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Bi-directional WLAN Channel Measurements in WLAN Environments with Mobility

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Chapter 1

Introduction

Wireless local area networks (WLAN) enjoy increasing popularity and, consequently, the interest in the behaviour of the wireless channel has also increased. Theory tells us that 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 propagation path; errors and signal variations are correlated in time; the wireless channel is reciprocal, i. e. it behaves similarly in both directions. These characteristics have great influence on the performance of wireless local area communications. Despite this, there are only very few experimental investigations of the actual behaviour of the wireless channel.

For this reason, we designed and realised a measurement campaign to investigate the actual behaviour of the wireless channel in environments we thought typical for WLAN communications, with low mobility of the sender and/or receiver and some mobility in the surroundings. We measured the channel in both directions simultaneously using two laptops and state-of-the-art WLAN cards with open source drivers so that we could change them accosding to our needs. We investigate the following characteristics of the wireless channel:

- variation with time;
- correlation of the variations in time;
- correlation between variations in the two directions.

In this report we present all the results graphically, including statistics of the received signal strength in both communication directions, namely:

- the time behaviour,
- mean and standard deviation over different time periods,
- histograms,
- FFT,
- auto-correlation,
- cross-correlation between the two directions.

This report presents the results of the measurement campaign and can be used as a guide to choosing measuremet sets to be used as traces in simulations or other evaluation of wireless communications.

Chapter 2

Measurement Description

2.1 Measurement Setup

Figure 2.1 depicts the measurement setup. We used two Laptops with the Linux operating system and 802.11b wireless LAN (WLAN) cards using the PRISM2 chip-set [1]. The WLAN card measures the received signal strength averaged over the duration of the packet — s_i in dBm —, as well as the noise just before the start of packet reception — n_i in dBm. We recorded these two values together with the time of the measurement — t_i — for every received packet on each laptop and they are refered to as the channel samples from now on.

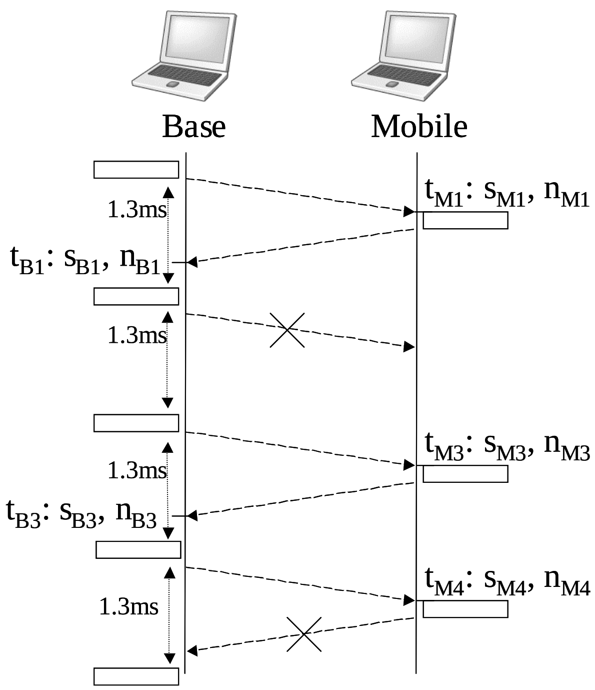


Figure 2.1: Measurement setup

One laptop was used as a base station (Base) and the other one as the wireless terminal (Mobile). It was only possible to sample the channel when data was received by the cards, so we used a UDP packet generator which generated packets carrying 1 Byte of data every

1.3 ms. This inter-packet-generation value was chosen after some tests to assess the speed of the Linux kernel, so that big variations in the sending times due to kernel queues were avoided (and thus the measured time series is more or less equidistant). It was not possible to send faster due to kernel scheduling delays as well as delays in the TCP/IP stack.

The Nyquist criterion requires a sampling interval $\Delta t_{\mathrm{Nyquist}}$ that satisfies $\Delta t_{\mathrm{Nyquist}} \leq \frac{1}{2f_D}$, where f_D is the maximum Doppler frequency $f_D = \frac{v}{\lambda}$. In our case, the carrier frequency is 2.4 GHz and λ=0.125 m. For a sampling interval of 1.3 ms, the maximum Doppler frequency for which the fading process will not be undersampled is approximately 48 m/s or 173 km/h. This speed is much higher than the speeds expected in the environments to be measured (maximum 50 Km/h), and we can reasonably be sure that the fading process measured is not undersampled.

The driver of the WLAN cards — the hostap driver [2] — was changed so that no acknowledgments were sent for the data, so that the card would not wait between sending two packets (the waiting would have increased the sampling interval further). The driver changes also included keeping packets with a wrong CRC-check, so that there were also measurement points with low SNR. The transmission bit-rate was set constant to 2 Mbps and trasnmission power adaptation turned off.

The measurement started with the Base sending a packet to the Mobile. On receiving a packet, the Mobile immediately responded with a new packet also containing 1 byte of data. Signal and noise were measured on packet reception both at the Mobile and 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). I. e. we measured both channel directions simultaneously in every measurement run.

2.2 Measurement Scenarios

Table 2.1 describes the measurement scenarios. We chose these scenarios as possible WLAN environments and so that a comparison of the influence of different mobility characteristics would be possible. In scenarios Archi, Carpark, Grass, Mensa, Maths and Road both Base and Mobile are static, but the objects in and around the propagation path show different moving paterns; in Archi and Road there are cars moving in the line-of-sight (LOS) path, in Mensa and Maths there are people moving around, in Carpark there was nothing explicitly moving. In environments Bike, Stadium 1, Stadium 2 and Walk the Mobile was actually moving at different speeds.

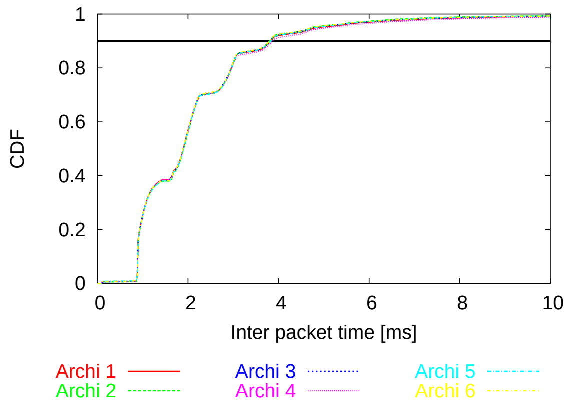
2.3 Measured Sampling Rate

Several queues in the protocol stack, the scheduling of processes of the Linux kernel and internal queues in the WLAN-card itself lead to different queueing times for each packet sent, so that the channel samples are not equidistant. Figures 2.2 to 2.10 show the cumulative distribution function (CDF) of the inter-packet times at the receiver for all measurement runs in all environments. We can see that 90 % of the packets (black line on the figures) have an interval of less than 4 ms to the previous one. For this inter-packet value, the maximum measurable Doppler process corresponds to a speed of 56 km/h, which is more or less the maximum speed expected to be found in the environments measured, and we can argue that

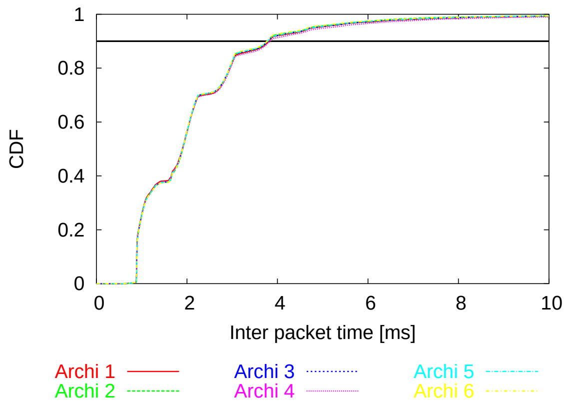
Scenario	N	Environment	Mobility
Archi	7	Roundabout with high traffic	Traffic between Base and Mobile
Bike	3	Grass surrounded by trees and bushes	Bicycle (approx. 15km/h)
Car-park	7	Parking lot surrounded by buildings on 3 sides	No mobility
Maths	4	Foyer of Maths building during intervals between lectures	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	Bicycle (approx. 15km/h)
Walk	3	Grass surrounded by trees and bushes	Pedestrian speed
Grass	7	Grass surrounded by trees and bushes	No mobility

Table 2.1: Measurement scenarios. N is the number of measurement runs in each scenario.

the actual sampling frequency is enough to characterise the fading, as intended.

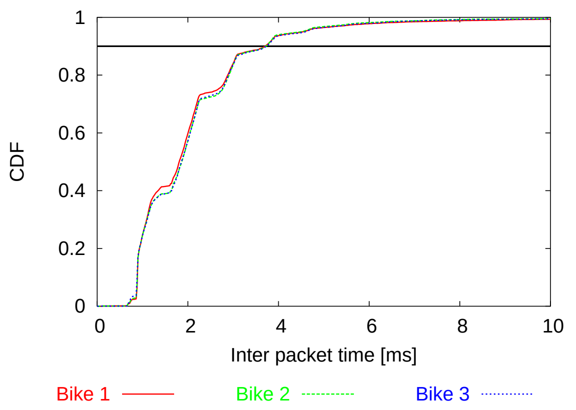


(a) Mobile

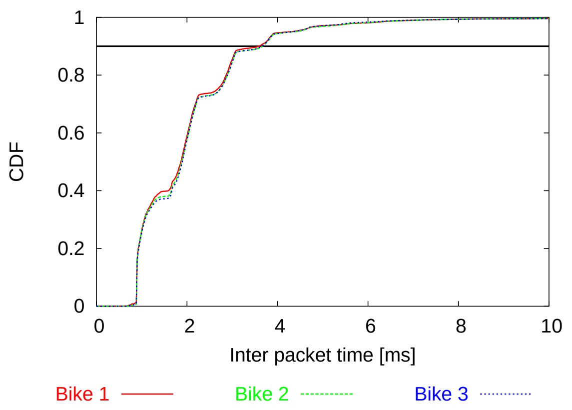


(b) Base

Figure 2.2: CDF of the measurement intervals for the environment Archi.

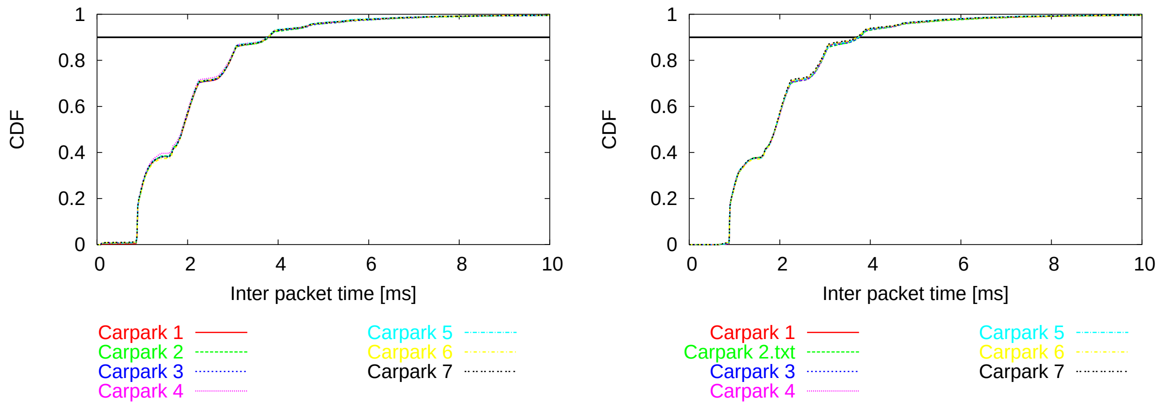


(a) Mobile



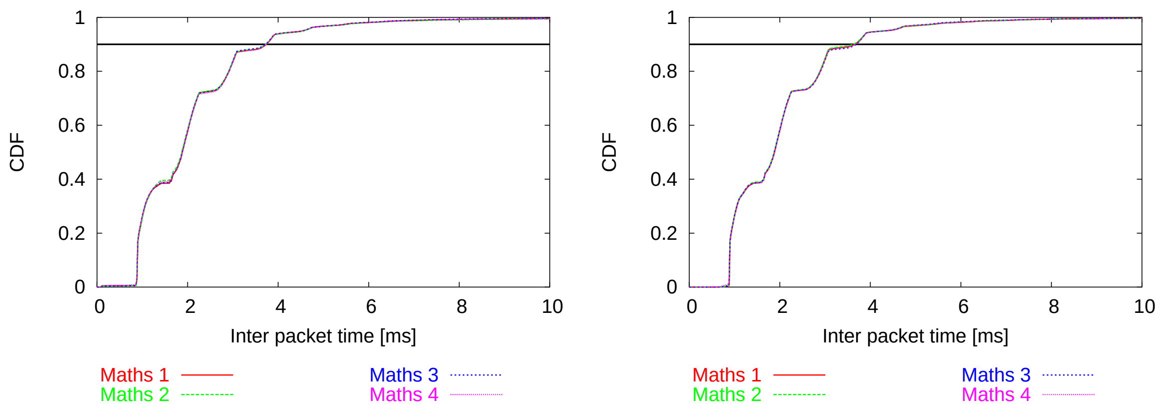
(b) Base

Figure 2.3: CDF of the measurement intervals for the environment Bike.



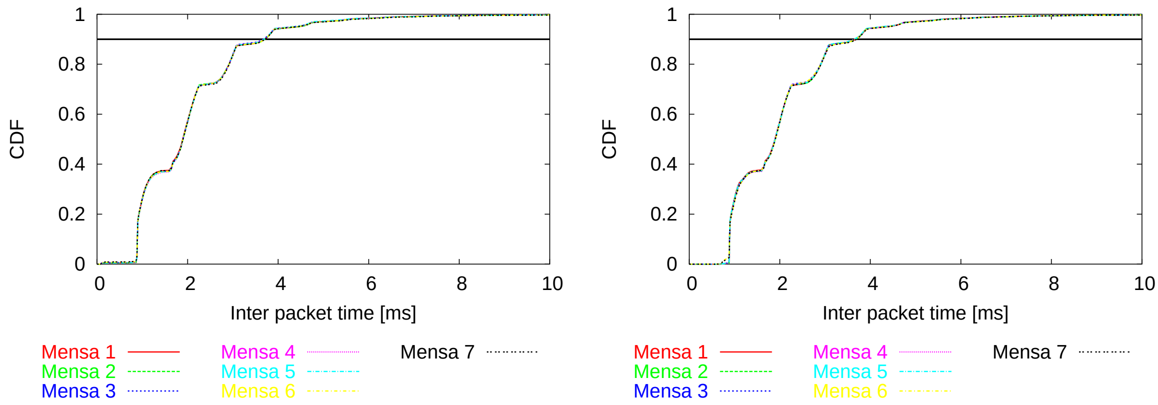
(a) Mobile (b) Base

Figure 2.4: CDF of the measurement intervals for the environment Carpark.



