adaptation Layer (PAL) in between. The PAL must map the functionality and requirements of DECT to that of 802.11 [7].

The system combines professional-quality real time services

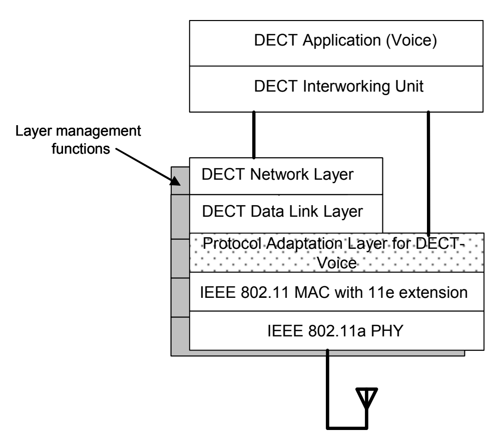

Fig. 1. WINDECT protocol stack

with conventional WLAN data services. For this reason in WINDECT seamless handover, load balancing, speech optimization and power consumption have been implemented in a different way compared to the typical WLAN systems, see [7] for details.

The WLAN equipment for IEEE 802.11a operates in frequency bands close to 5.2 GHz while DECT uses frequencies in the range 1.88 - 1.9 GHz. For the same path loss exponent this results in a path loss that is several times larger for the former system and consequently a smaller coverage area is obtained for each AP and so higher infrastructure cost may be incurred. DECT uses the Gaussian Frequency Shift Keying (GFSK) modulation scheme, whereas the IEEE 802.11a WLAN is based on a multicarrier Orthogonal Frequency Division Multiplexing (OFDM) scheme with 52 sub-carriers. The modulation on each sub-carrier depends on the required bitrate, i.e. Binary Phase Shift Keying (BPSK) for the data rate of 6 and 9 Mbit/s. Applying OFDM with the appropriate guard intervals prevents inter-symbol interference and makes the system robust against multi-path effects. Applying the Forward Error Correction (FEC) in 802.11a data loss is reduced in WINDECT and throughput is increased.

III. COVERAGE MEASUREMENTS

In order to compare the indoor coverage range of WINDECT (802.11a) with that of DECT 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 Access point and a CardBus 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. 2. We began the measurements in room 110 where the AP was located and continued towards the other side of the corridor until we received no signal, see [8] for more details. The measurements of Frame Error Rate (FER) show that a threshold was reached, after which the FER

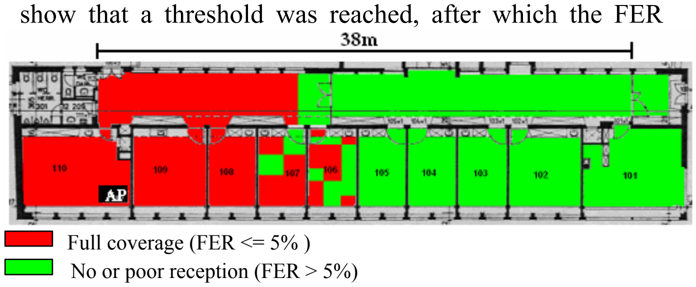

Fig. 2. WINDECT coverage range

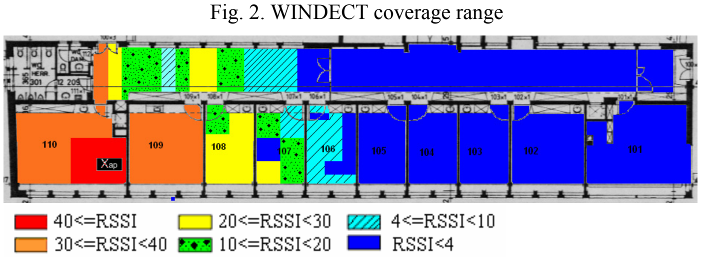

Fig. 3. Map of RSSI

quickly increased, so resulting in a quick transition from working to not working. Using the results seen in Fig. 4 we choose to define successful coverage when the FER was 5% or less. This is also acceptable according to WINDECT's QoS requirements. Any FER larger than this value corresponds to the non-covered area. It can be observed that there are very few occurrences below 95% FSR (Frame Success Rate) and the lower coding rates have a smaller spread of FSR than the higher coding rates. Fig. 2 shows the measurement results considering the FER and Fig. 3 the Received Signal Strength Indication (RSSI) for the same scenario. The RSSI values are neither calibrated nor represent any well-known units. They are a measure of the received field strength and can be used only as measurements relative to other RSSI measurements reported by the same test equipment. In our case RSSI is a number between 0 and 60.

