In Proc. Vehicular Technology Conference (VTC Spring), Milan, Italy, May 2004

Bi-directional WLAN Channel Measurements in Different Mobility Scenarios

Ana Aguiar, Jirka Klaue
Telecommunication Networks Group, Technical University Berlin

Abstract— **The interest in the behaviour of the wireless channel increases as WLAN access points become more widespread. In order to enhance the performance of existing applications in wireless environments, especially when mobility is present, knowledge about channel behaviour is of great importance. Nevertheless, very few experimental results have been documented and evaluated. We designed and realised a measurement campaign to investigate channel characteristics in different mobility conditions and different environments. Special attention is paid to the correlation between both channel directions. This is particularly interesting for channel-adaptive mechanisms; the strength of this correlation is important for the use of such techniques without the need for additional signalling or feedback of channel state information. In this paper we present the results of this measurement campaign. We evaluate the channel behaviour in various scenarios typical for WLAN. The linear time dependences within the same direction and between the opposite directions are calculated and compared. Finally we studied the usefulness of the results for channel prediction.**

I. INTRODUCTION

Wireless local area communications enjoy increasing popularity and the interest in the behaviour of the wireless channel has increased proportionally. Several characteristics are known from theory: the wireless channel is time-varying due to movement either of the sender or receiver, or to movement in the environment surrounding sender, receiver and/or path; errors and signal variations are correlated in time; the wireless channel is reciprocal, i. e. it behaves similarly in both directions. Although these characteristics have great influence on the performance of wireless local area communications, there are only few experimental investigations of the actual behaviour of the channel under different mobility environments typical for WLAN communications. For this reason, we designed and realised a measurement campaign in different mobility conditions and different environments to investigate the following characteristics of the wireless channel: variation with time, correlation of the variations in time and correlation between variations in the two directions.

II. MEASUREMENT SETUP

We used two Laptops with the Linux operating system with 802.11b wireless LAN (WLAN) cards using the PRISM2 [1] chip-set to make the measurements. One Laptop was used as a base station (Base) and another one as the wireless terminal (Mobile). A UDP packet generator was implemented which generates UDP packets carrying 1 Byte of data every 1 ms and immediately "reflects" packets to the base. The value of 1 ms was chosen after some tests to assess the speed of the Linux kernel, so that big variations in the sending and receiving times due to kernel queues were avoided (and thus the measured time series would be more or less equidistant).

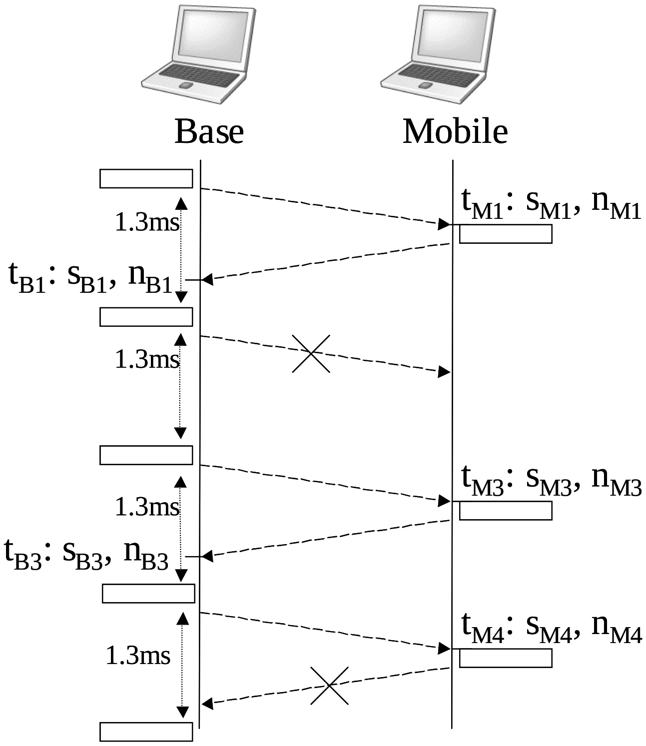


Fig. 1

MEASUREMENT SETUP

The driver of the WLAN cards — the hostap driver [2] — was changed so that no acknowledgments were sent and packets with a wrong CRC-check were not discarded. This was done to increase the number of measurement points. The transmission bit-rate and power were set constant to 2 Mbps and the maximum possible, respectively.