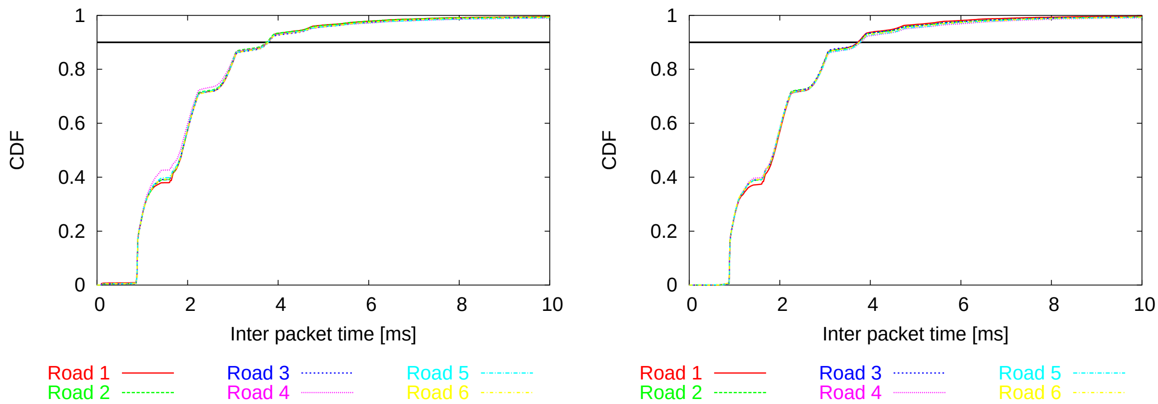
(a) Mobile (b) Base

Figure 2.5: CDF of the measurement intervals for the environment Maths.



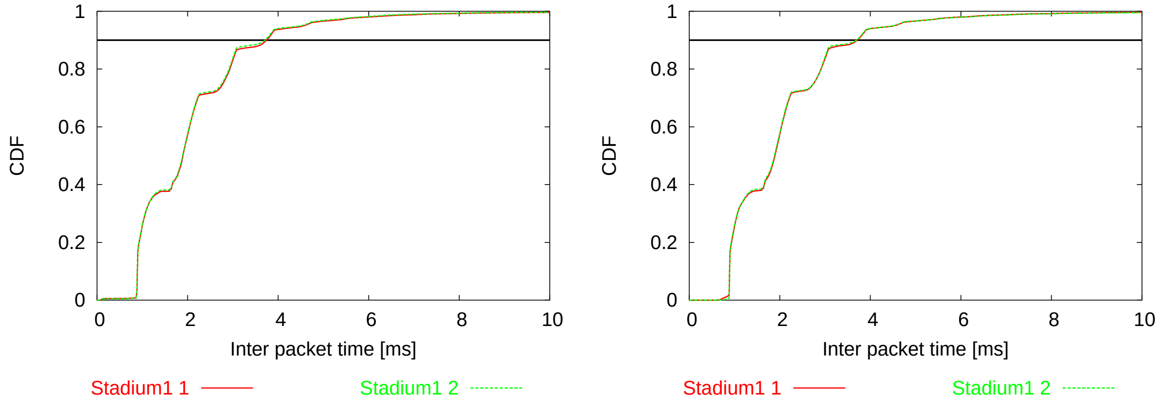
(a) Mobile (b) Base

Figure 2.6: CDF of the measurement intervals for the environment Mensa.



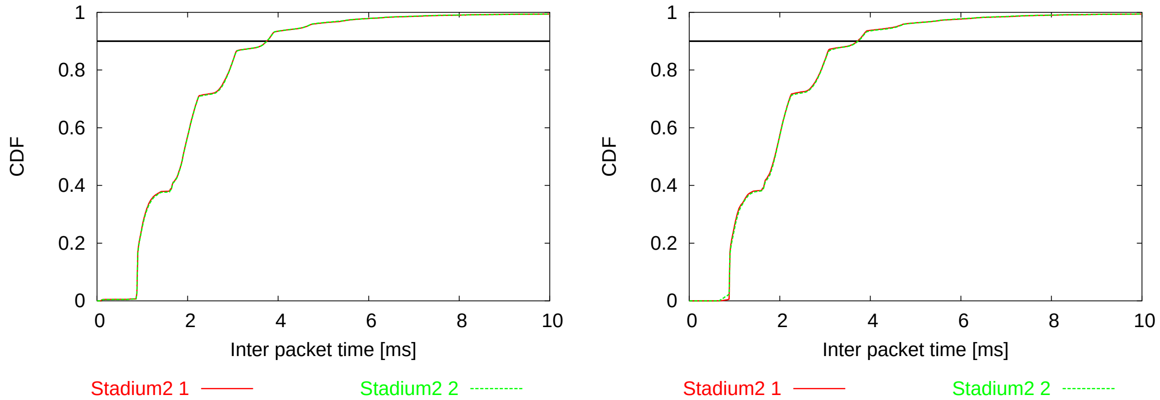
(a) Mobile (b) Base

Figure 2.7: CDF of the measurement intervals for the environment Road.



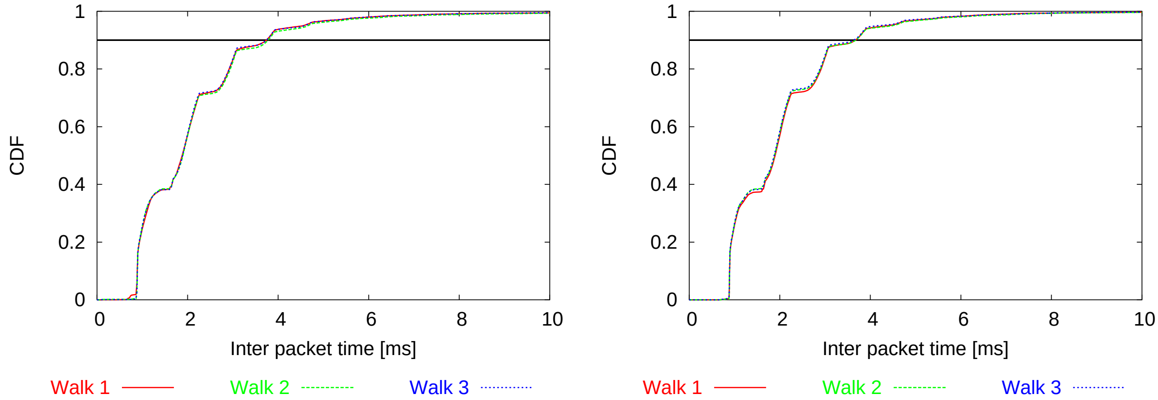
(a) Mobile (b) Base

Figure 2.8: CDF of the measurement intervals for the environment Stadium1.



(a) Mobile (b) Base

Figure 2.9: CDF of the measurement intervals for the environment Stadium2.



(a) Mobile

(b) Base

Figure 2.10: CDF of the measurement intervals for the environment Walk.

Chapter 3

Statistics of the Channel Measurements

As mentioned in Chapter 2, internal queues in the protocol stack of the Laptops and the NIC and process sheduling by the Linux kernel — factors over which we have no control — lead to variations in the packet inter-arrival time, i. e. the channel samples are not equidistant and cannot be processed as a time series. To obtain equidistant data we re-sampled the received data at 1 KHz, where each sample is the result of the linear interpolation between the two nearest measured values. Since, for reasons discussed in previous sections, we expect the bandwidth of the data to be much lower than 500 Hz, the 1 KHz sampling frequency and the linear interpolation are enough.

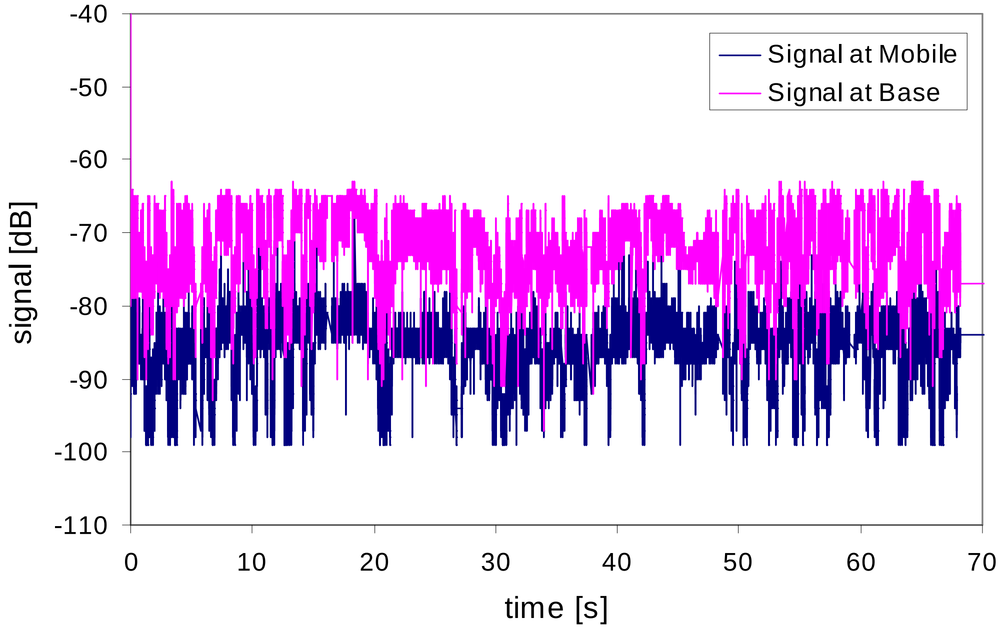
Further, since the measured channel samples were noisy, we smoothed (time domain noise removal) the received signal by averaging the measured results over a 40 ms moving window. As an example, Figure 3.1-a shows the original measured values for one measurement run of the scenario Road and Figure 3.1-b the corresponding equidistant smoothed time series.

The equidistant interpolated channel samples were used for the first order statistics in Section 3.2 and the histograms in Section 3.3. The smoothed equidistant time series were used for the time behaviour plots, the FFT, auto-correlation and cross-correlation.

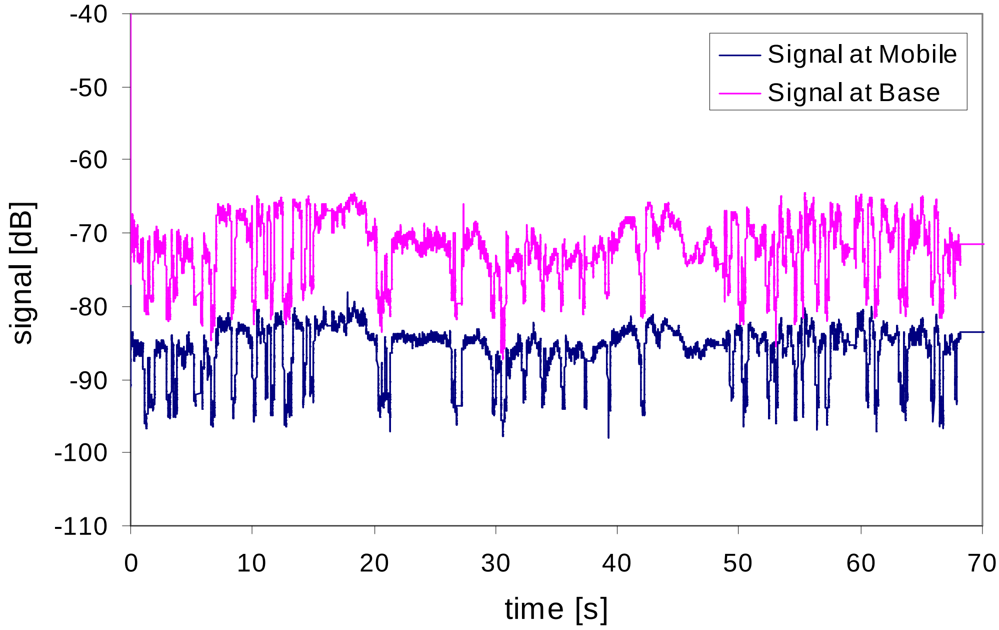
3.1 Time Behaviour

The time behaviour of the received signals for all runs and scenarios can be seen in Figures 3.2 to 3.10. In scenario Bike there are channel samples missing over quite long periods of time; in scenario Grass there were entire measurement runs missing so that we do not show any results at all.

There is a difference of approximately 15 dB in the mean value of the received signal at both sides(this can be clearly seen in Figures 3.2 to 3.10). Since the difference is the same for all measurement runs in all scenarios, we attribute it to differences on the transmission, reception or measurement hardware of the NICs used.



(a) Measured Values



(b) Smoothed Values

Figure 3.1: Signal and smoothed signal (40 ms moving window) of scenario Road

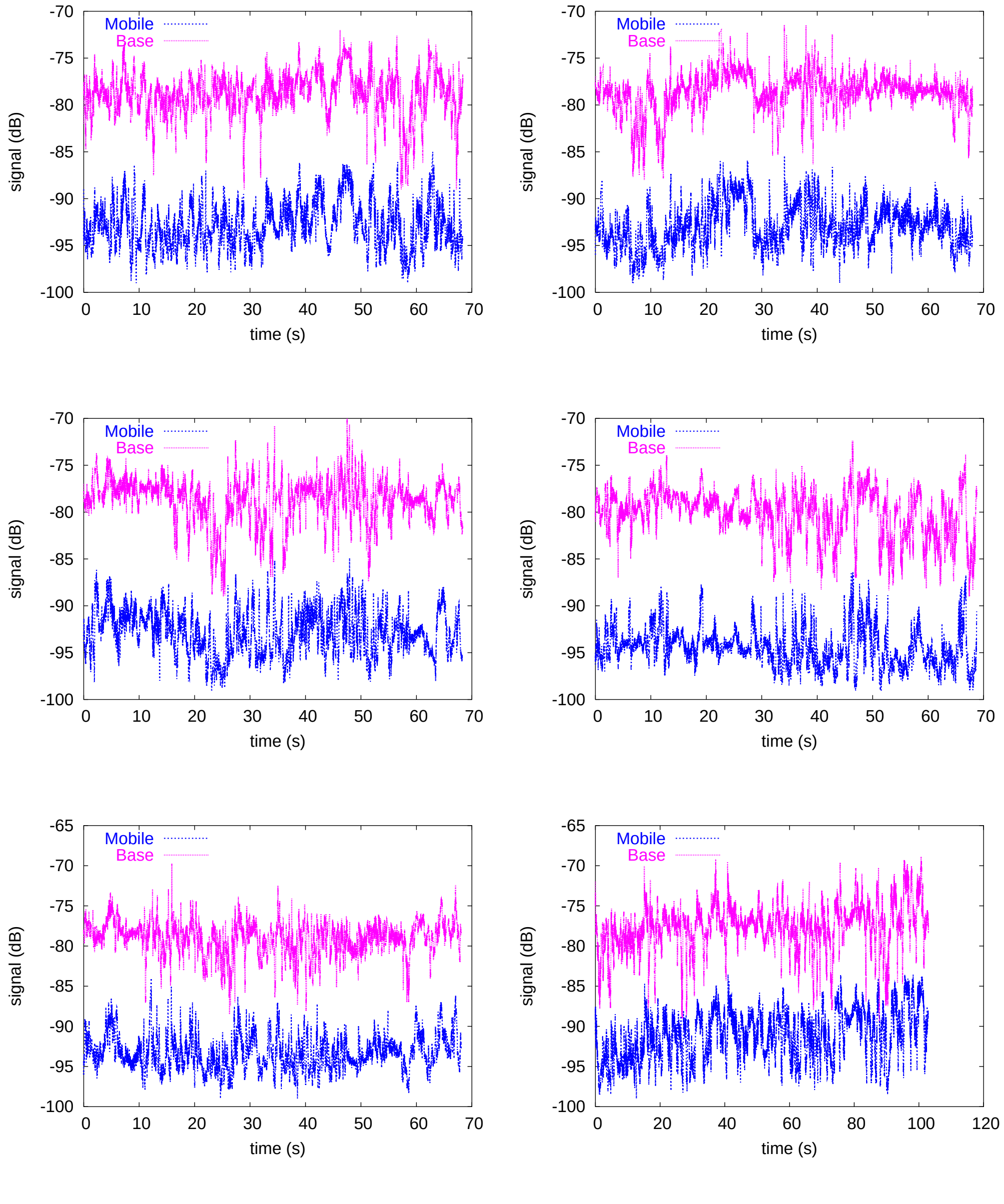


Figure 3.2: Time behaviour of the received signal for all measurement runs of the scenario Archi.