The highest coverage range is achieved by applying the lowest data rate; i.e. 6 Mbit/s. In Fig. 2 only the results obtained for 6 Mbit/s are shown. 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 neighboring buildings as well as the copper layer on the corridor's roof which is installed 7m from the left wall of the corridor (in front of the door of the room 108) and continues to the door in the middle. Inside the rooms we obtained higher signal strength close to the door and the windows. One reason for that is the metal trunking under the windows in the offices which runs the entire length of the building.

The same measurements campaign has been performed using DECT handsets, locating the DECT Base Station (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 AP at the beginning of corridor and WINDECT LoS (line-of-sight) measurements have been carried out. In this case we had full coverage in the whole corridor.

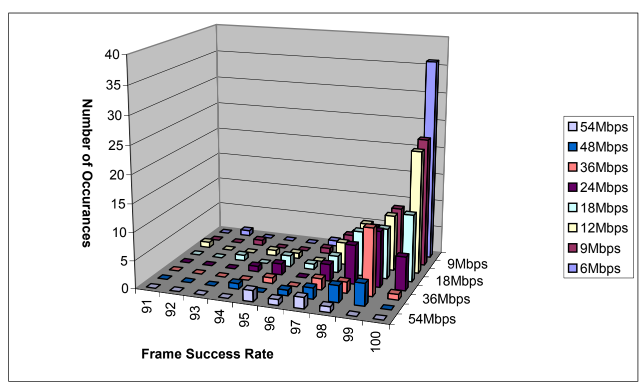

Fig. 4. Frame Success Rate Distribution between 90% and 100%

IV. SIMULATION RESULTS

For the 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.

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

With $\gamma = \begin{cases} 2, & d \le 5m \quad (LoS) \\ 3, & d > 5m \quad (NLoS) \end{cases}$

Where d is the distance between transmitter and receiver, d_0 reference distance which is equal to 1m, and γ the path loss exponent and we assumed that the room length is 5m (LoS) and for distances larger than 5 we are outside the room and do not have line of sight (NLoS). In table 1 the main parameters used in the simulations are presented.

Table 1 main simulation parameters

	DECT	WINDECT
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, and we will show that these measurements are close to what is predicted by simulation at the end of this section. That is why we focus on the non-line-of-sight (NLoS) scenario in this section. For WINDECT we use a NLoS indoor channel model from [9] with RMS delay spread of 100 ns. This model has been recommended for HIPERLAN/2 but due to the similarity of PHY layers in HIPERLAN/2 and IEEE 802.11a we have employed this model for WINDECT. The model consists of 18-tap delay line. The general tap-delay line model assumed for a time-invariant channel is given by equation 2 where $h(\tau)$, α_n, φ_n and τ_n are respectively the channel impulse response, amplitude, Doppler phase shift and delay of each resolvable path nth and N is the total number of resolvable multi-paths components. For DECT a single-tap model has been considered. For a fair comparison between DECT with single-tap model and WINDECT with 18 taps, average energy of the total taps is kept the same as that of the one tap.

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

According to [10] 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 and calculated as the proportion of the area within the cell that does not meet its minimum power requirement P_{min}. Considering this definition we employ the outage probability as a parameter which indicates the coverage. In Fig. 5 the outage probability for DECT and WINDECT 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. In our scenario this definition matches to the definition in equation 3.

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

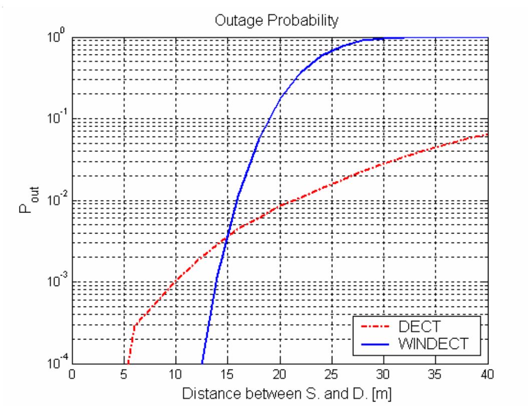

Fig. 5. Outage probability

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

Considering the outage probability of 5% employing during measurements, the WINDECT 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 the WINDECT 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.