The setup can be seen in Figure 1. The WLAN card measured the received signal power in dBm averaged over the duration of the packet — s_i —, as well as the noise in dBm just before the start of packet reception — n_i . These two values were recorded with the time of the measurement — t_i — for every received packet both at the Base and at the Mobile. The measurement started with the Base sending a packet to the Mobile. On receiving a packet, the Mobile responded with a

Scenario	N	Environment	Mobility
Archi	7	Roundabout with high traffic	Traffic between Base and Mobile
Bike	3	Grass surrounded by trees and bushes	Bicycle speed (approx. 15km/h)
Car-park	7	Parking lot surrounded by buildings on 3 sides	No mobility
Maths	4	Foyer of Maths building during intervals between lectures	People moving between and around Base and Mobile
Mensa	7	Student canteen of the TU Berlin at busy hour	People moving between and around Base and Mobile
Road	7	Street with high traffic	Traffic between Base and Mobile
Stadium1	2	Wide open area in front of the Olympic Stadium	Pedestrian
Stadium2	2	Wide open area in front of the Olympic Stadium	No mobility
Walk	3	Grass surrounded by trees and bushes	Pedestrian speed
Grass	7	Grass surrounded by trees and bushes	No mobility

TABLE I

MEASUREMENT SCENARIOS. N IS THE NUMBER OF MEASUREMENT TRACES MADE IN EACH SCENARIO.

new packet, for which the signal and noise were measured at the Base. Thus, both Base and Mobile were sender and receiver, with the difference that the Mobile only “answered” packets from the Base (if a packet was not received at the Mobile, there was no answer). The values were measured in dBm.

In Figure 2 the cumulative distribution function (CDF) of the inter-packet times is exemplarily shown. It demonstrates that 85 % of the packets have a distance of less than 2.5 ms in this case.

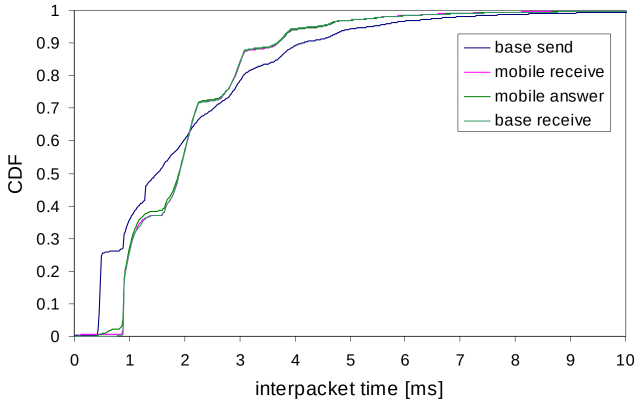


Fig. 2

CDF OF INTER-PACKET TIME (SCENARIO MENSA)

III. MEASUREMENT SCENARIOS

The measurement scenarios are summarised in Table I. They were chosen as possible environments for WLAN and so that a comparison of the influence of different mobility characteristics would be possible: no mobility in different static environments, pedestrian and faster mobility of a terminal, slow and fast moving environment for no terminal mobility.

IV. STATISTICAL EVALUATION OF THE MEASUREMENT RESULTS

Different runs in each scenario were compared and it was confirmed that the conditions had not changed over the different runs and the results were not random.

We calculated the loss rates in each run, as well as the mean values of the received signal in each direction. We noticed that the mean value of the received signal at the Mobile was higher than the mean value of the received signal at the Base. Since this happened for all measurement runs in all scenarios, we attribute it to differences on the transmission, reception or measurement hardware of the NICs used.