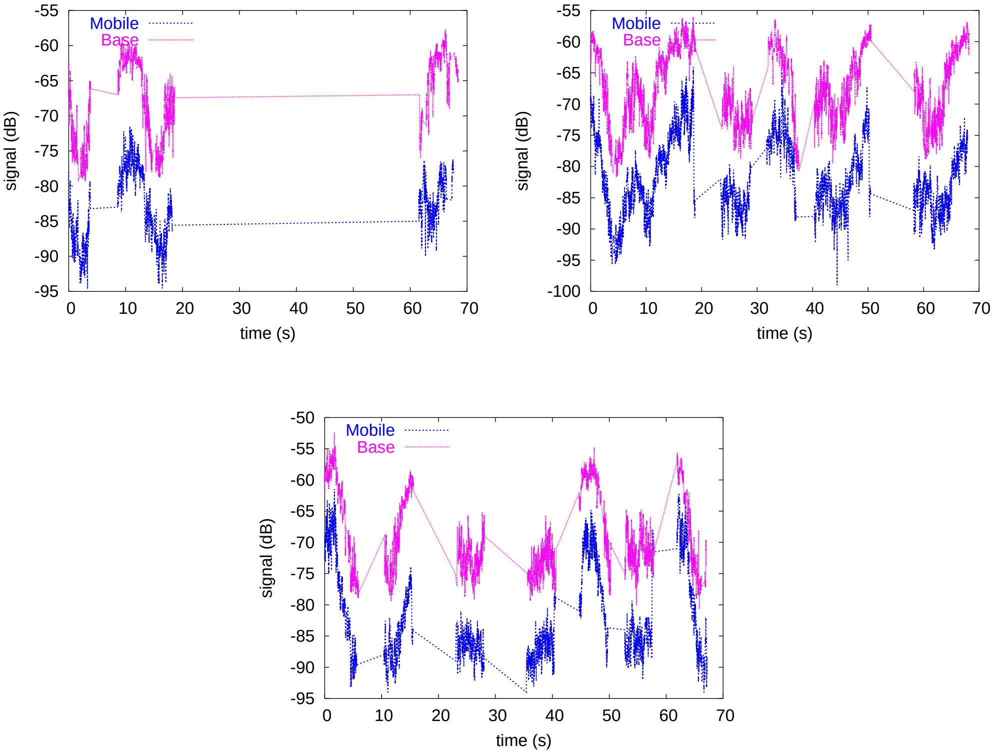


Figure 3.3: Time behaviour of the received signal for all measurement runs of the scenario Bike.

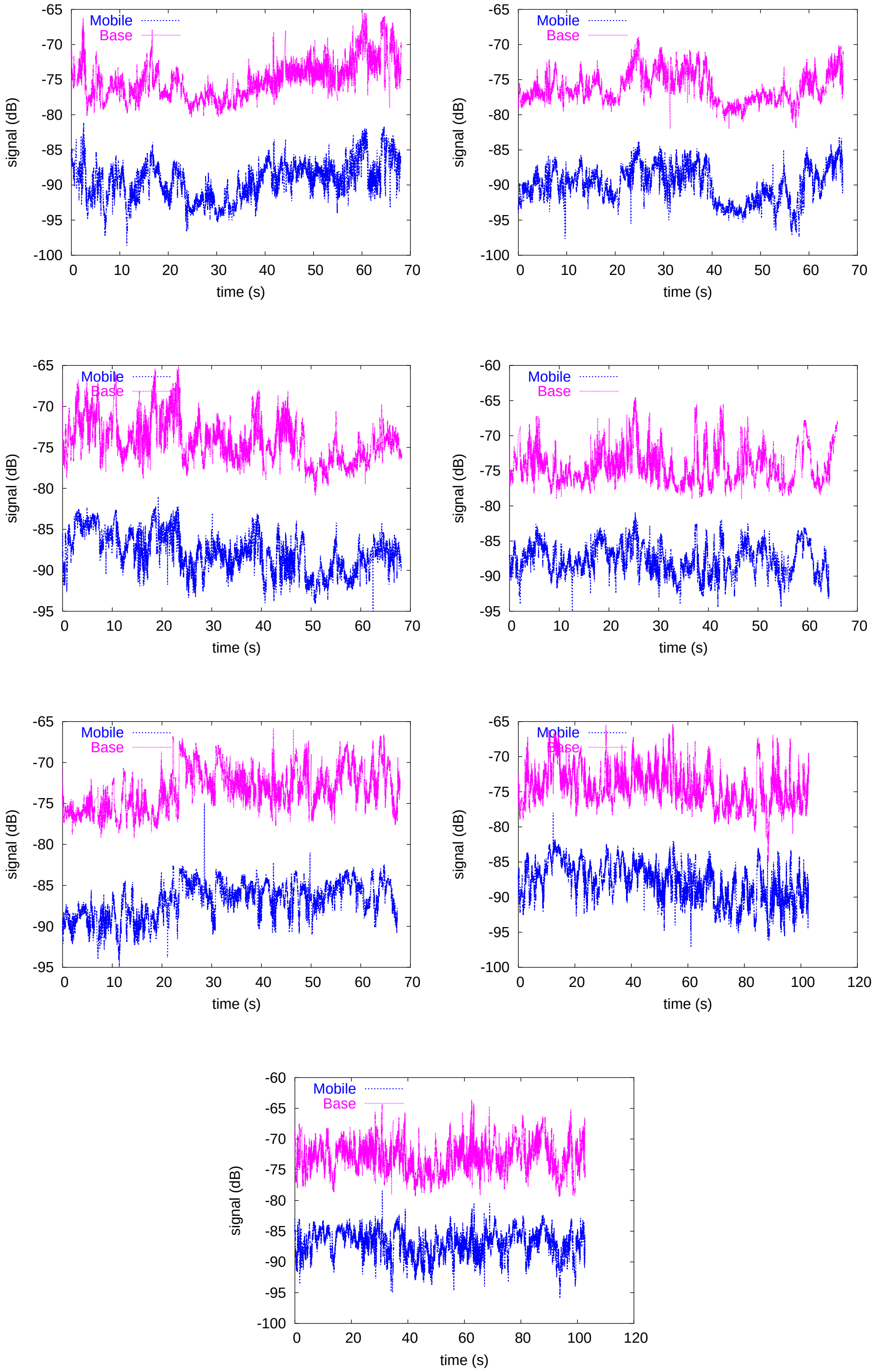


Figure 3.4: Time behaviour of the received signal for all measurement runs of the scenario Carpark.

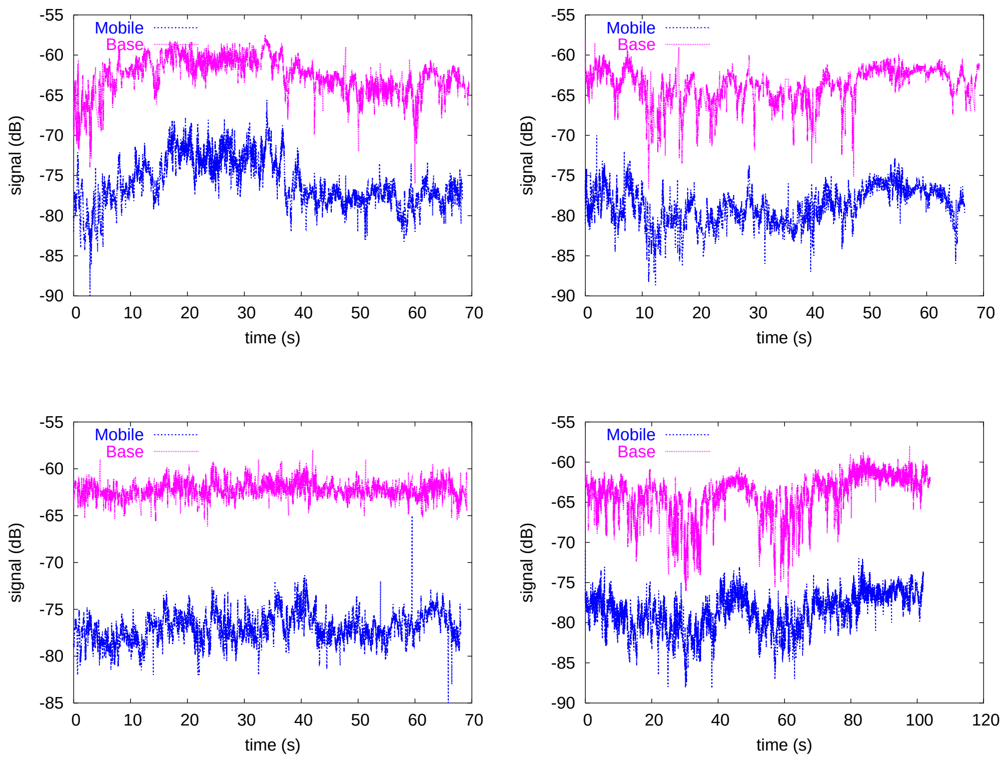


Figure 3.5: Time behaviour of the received signal for all measurement runs of the scenario Maths.

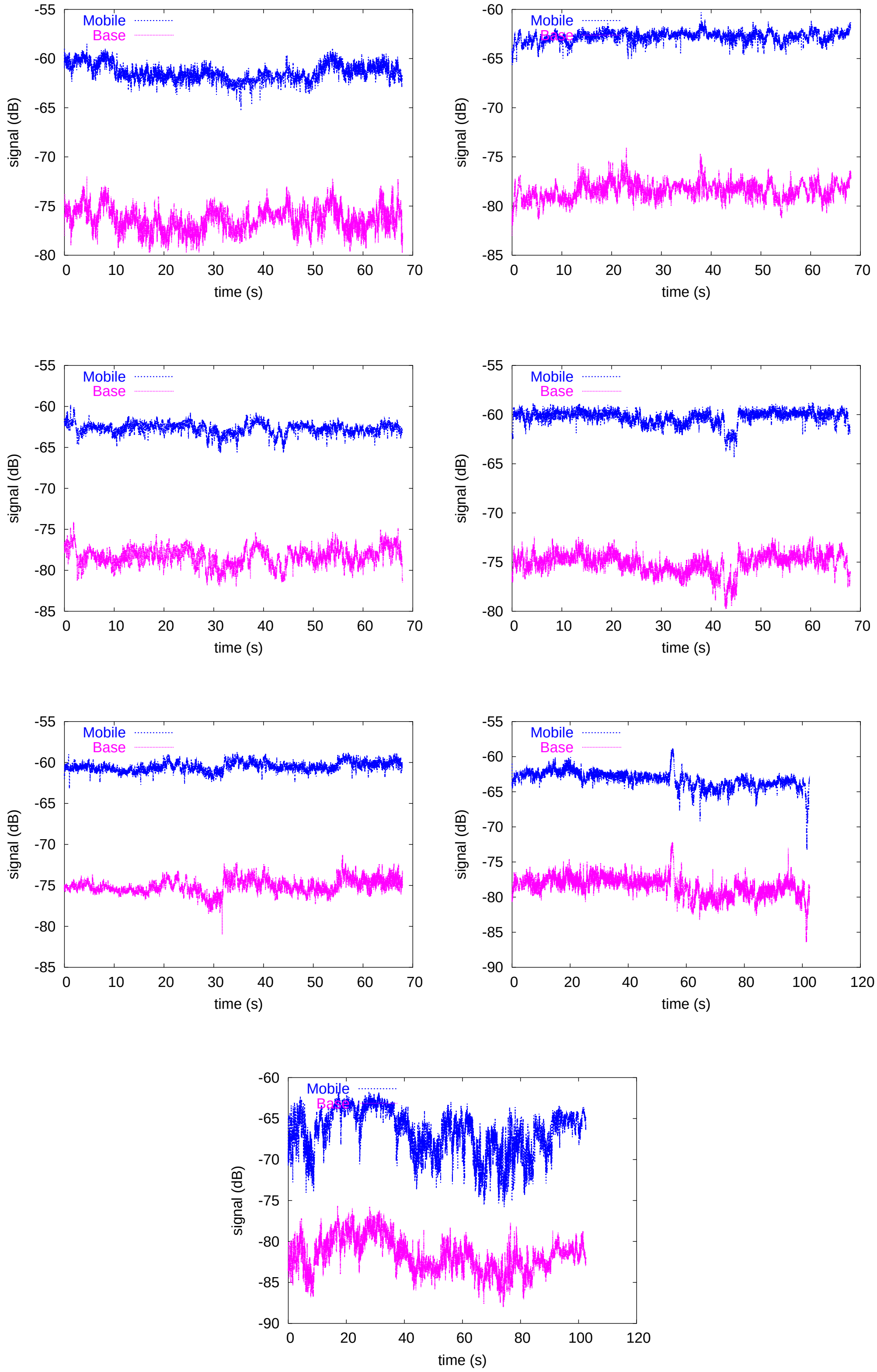


Figure 3.6: Time behaviour of the received signal for all measurement runs of the scenario Mensa.