In Fig. 5 it is seen that WINDECT outage probability has deeper slope. This is due to the frequency diversity achieved from FEC coding across OFDM sub-carriers. But frequency diversity is not enough to improve the coverage range of WINDECT and we need to apply other diversity techniques to increase the range. We have considered a MISO (Multiple Input Single Output) and SIMO (Single Input Multiple Output) system instead of a SISO (Single Input Single Output) system and applied two simple and effective schemes; antenna selection as a low complexity diversity method and beamforming as a technique which leads to the upper bounds of diversity gain [11]. In selection diversity the stream with the 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 antenna (TX beamforming) or for each receive antenna (RX beamforming) in such a way that the SNR at receiver is maximized. We assume the 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 and a feedback from the receiver to the transmitter is required. This feedback is usually available in the WLAN systems. The MISO structure for the downlink (AP to 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. 6 where plots using these schemes are compared with the SISO. Applying RX beamforming (Maximum Ratio Combining) we achieve not only diversity gain but also array gain [12]. These results show the possibility of a maximum of 16m range improvement with 4 antennas RX beamforming and 5m with 4 antennas TX beamforming for achieving 5% outage. By comparing these results with the outage probability of DECT (Fig. 5) we see that with RX beamforming the achievable range of WINDECT is only about 1m below the DECT's range for outage of 5%.

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 got no outage for the distance range of 40m. This matches our coverage measurement in section III.

V. Channel Measurements

To examine the simulation results and adjust model parameters, channel measurements in the same location have been carried out. Five independent wireless nodes (RACooN lab) [13] 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 have 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.

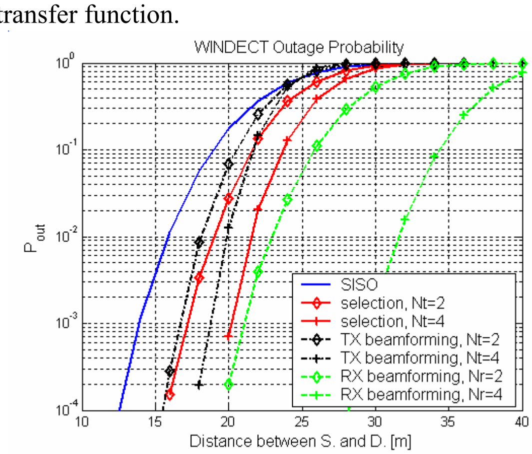

Fig. 6. Outage probability using diversity techniques

Two scenarios have been defined; LoS and NLoS. Fig. 7 shows an example of one of the transfer functions and IRs of the channels between each of the receive antennas and the transmitter.

Fig. 8 depicts locations where measurements have been performed along the corridor and it also shows the coverage enhancement achieved by applying RX beamforming. The range was increased from 12.6m to 21.5m. One should note that we defined 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. Capacity

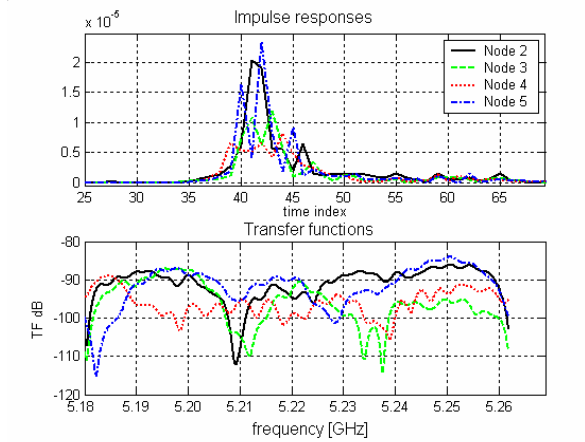

Fig. 7. IR and Transfer function in NLoS case and d=12.5m

increase due to the RX beamforming compared to the original has been shown as a number of bars above each location. Each white bar represents 6 Mbit/s capacity and the blue bar 3 Mbit/s.

In the simulations, so far a path loss exponent of 3 has been used for 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 3.5. Using the new parameter we achieve a model that conforms better to the measurements compared to our previous model. Results from simulations with the new set of parameters are shown in Fig. 9.