The distribution of the received signal values were calculated taking into account all the measurement runs in an environment. Due to the difference in the measured mean values, the series from the Base and Mobile had to be corrected so that their distributions could be compared: the respective mean signal value was subtracted from each series of measured signal values. This has no further influence on the evaluation, since we are interested only in the variations of the received signal values and their correlation over time in both directions.

The measured series of received signal power were smoothed by averaging the measured results over a 40 ms moving window to remove random fluctuations from the measurement (the 40 ms were chosen since they are lower than the expected correlation time for the selected environments).

The smoothed series were then used for the time correlation analysis. The auto-correlation function of each received signal power series was calculated, as well as the cross-correlation coefficient of the signal power received at the Mobile and at the Base. These results allow us to verify the validity of the assumption that the channel is time-correlated, i. e., that its changes are not independent in time, and that it is reciprocal, i. e., that it behaves similarly in both directions.

V. RESULTS

We plotted and compared all the time behaviours of the received signals for all runs and all scenarios. For space limitations we do not present them here. All results will be available in a technical report [3].

We observed much faster variations for bicycle than pedestrian speeds. Also, for the Mensa and Maths (moving people) scenarios, the signal variations are much slower and the fades less deep than for the scenarios with cars moving around. This is due to cars reflecting waves and thus increasing multipath and scattering, while people merely can cause shadowing. Comparing the results of the cases when the Mobile is actually moving (Bike, Walk, Stadium2) with those cases when the movement comes only from the environment (Archi, Mensa, Maths, Road, Stadium1, Grass) we can conclude that movement of one of the terminals clearly produces faster and deeper variations than movement in the environment.

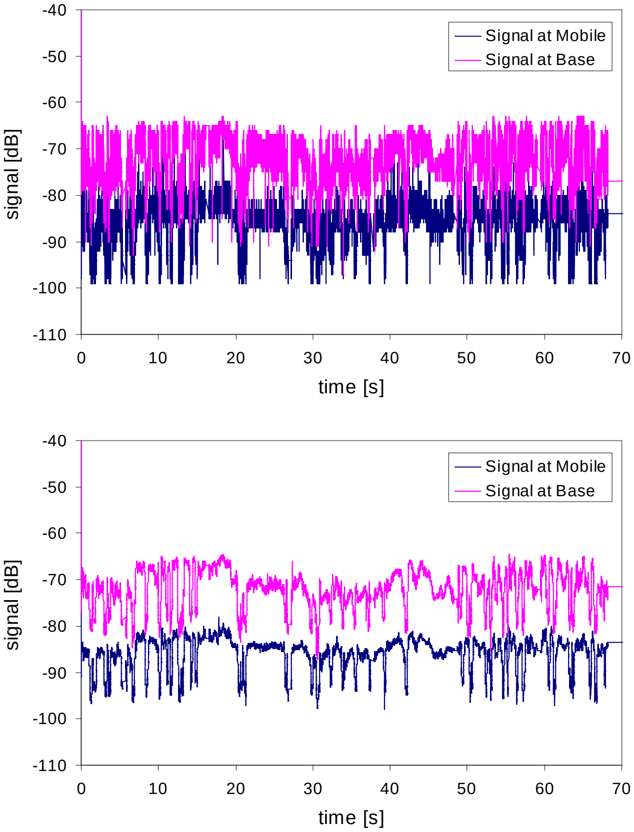


Fig. 3

SIGNAL AND SMOOTHED SIGNAL (40 MS MOVING WINDOW) OF SCENARIO ROAD

Figure 3 shows, for the example scenario Road, the measured received signal series at the Mobile and Base and the smoothed signal series. The distributions of the normalised received signal power values of all scenarios are available in [3].