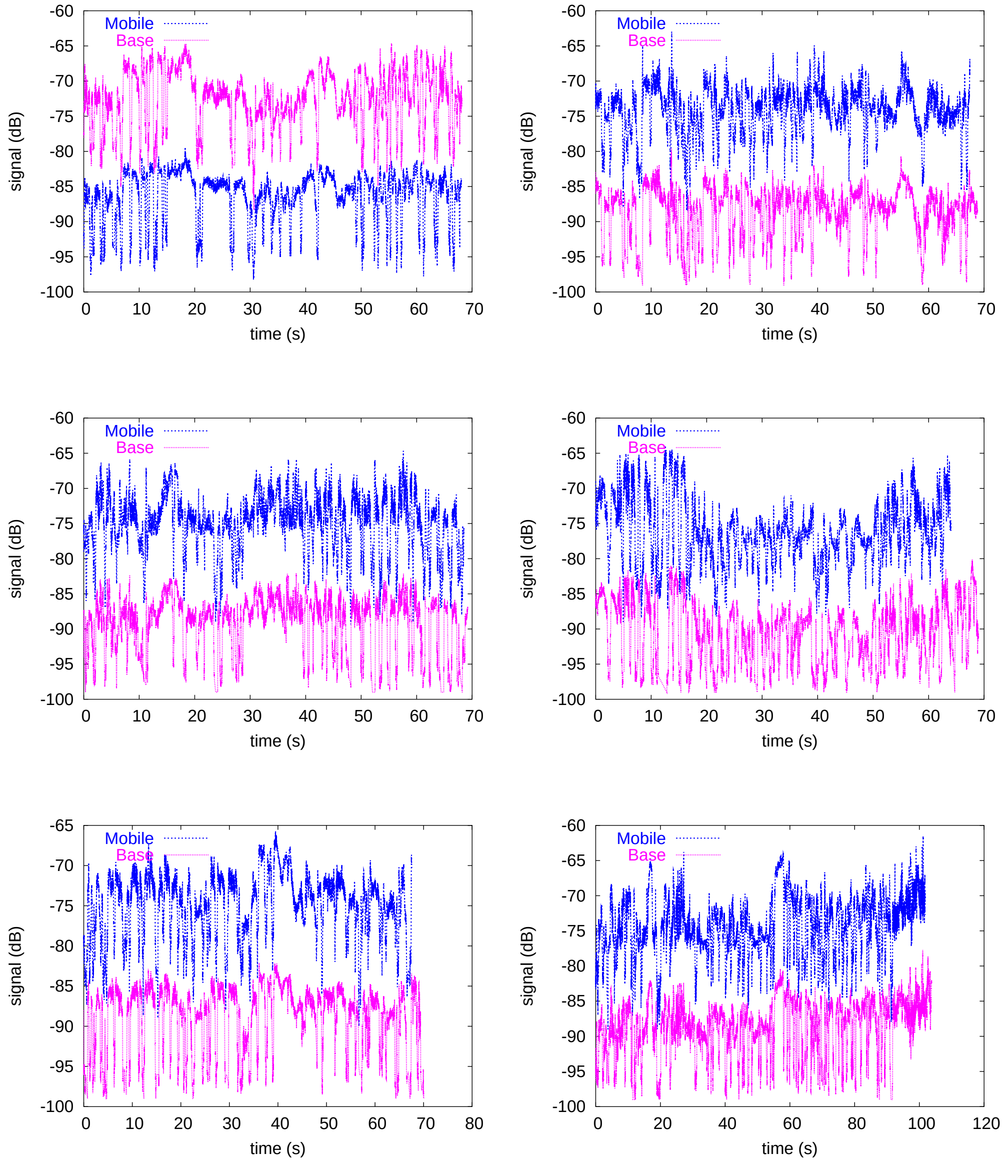


Figure 3.7: Time behaviour of the received signal for all measurement runs of the scenario Road.

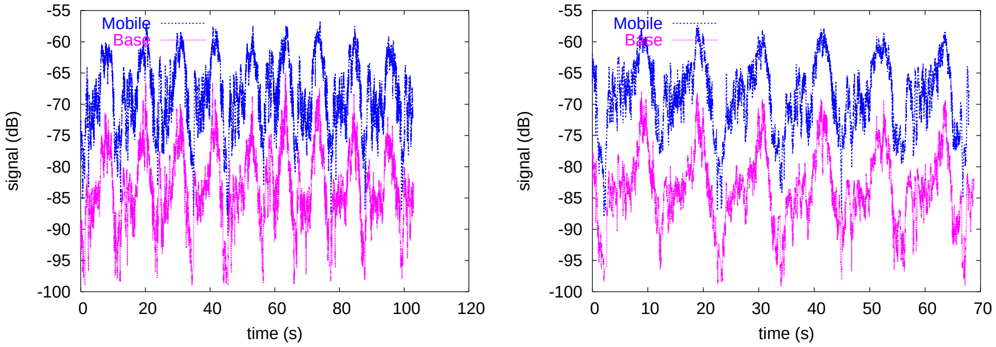


Figure 3.8: Time behaviour of the received signal for all measurement runs of the scenario Stadium1.

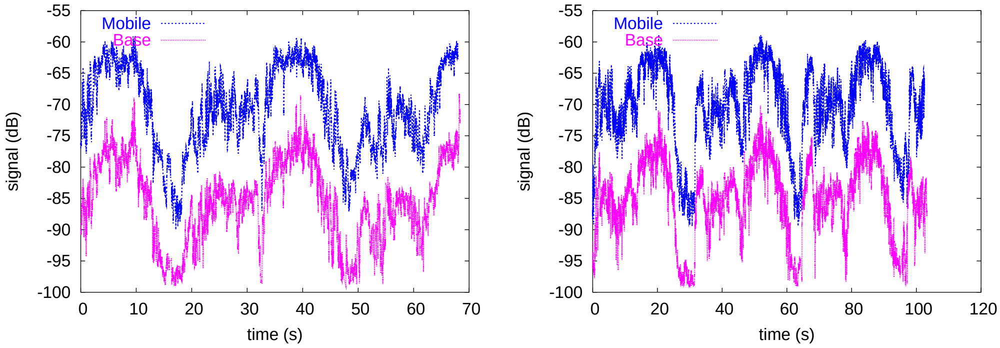


Figure 3.9: Time behaviour of the received signal for all measurement runs of the scenario Stadium2.

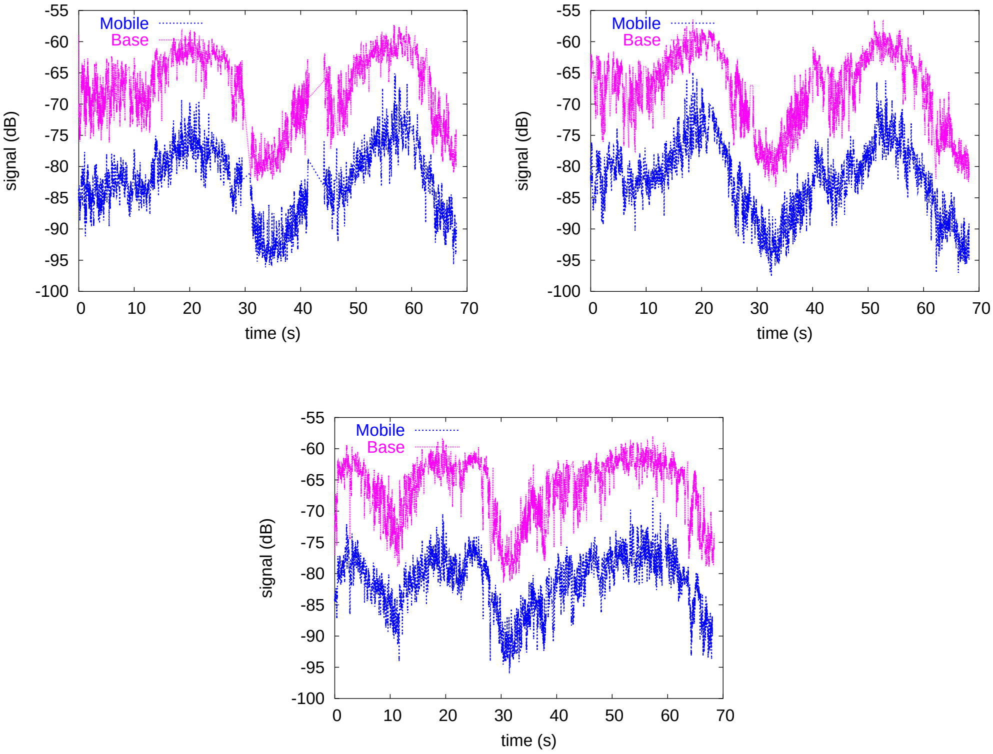


Figure 3.10: Time behaviour of the received signal for all measurement runs of the scenario Walk.

Scenarios Bike and Stadium 1 show faster long term variations than Walk and Stadium2, as can be expected since the Mobile was on a bycicle in the first and moving at pedestrian speed in the latter. In thesw scenarios we can clearly recognise variations of the average received signal caused by shadowing or distance changes between Base and Mobile.

For the Mensa and Maths scenarios, the signal varies very slowly, the signal variations are very small, happen mostly in both directions. We can also see some shadowing, due to people moving between Base and Mobile. The variations for the Mensa environment actually look like white noise. This happens probably because the Mensa is a very big and high room, so that reflected paths are very long (the attenuation is too high and almost no energy from reflected signals is seen at the receiver). For the Maths environment it is not so much so, since there are many more possibilities for reflected and diffracted paths, which also change when people move around (and there is more movement in a foyer than in a canteen), causing the fading pattern.

The variations in both Mensa and Maths environments are due to noise, whereas for the scenarios with cars moving around (Archi and Road) the fast fading can clearly be seen. This is due to cars reflecting waves and thus creating an interference pattern characterised by multi-path and scattering, while people merely can cause shadowing (people absorb waves, they do not reflect them). The scenarios Archi and Road show very similar behaviour, as was expected since they have similar characteristics.

3.2 First Order Statistics

In this section we evaluate first order statistics — average and standard deviation — of the measured received signals over different time intervals. For scenarion Bike there are big variations in the mean and standard deviation values over 1 s due to the many missing values. In Figures 3.17 to 3.19 the shadowing/pathloss for the Stadium scenarios can be clearly seen in the big variations of the average value.

Otherwise, the mean value of the channel samples over 1 s periods do not differ much from the mean value of the sample over the whole measurement run.

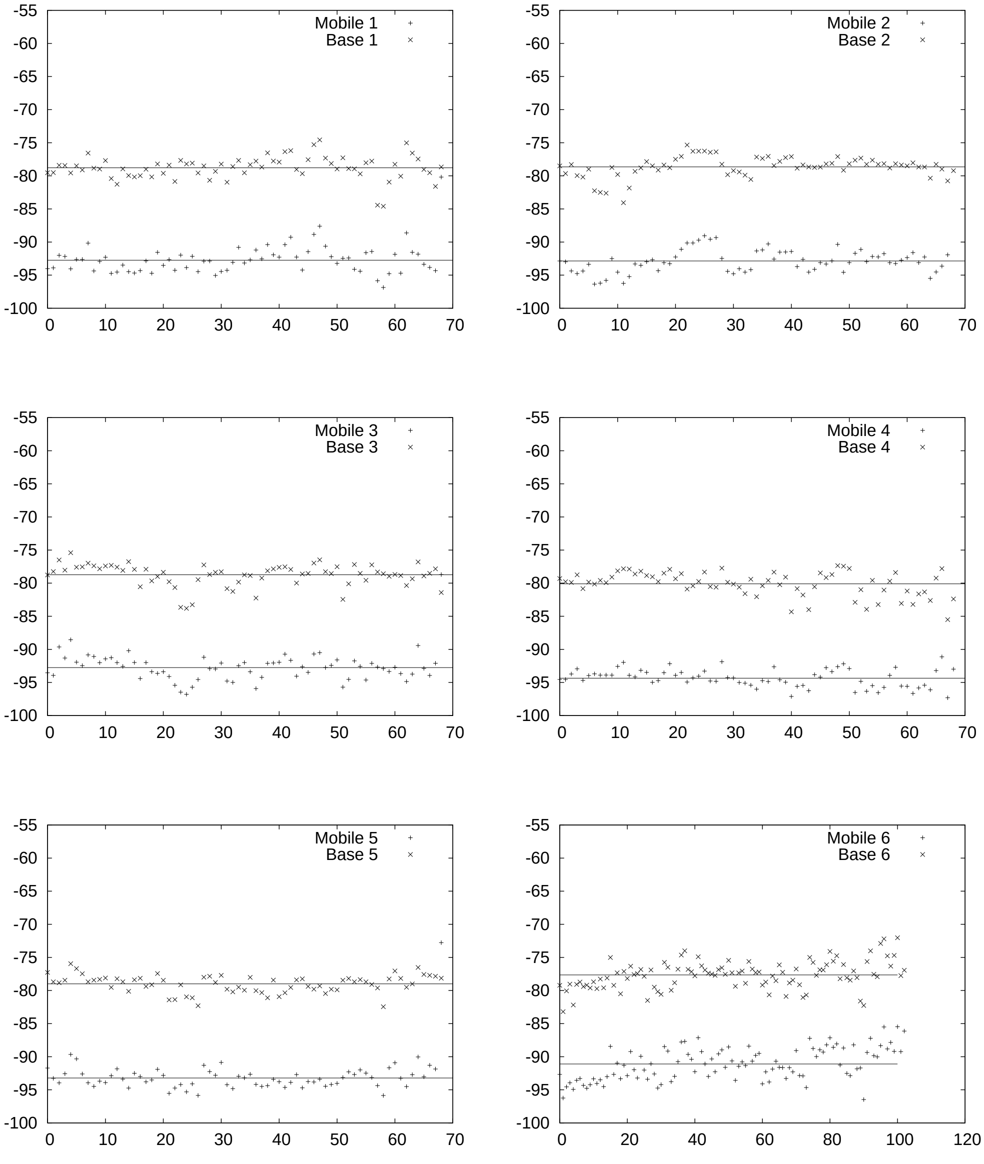


Figure 3.11: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Archi (straight lines are the mean values over the whole run).