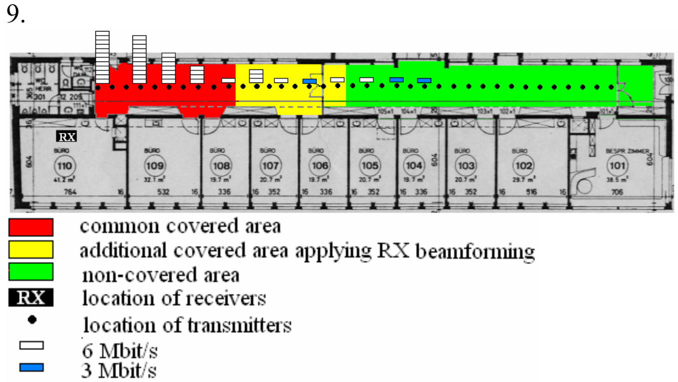

Fig. 8. Coverage performance applying the RX beamforming

It is obvious that in order to reach the coverage performance we should be able to apply these techniques in both directions: uplink (STA to AP) and downlink (AP to STA). This results in a MIMO (Multiple Input Multiple Output) system. Results for the 2x4, 4x2 and 2x2 MIMO systems are shown in Fig. 10. Capacity of MIMO system is calculated according to [11] from the following equation:

$$C = \log_2 \det(I_{M_R} + \frac{E_S}{M_T N_o} HH^H) \qquad (5)$$

With M_T and M_R number of antennas in the transmitter and receiver, H the matrix of channel impulse response coefficients, E_S power of transmit signal, N_o noise power and

I_{M_R} the identity matrix with the dimension of M_R. Result for antenna selection in a 4x2 MIMO system is also depicted in Fig. 10, 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. 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.

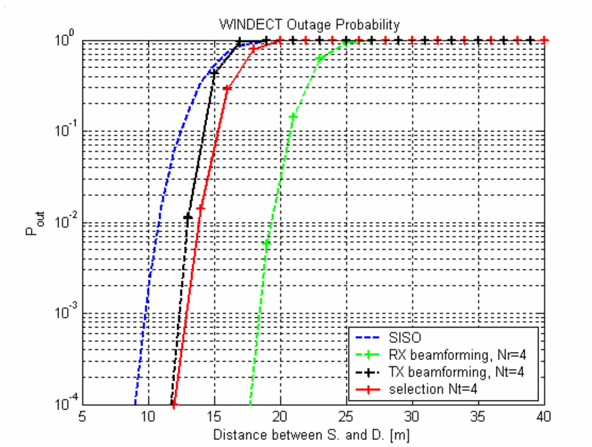

Fig. 9. NLoS Outage probability with gamma of 3.5

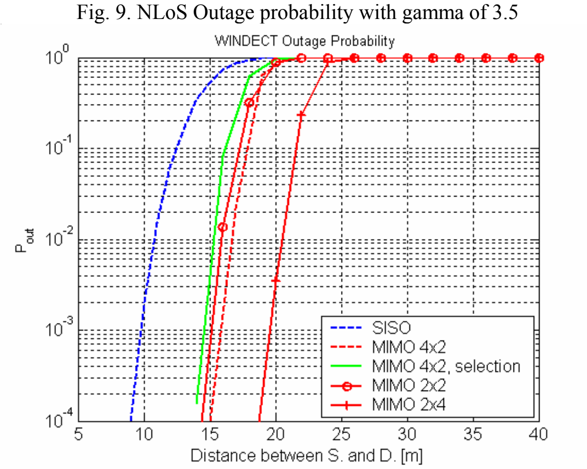

Fig. 10. NLoS Outage probability for MIMO case

VI. CONCLUSION

In this paper WINDECT, as a new approach to voice over WLAN, is reviewed. The new system is an integration of the DECT higher layers with the MAC and PHY layers from WLAN technology. Coverage measurements were carried out. Results from these measurements and also from simulation showed that coverage range of WINDECT is smaller than that of DECT. In order to increase this range two schemes, antenna selection and beamforming, have been applied in a MISO and SIMO system with co-located antennas.

To confirm our simulation results and adjust the model parameters, channel measurements have been performed in the same places where coverage measurements were performed. By adjusting the path loss exponent according to the channel measurement results, a new channel model was obtained which conforms to the real channel. As it was expected, the coverage range has been increased by up to 16m in the first simulation, 9m in the channel measurement and 8m in the simulation with the new parameter, for an outage probability of 5%. It is important to note that we benefit from maximum frequency diversity available in HIPERLAN/2 channel model and in situations where not so much frequency diversity is available we can even gain more from antenna diversity.

Due to the reciprocity of the voice channel, we can enhance the coverage using RX beamforming up to the range which we mentioned only if we can use these schemes in both the uplink and the downlink. This requires having a MIMO system instead of a MISO/SIMO. Many GSM and UMTS mobile phones have already been equipped with two antennas in the handsets and implementing MIMO with 4 or more antennas in the APs and 2 antennas in the mobile STAs can be easily done.

So far only co-located antennas have been considered; in the next step we will investigate the coverage enhancement in a distributed antennas system.

VII. ACKNOWLEDGEMENT

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