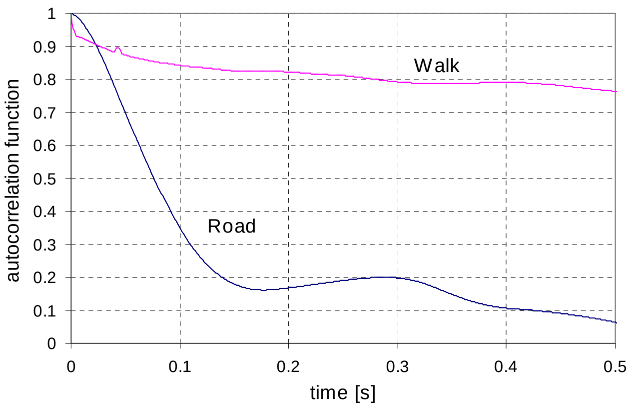


Fig. 4

AUTO-CORRELATION FUNCTION OF THE SCENARIOS ROAD AND WALK

In addition, the behaviour of the auto-correlation function and cross-correlation coefficient are shown and compared for different scenarios. In Figure 4 the auto-correlation function of the scenarios Road and Walk is shown exemplarily. The different dynamic of the channel is clearly visible — the slower fading scenario (Walk) has a much slower decreasing auto-correlation than the scenario Road.

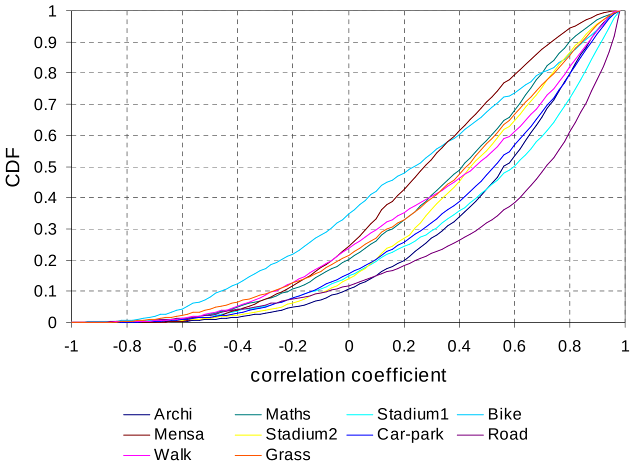


Fig. 5

CDF OF CROSS-CORRELATION COEFFICIENT OF ALL SCENARIOS

Figure 5 shows the cumulative distribution function (CDF) of the cross-correlation coefficient r (Equation 1) of all scenarios. This coefficient was calculated within a sliding window of 1 sec. It shows the linear correlation of two signal series [4]. A correlation coefficient of 1 means a high correlation, 0 no correlation and -1 reciprocal correlation.

$$r = \frac{\frac{1}{N}\sum_{i=0}^{N}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\frac{1}{N-1}\sum_{i=0}^{N}(x_i-\bar{x})^2}\sqrt{\frac{1}{N-1}\sum_{i=0}^{N}(y_i-\bar{y})^2}} \qquad (1)$$

$$-1 <= r <= 1$$

Although there are differences in the correlation of the signals between the scenarios, the cross-correlation coefficient is greater than 0 for 20 % of the time in most cases and greater than 0.6 for 60 % of the time.

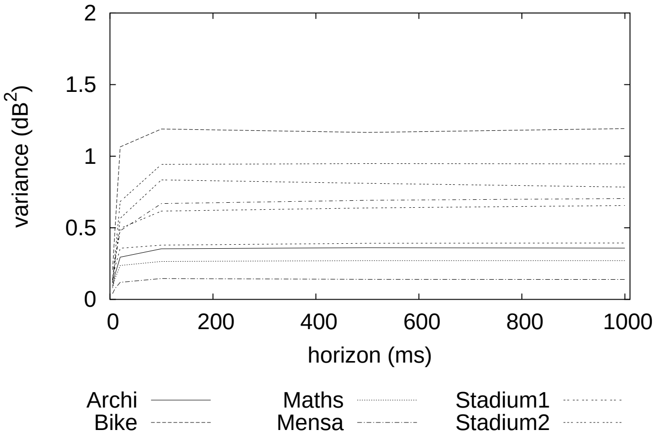
All measurement traces will be publicly available, after the analysis of the results has been concluded and published. In addition, the program sources to read and evaluate these traces will be provided.