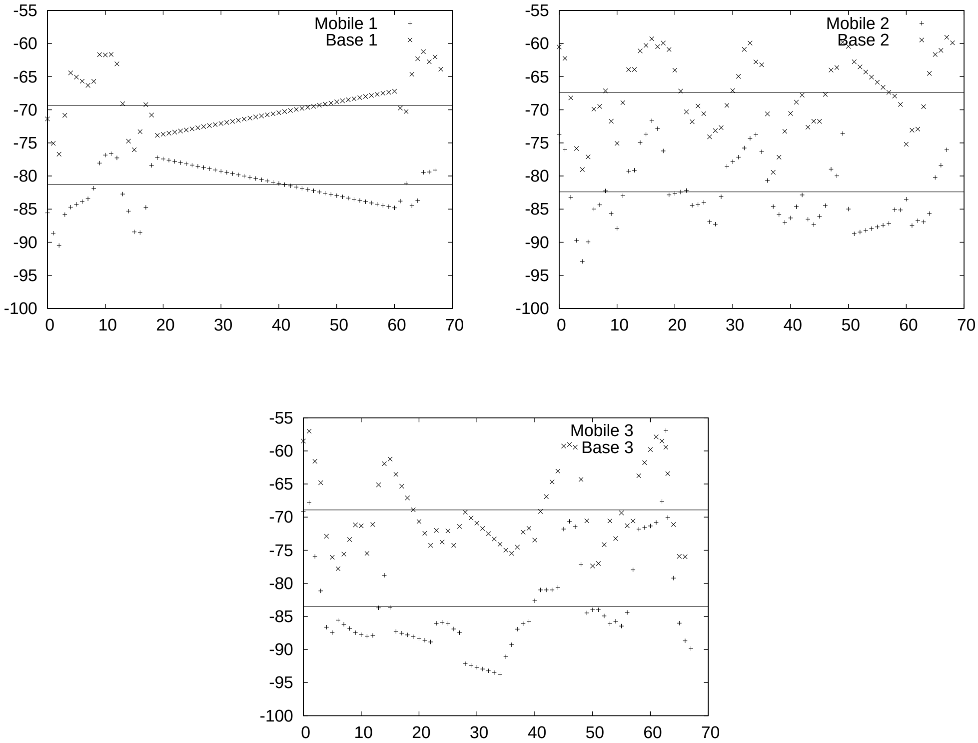


Figure 3.12: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Bike (straight lines are the mean values over the whole run).

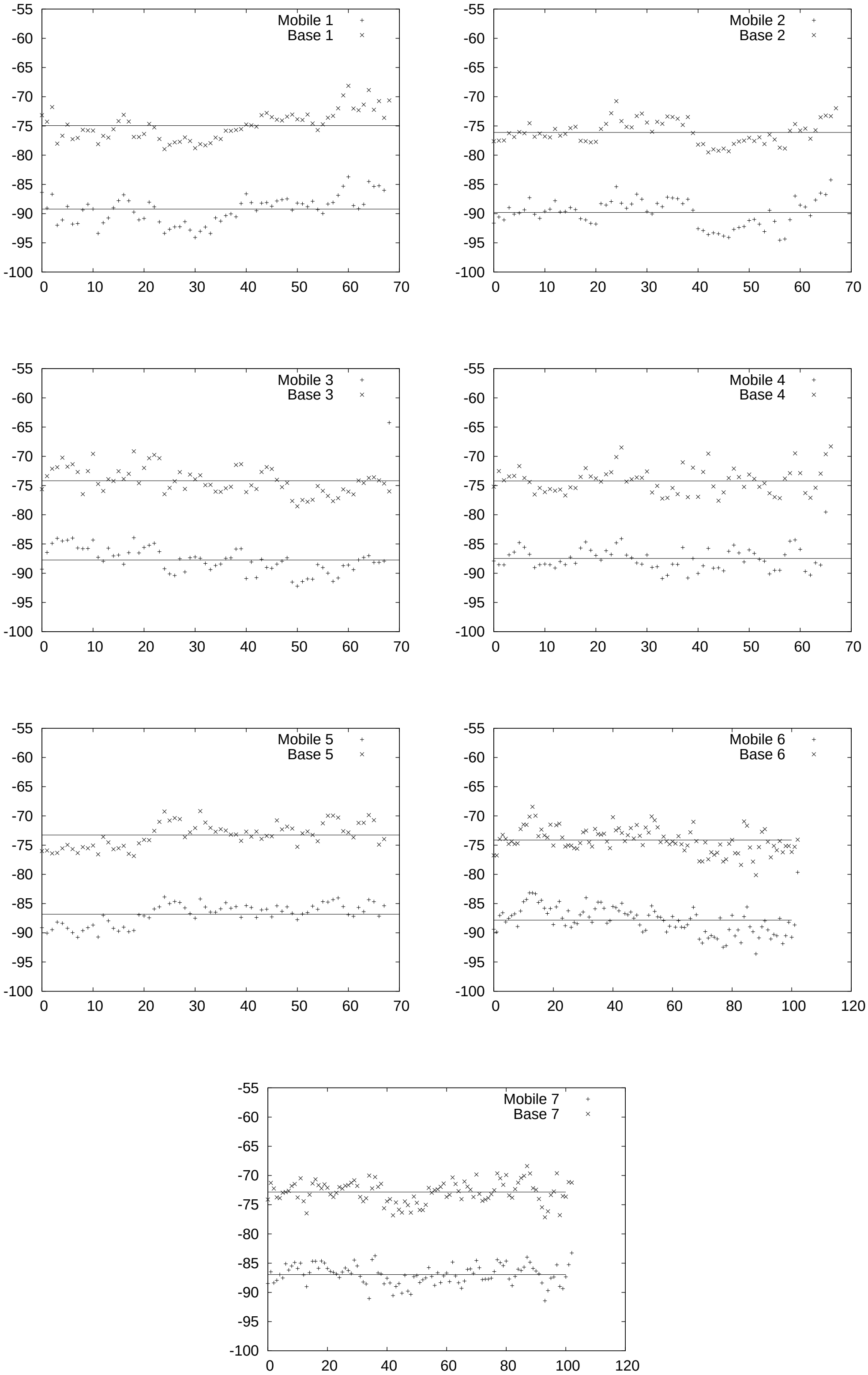


Figure 3.13: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Carpark (straight lines are the mean values over the whole run).

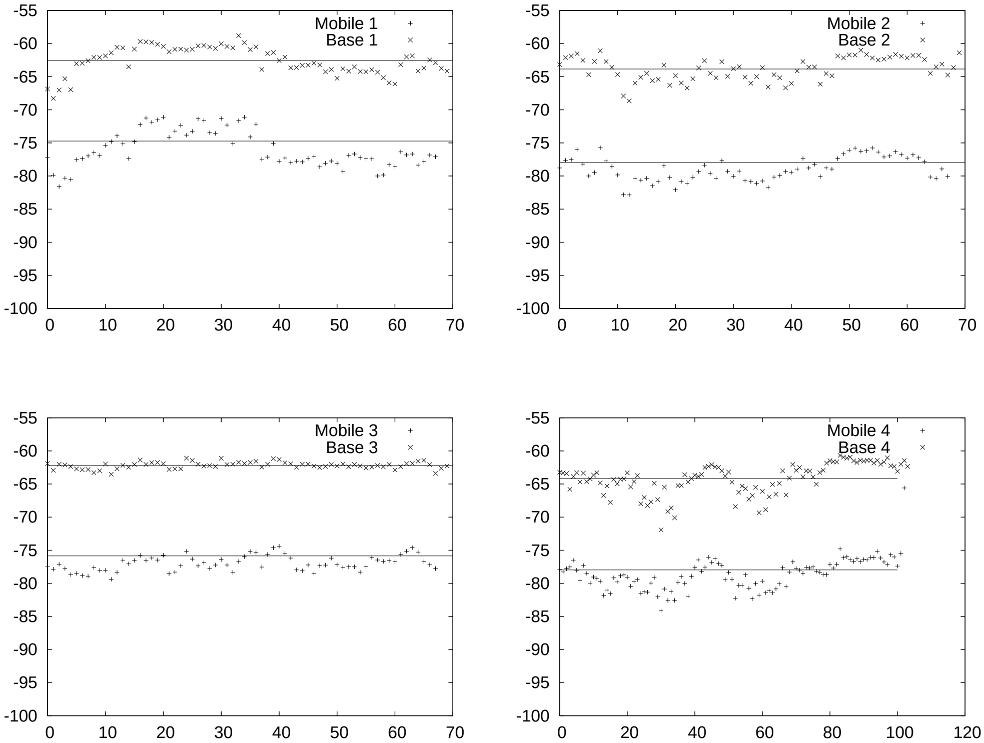


Figure 3.14: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Maths (straight lines are the mean values over the whole run).

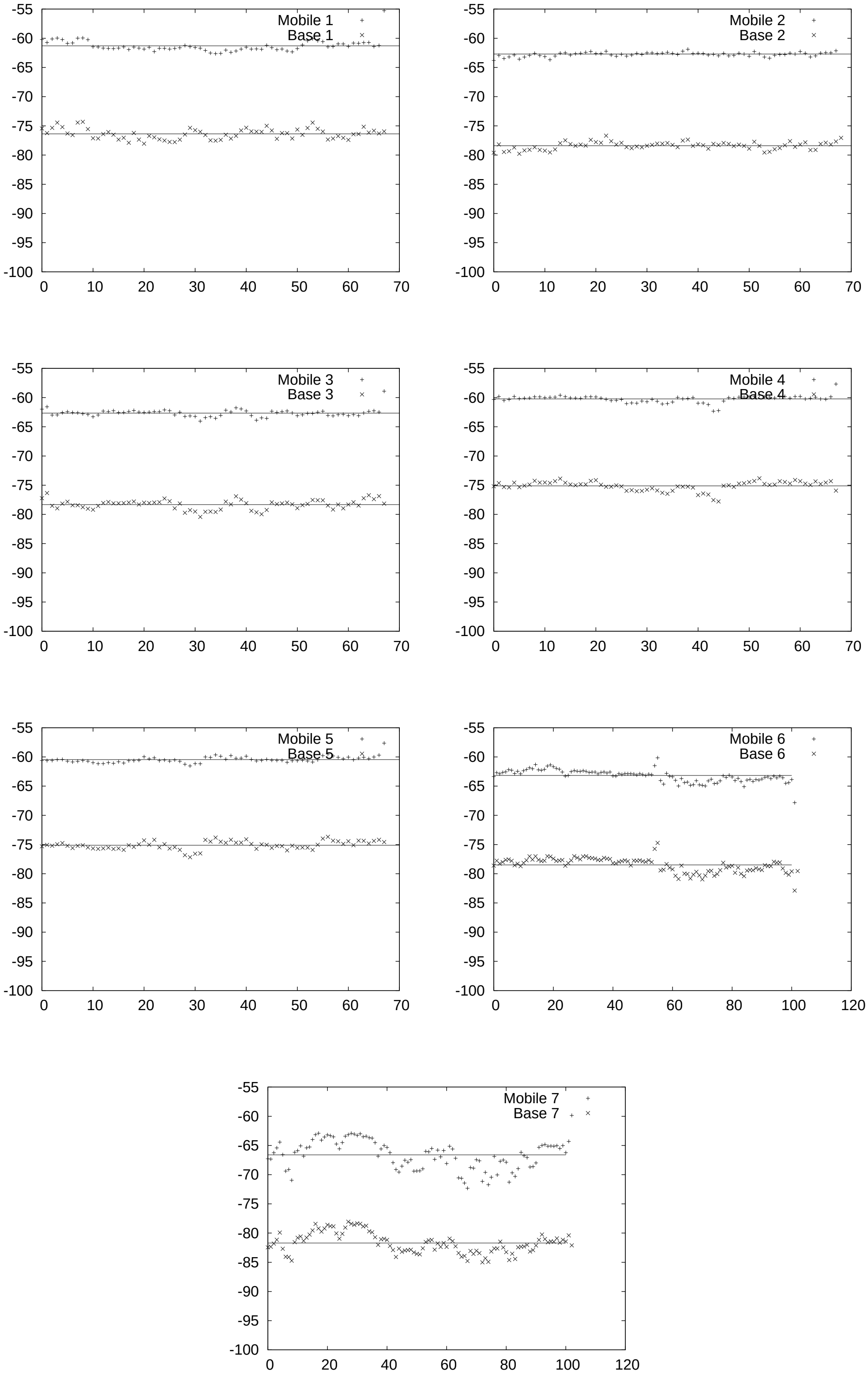


Figure 3.15: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Mensa (straight lines are the mean values over the whole run).

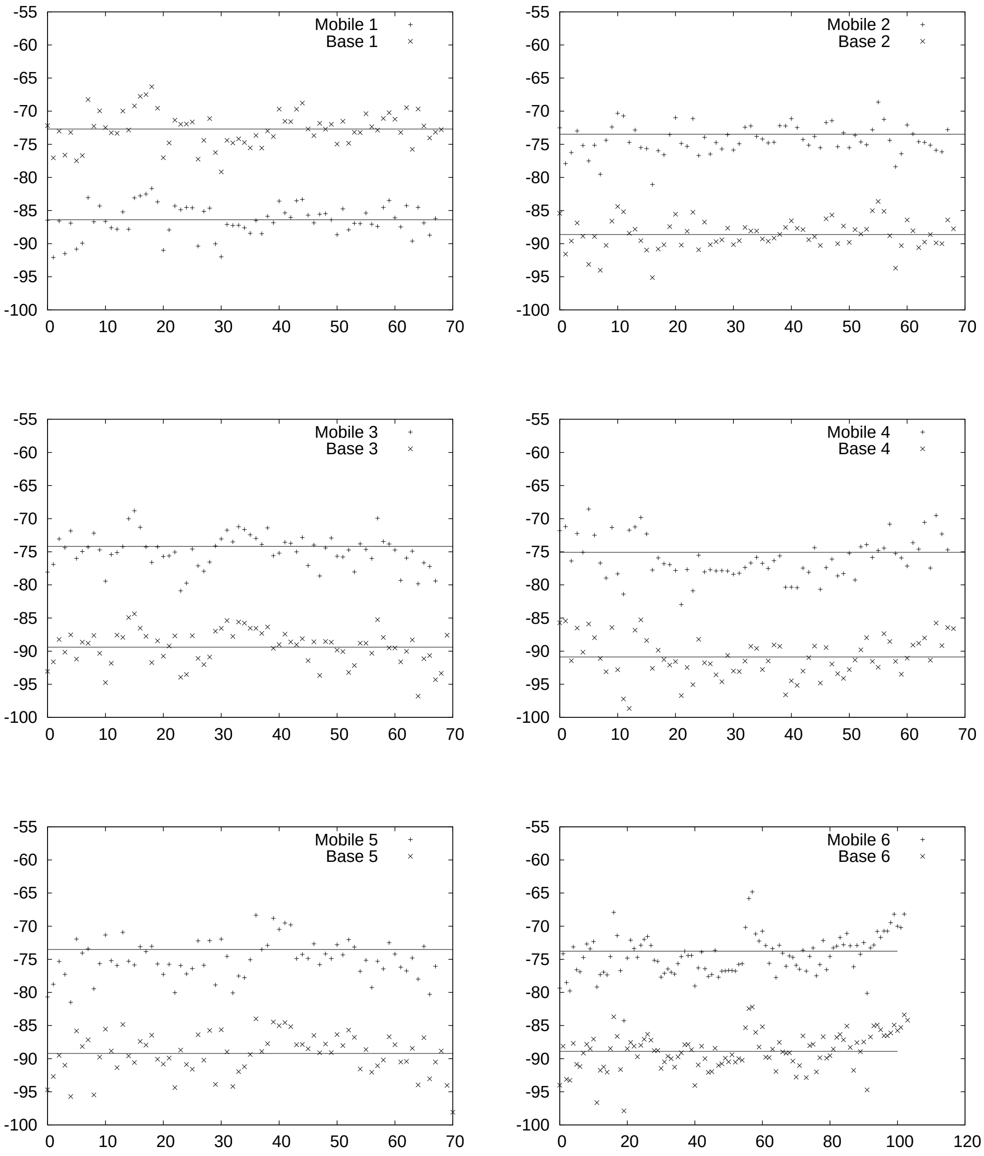


Figure 3.16: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Road (straight lines are the mean values over the whole run).

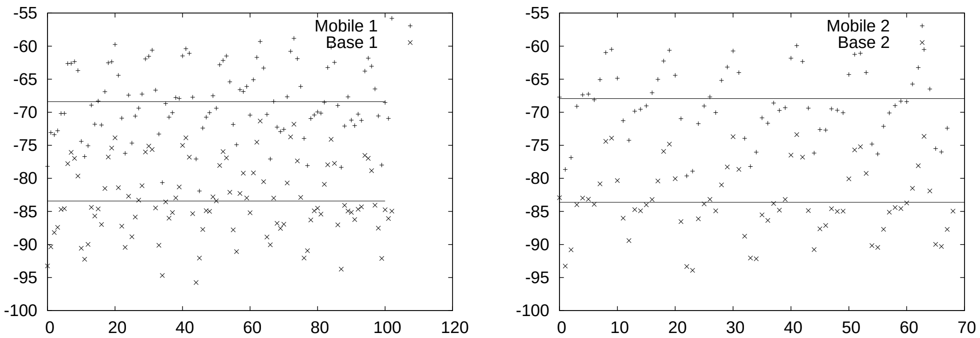


Figure 3.17: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Stadium1 (straight lines are the mean values over the whole run).

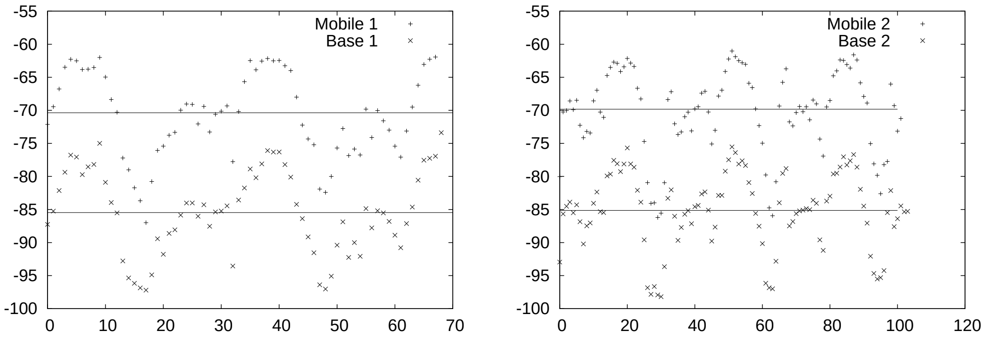


Figure 3.18: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Stadium2 (straight lines are the mean values over the whole run).

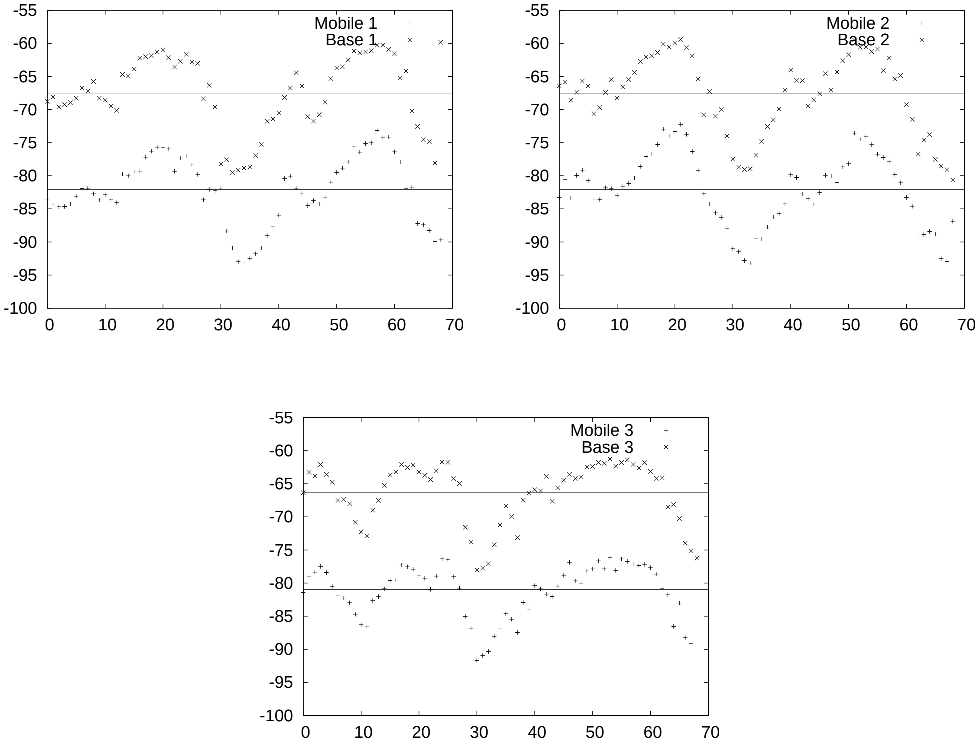


Figure 3.19: Mean value of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Walk (straight lines are the mean values over the whole run).

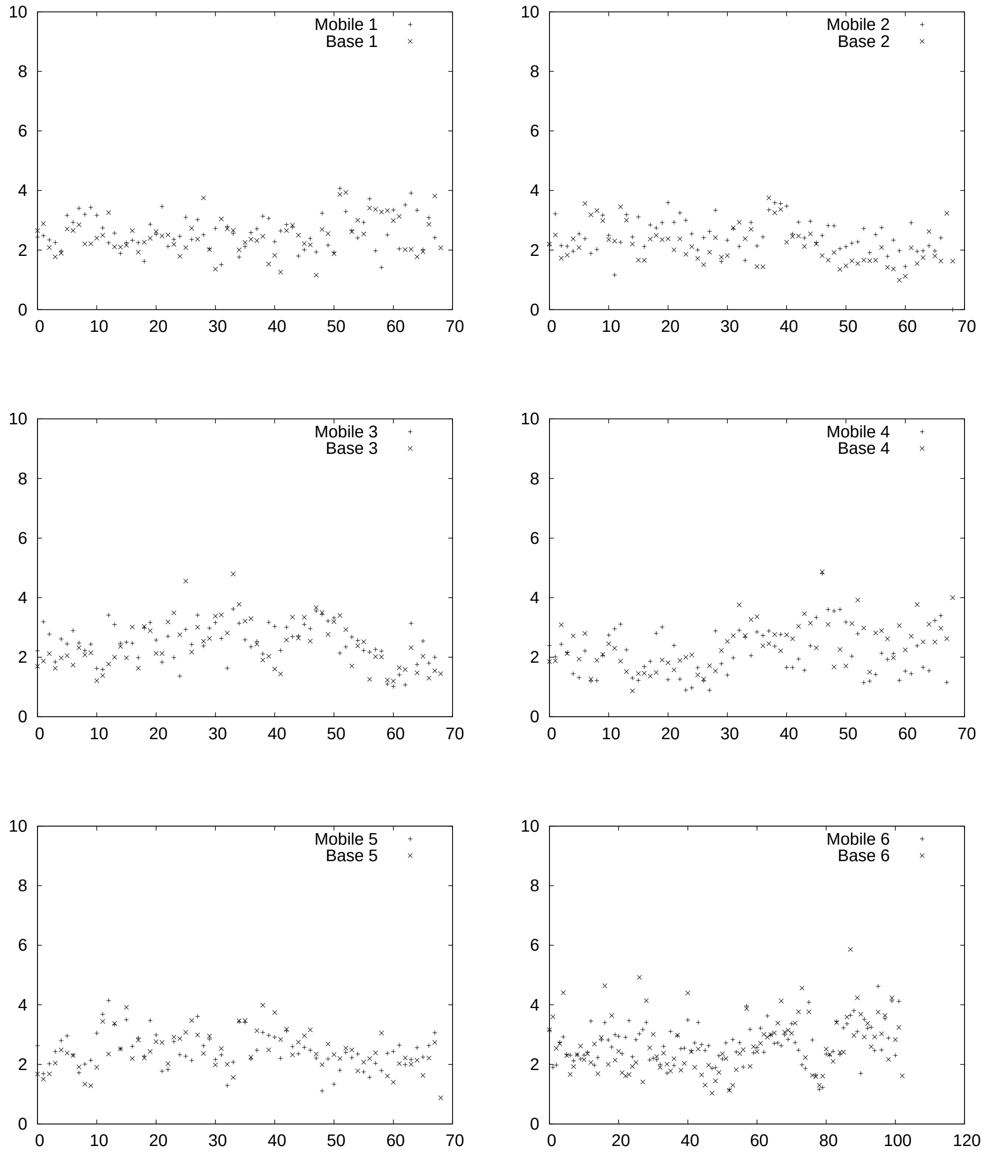


Figure 3.20: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Archi (straight lines are the mean values over the whole run).

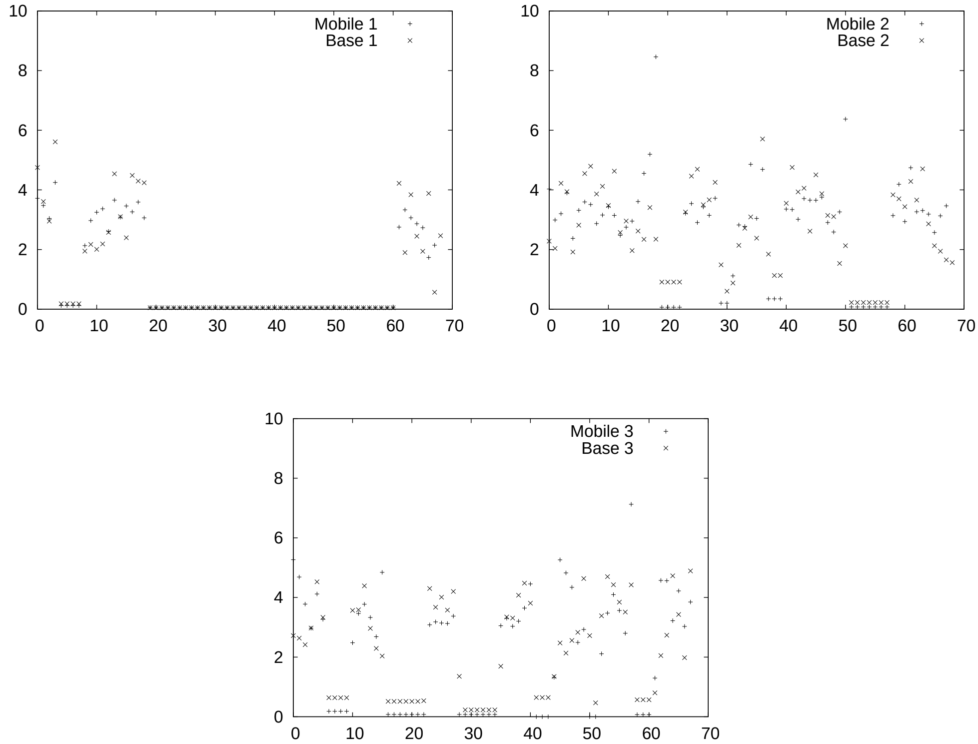


Figure 3.21: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Bike (straight lines are the mean values over the whole run).

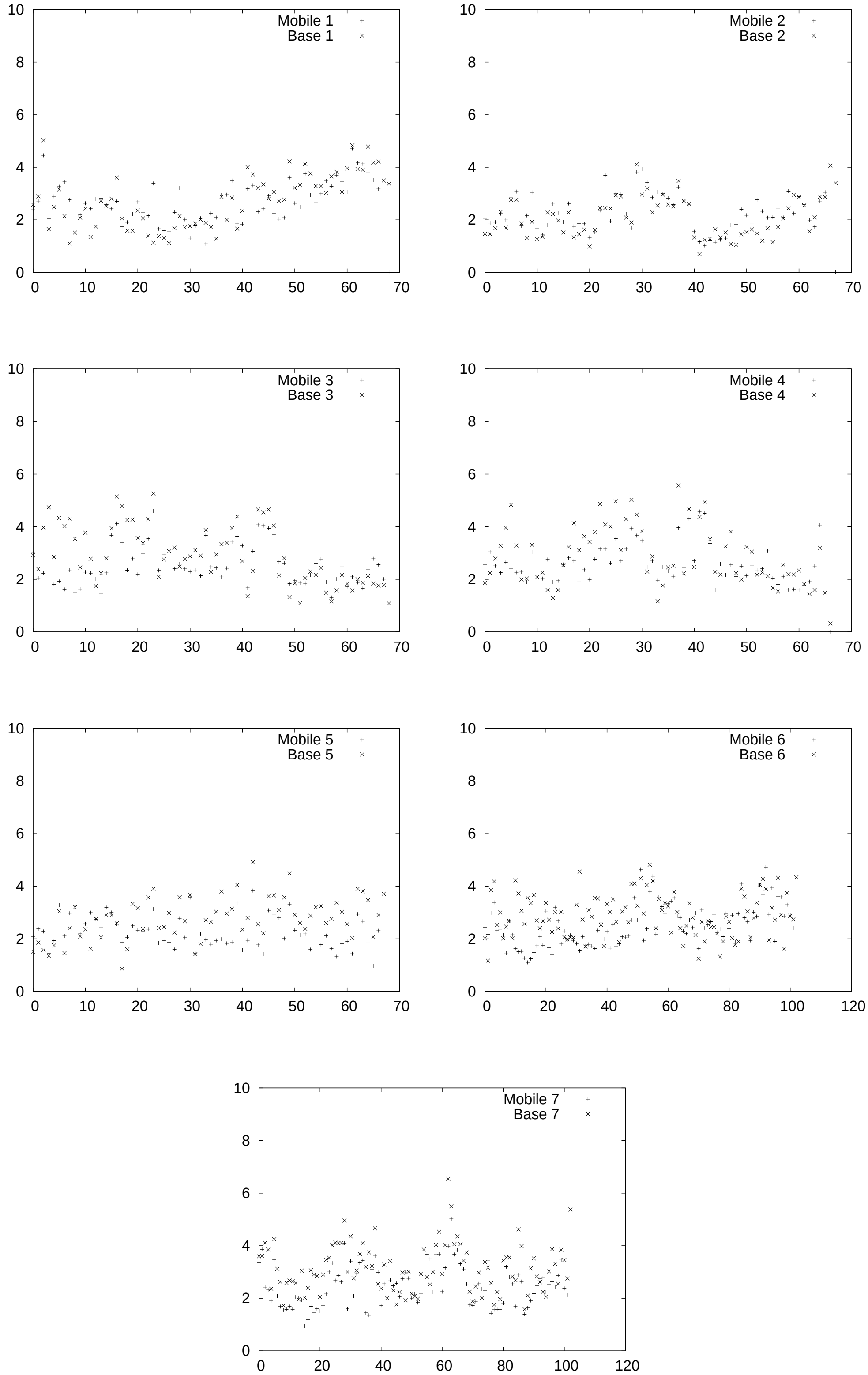


Figure 3.22: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Carpark (straight lines are the mean values over the whole run).