VI. CHANNEL PREDICTION

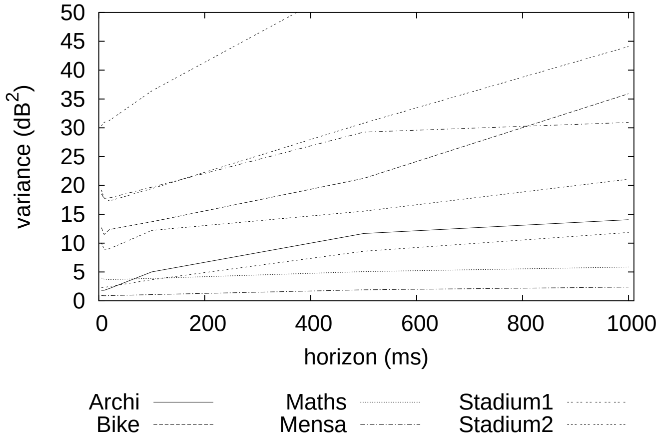
The correlation results obtained in the previous section lead us to ask some questions regarding channel prediction. Can the signal power received at the Mobile be used as an estimate for the signal which will be received later at the Base and vice-versa? If yes, for which period is this estimate valid? How good is this estimate compared to using the signal received in one direction as an estimate for that same direction (which implies using feedback)? Two heuristic prediction methods are implicit in these questions: using s_x at time instant t_x to estimate s_x at time instant $t_x+\Delta$ ($x \in \{B, M\}$), which we call same direction prediction (SDP), and using s_x at time instant t_x to estimate s_y at time instant $t_x+\Delta$, $x \in \{B, M\}$ and $y = \{B, M\}\backslash x$, which we call opposite direction prediction (ODP).

We calculated the estimation error for both prediction methods using different time horizons. Since we were interested in the variations of the received signal, we subtracted the average received signal over the last 20 ms from the measured value. According to this, the prediction error for ODP is defined as $e_x = [(s_{yi} - \mu_{yi}) - (s_{xi} - \mu_{xi})]$, where $\mu_{zi} = \frac{\sum_{t_{zi}-20\text{ms}<t_x<t_{zi}} s_{zi}}{n}$, where n is the number of existent values in the interval $[t_{zi} - 20\text{ms}, t_{zi}]$, $z \in x, y$, $x \in \{B, M\}$ and $y = \{B, M\}\backslash x$. The error for SDP is defined similarly, only $y = x$. We then calculated the average μ and variance σ^2 of the error.

We looked at the distribution functions of the errors. In all scenarios, the prediction errors have a normal distribution with average very close to 0 dB. The variance depends on the prediction horizon and the environment, and can be seen in Figure 6. The environments with only human movement (Maths and Mensa) show the lowest errors, and the accuracy almost does not change for the prediction range considered. The biggest errors and highest sensitivity to increase in prediction horizon happen for the environments when the Mobile was moving. The prediction errors for when the environment changes but neither Base nor Mobile move lie between the two extremes. These results are explained by the differences in channel behaviour, in concrete deepness of fades and speed of changes, observed in the previous section.



(a) variance same direction



(b) variance opposite direction

Fig. 6

VARIANCE OF THE PREDICTION ERROR A) WHEN THE SIGNAL RECEIVED IN ONE DIRECTION IS USED AS AN ESTIMATE FOR THE SIGNAL RECEIVED IN THE SAME DIRECTION AT A LATER TIME (HORIZON), B) WHEN THE SIGNAL RECEIVED IN ONE DIRECTION IS USED AS AN ESTIMATE FOR THE SIGNAL RECEIVED IN THE OPPOSITE DIRECTION AT A LATER TIME (HORIZON).