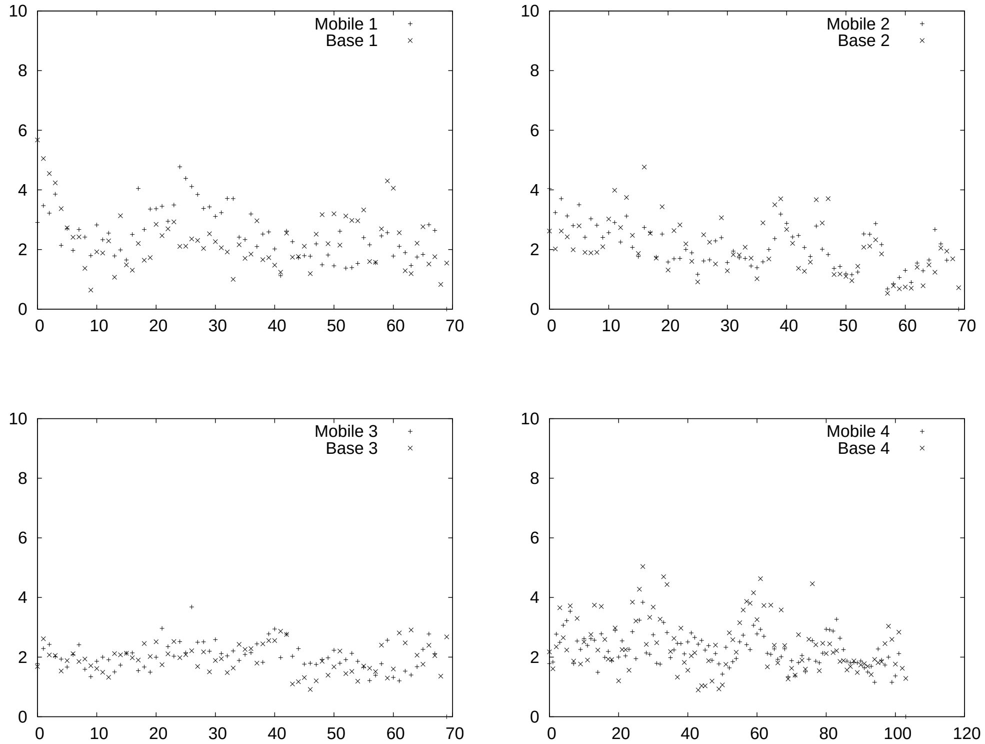


Figure 3.23: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Maths (straight lines are the mean values over the whole run).

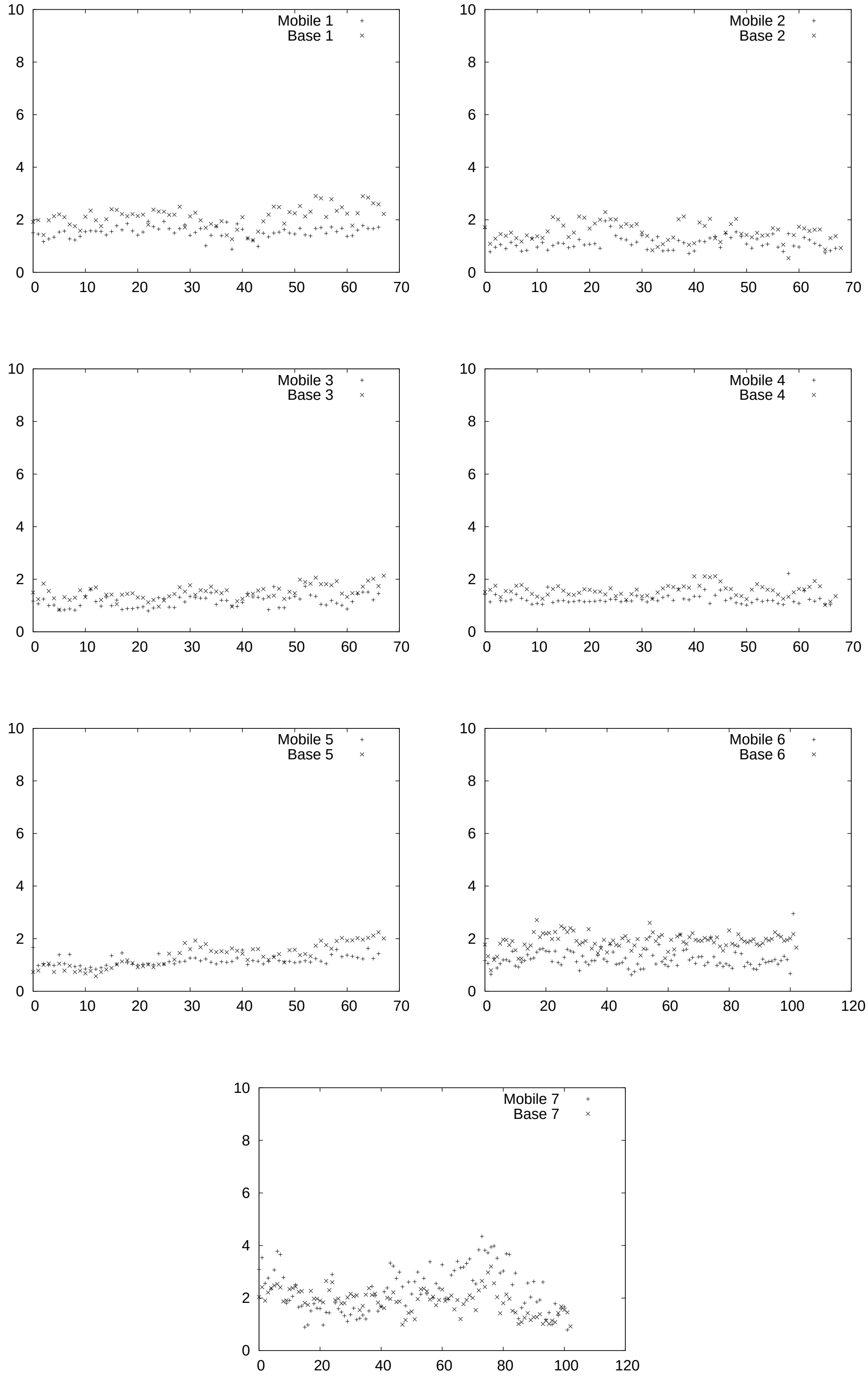


Figure 3.24: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Mensa (straight lines are the mean values over the whole run).

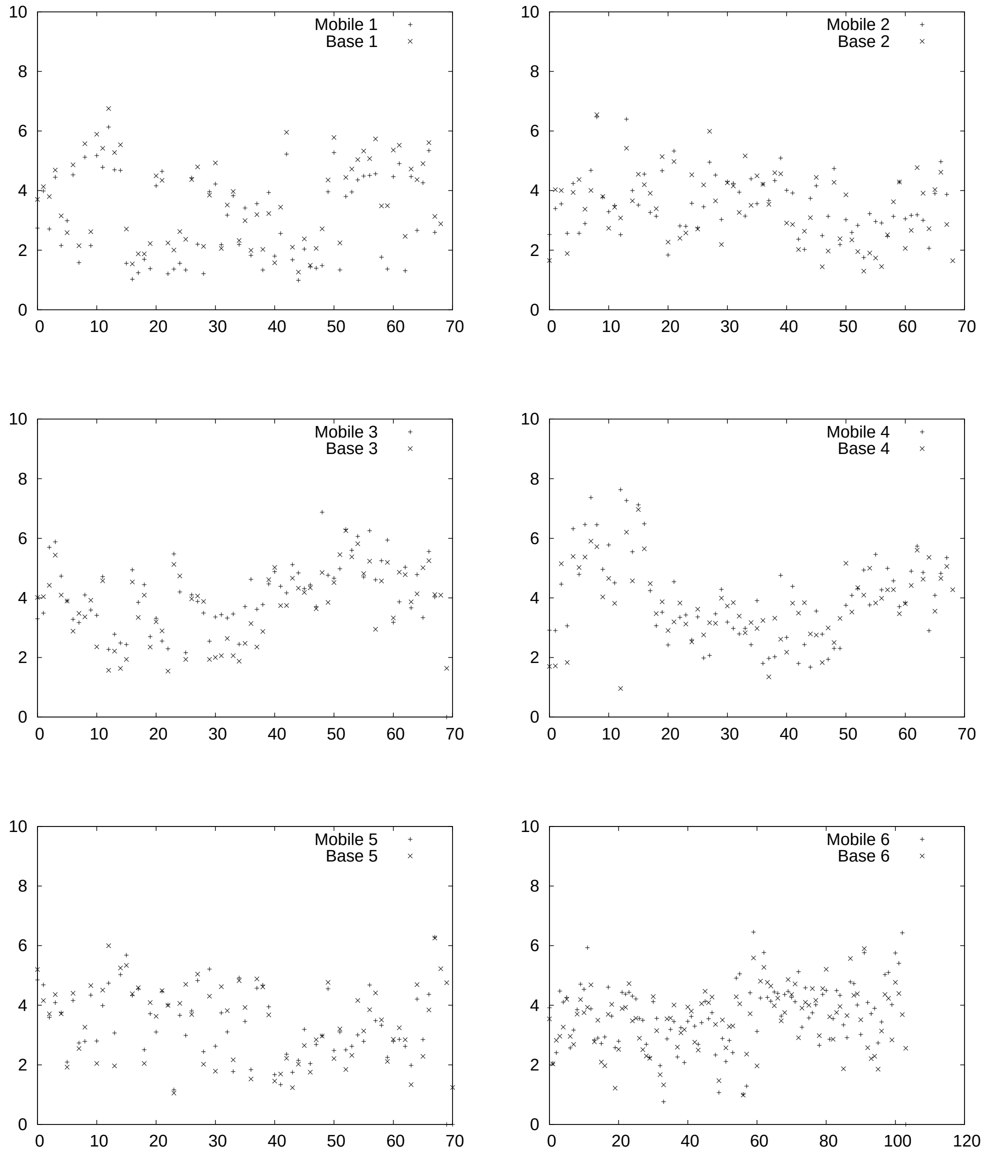


Figure 3.25: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Road (straight lines are the mean values over the whole run).

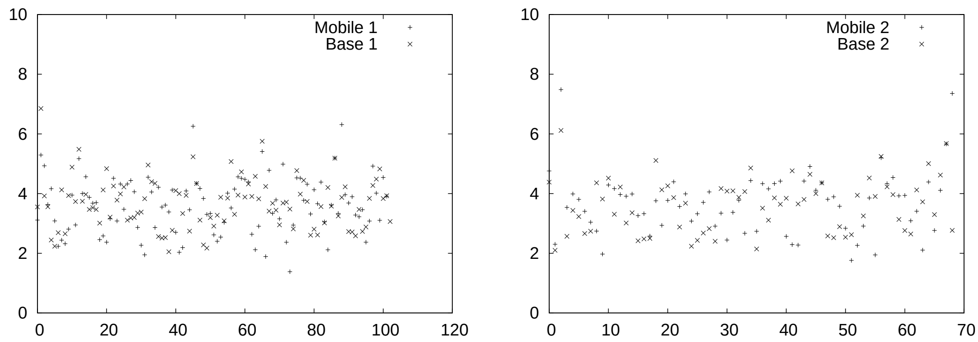


Figure 3.26: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Stadium1 (straight lines are the mean values over the whole run).

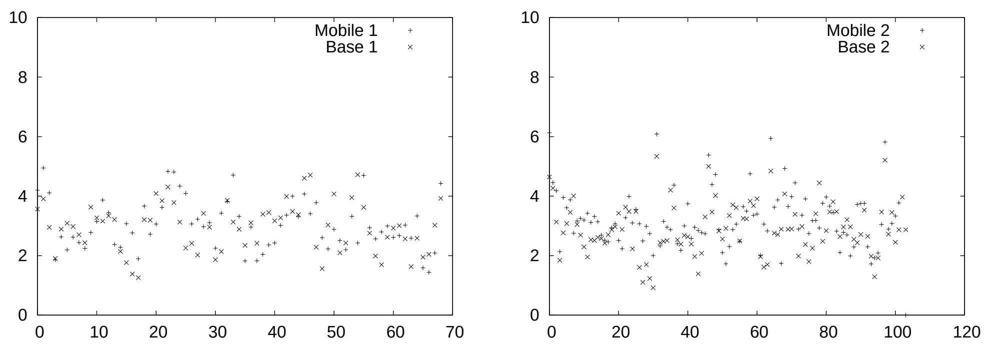


Figure 3.27: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Stadium2 (straight lines are the mean values over the whole run).

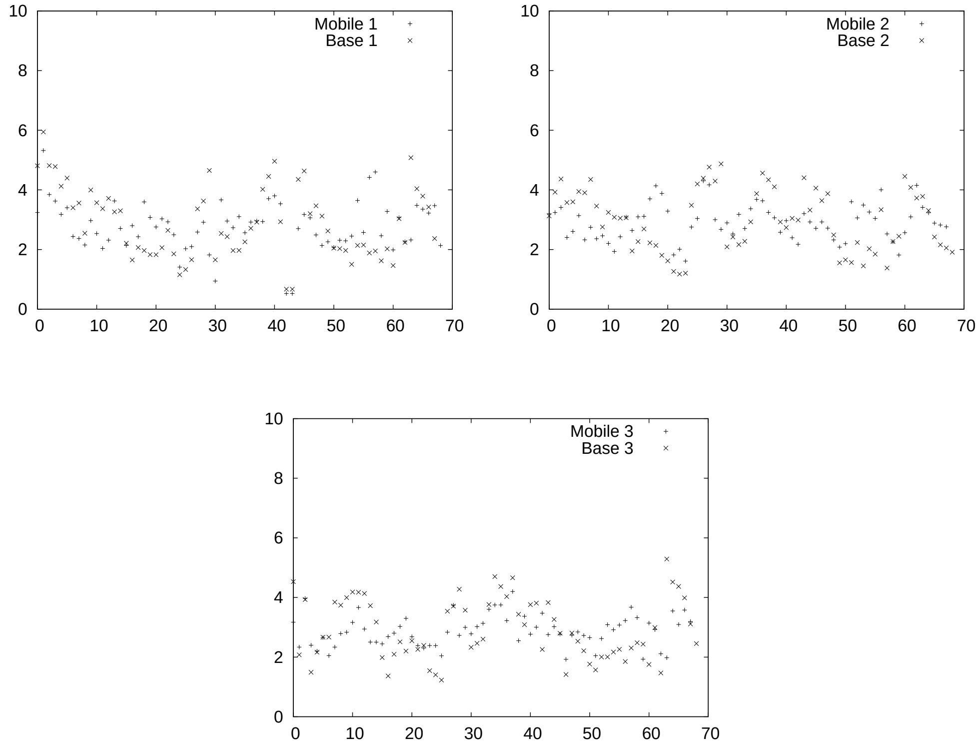


Figure 3.28: Standard deviation of the received signal over 1000 samples (1 s) for all measurement runs of the scenario Walk (straight lines are the mean values over the whole run).