As mentioned above, we want to compare two kinds of heuristic prediction methods: SDP and ODP. The second case, when feasible, spares the need for feedback of the received signal value from the receiver to the sender to enable prediction. Comparing Figures 6 a and b, a big difference in the error values of both methods can be seen. It is especially noticeable that, whereas the errors of SDP are very close to 0 and do not vary much in the range of prediction horizons studied, the ODP shows much bigger errors for increasing horizons, especially for the cases when the Mobile is moving.

For ODP, we can also observe that for farther prediction horizons, the error distributions are wider, i. e. bigger errors occur. The comparison of different scenarios shows that bigger errors occur for scenarios with movement. Also, smaller errors can be expected for slower movement, as can be seen comparing the curves in Figure 7, which shows μ and the interval $[\mu - \sigma, \mu + \sigma]$.

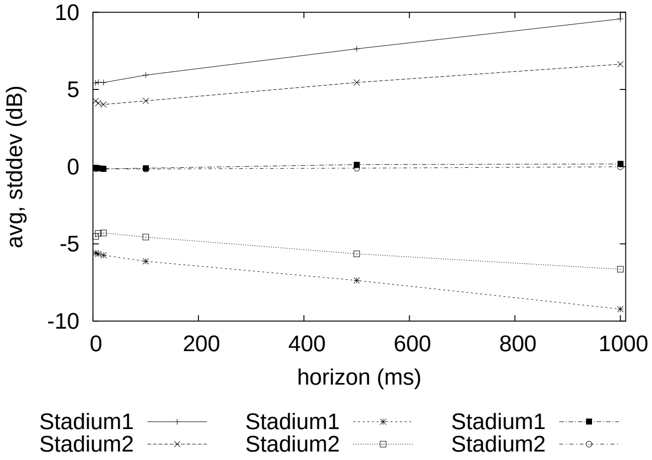


Fig. 7

Average and standard deviation of the prediction error, when the signal received in one direction is used as an estimate for the signal received in the opposite direction at a later time (defined by horizon).

VII. Conclusions

We measured the signal received by two computers communicating over wireless LAN in several environments with varied mobility conditions. We analysed them regarding the differences in deepness and speed of the fading behaviour. We concluded that when neither computer is moving, the fades are less deep and the changes slower than when one of the computer moves. Also, if no computer is moving, but movement of objects around the propagation path exists, cars cause faster and deeper changes in the received signal than people.

An analysis of the correlation of the measured data obtained for both communication directions indicates that the data series are highly correlated. This fact enables the use of values received at one computer to estimate the signal behaviour at the other computer. We first evaluated the prediction errors when the signal received at one computer is used as an estimate for the signal which will be received at a later time at the same computer (SDP). The results show that the errors have a normal distribution with average mean 0 dB and a variance which depends on the environment and very little on the prediction horizon.

We then studied the case when the signal received at one computer is used as an estimate for the signal which will be received at a later time at the other computer. The results show that the prediction errors are bigger and more dependent on the environment and prediction horizon than in the previous case. Still, this subject needs to be further studied, evaluating other more complex prediction methods, and checking in which situations the error values are acceptable.

The measurement traces and evaluation software will be made publicly available in order to provide interested researchers the possibility to compare simulation results with real-world measurements.

References

[1] *PRISM Driver Programmer's Manual (Version 2.10)*, Intersil Corporation, 4243-3 Medical Drive, San Antonio, TX, Aug 2001.

[2] J. M. (jkmaline@cc.hut.fi), *Host AP driver for Intersil Prism2/2.5/3*, http://hostap.epitest.fi/.

[3] A. Aguiar and J. Klaue, "Statistical evaluation of bi-directional wlan channel measurements in various environments," Telecommunication Networks Group, TU-Berlin, Tech. Rep., 2004.

[4] R. Schlittgen and B. H. J. Streitberg, *Zeitreihenanalyse.* R. Oldenbourg, 1999.