3.3 Histograms of Received Signal

The histograms of the received signal values were calculated dividing the interval between minimum and maximum value measured into 1000 bins. In Figures 3.29 to 3.37 we plotted the histogram of the received signal at Base and Mobile for each measurement run in every scenario.

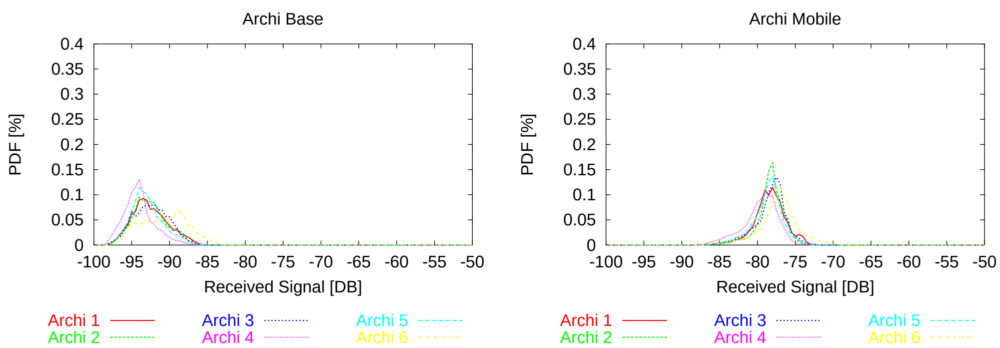


Figure 3.29: Histogram of the received signal for scenario Archi.

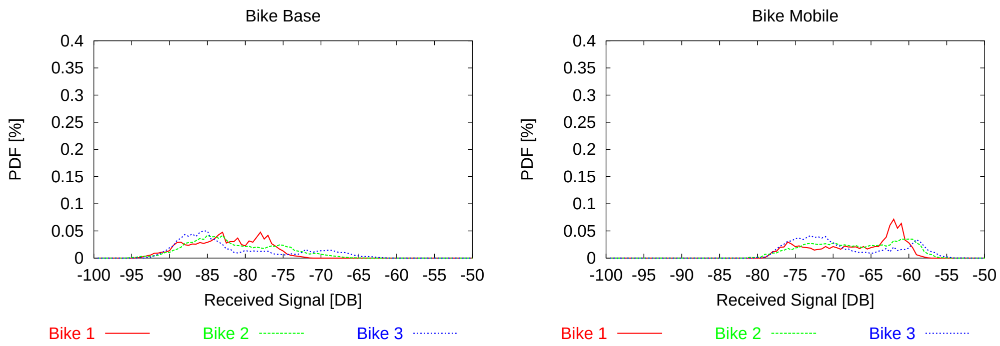


Figure 3.30: Histogram of the received signal for scenario Bike.

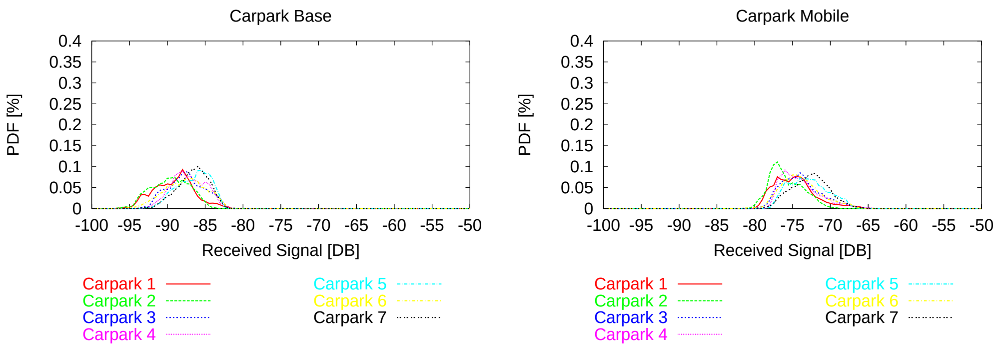


Figure 3.31: Histogram of the received signal for scenario Carpark.

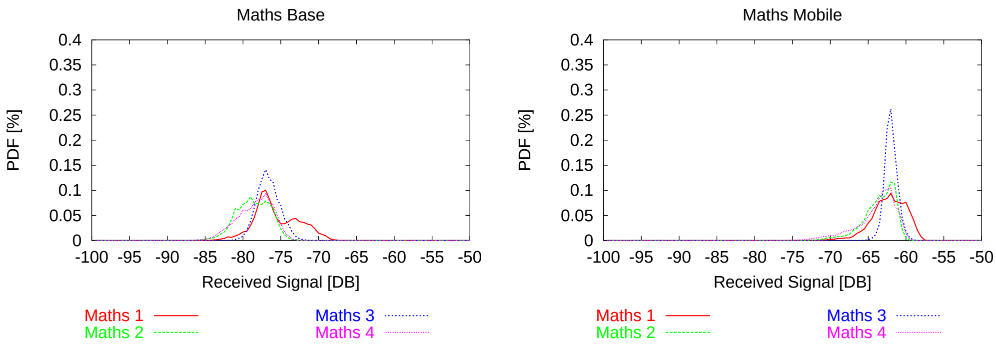


Figure 3.32: Histogram of the received signal for scenario Maths.

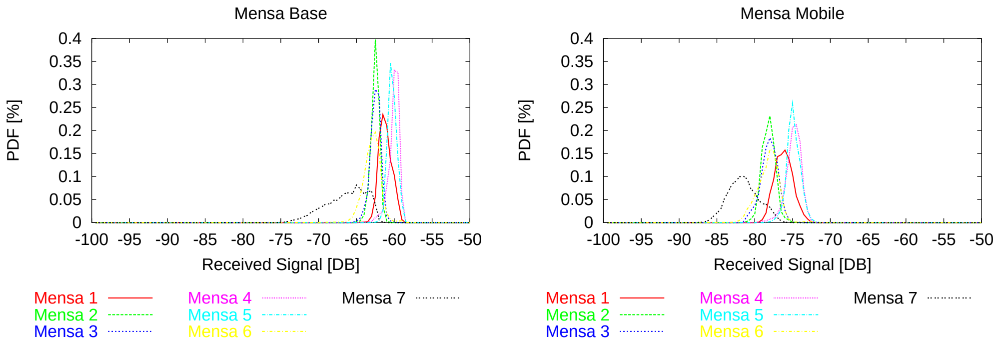


Figure 3.33: Histogram of the received signal for scenario Mensa.

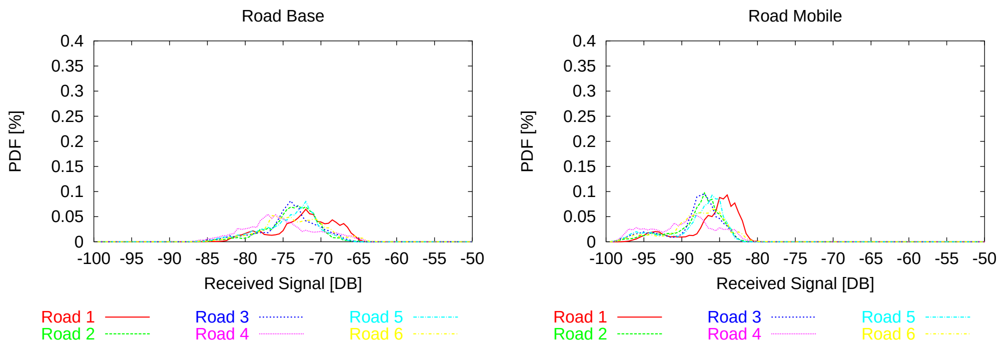


Figure 3.34: Histogram of the received signal for scenario Road.

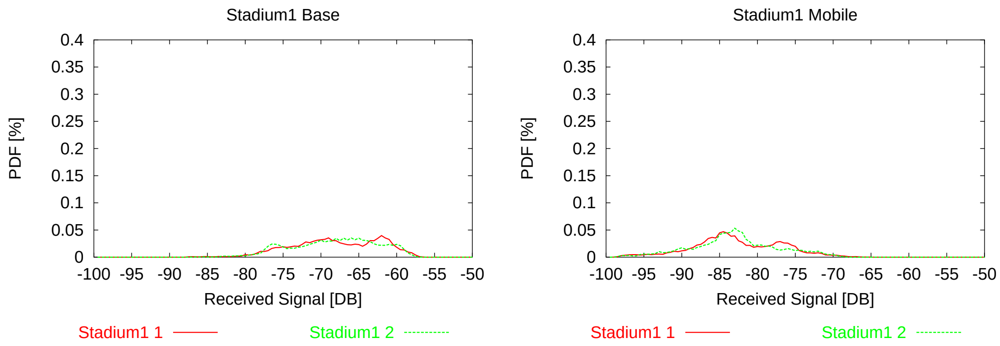


Figure 3.35: Histogram of the received signal for scenario Stadium 1.

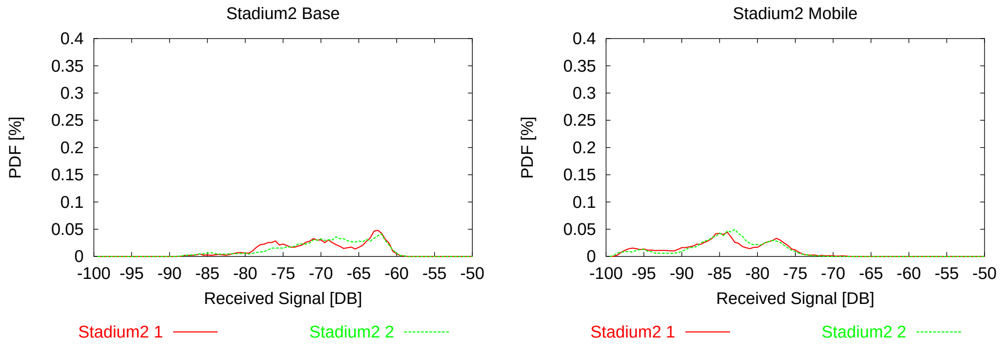


Figure 3.36: Histogram of the received signal for scenario Stadium 2.

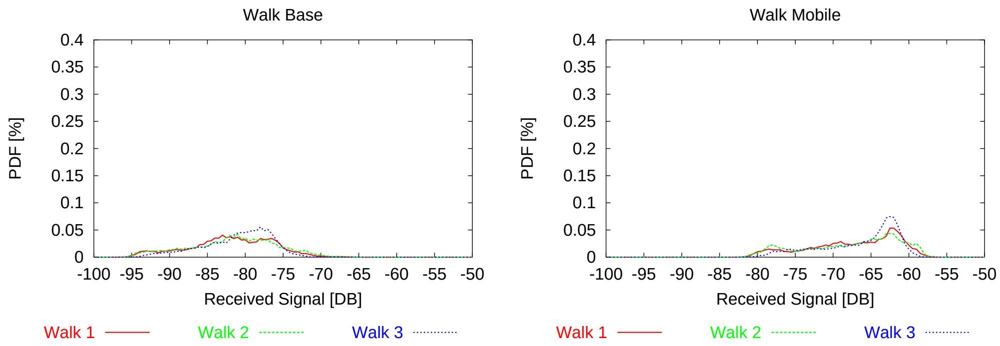


Figure 3.37: Histogram of the received signal for scenario Walk.

3.4 Fast Fourier Transform (FFT)

In this section we show the FFTs of the equidistant measured data before and after the time domain noise filtering.

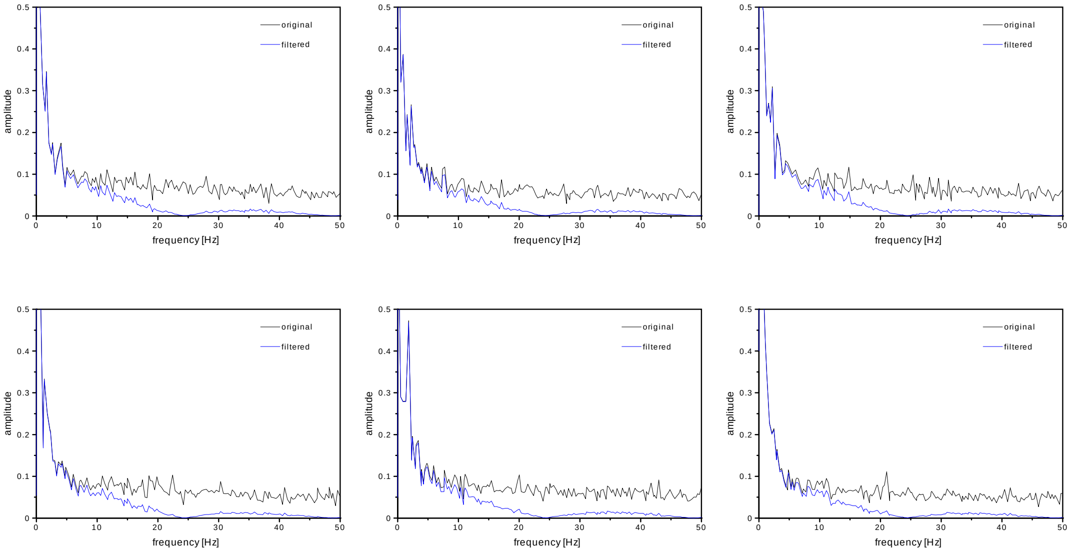


Figure 3.38: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Archi.

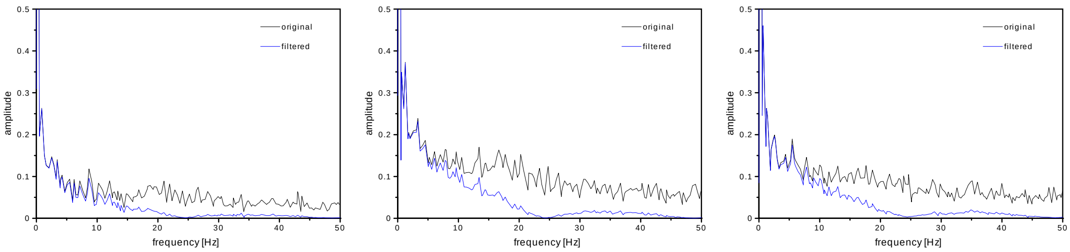


Figure 3.39: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Bike.

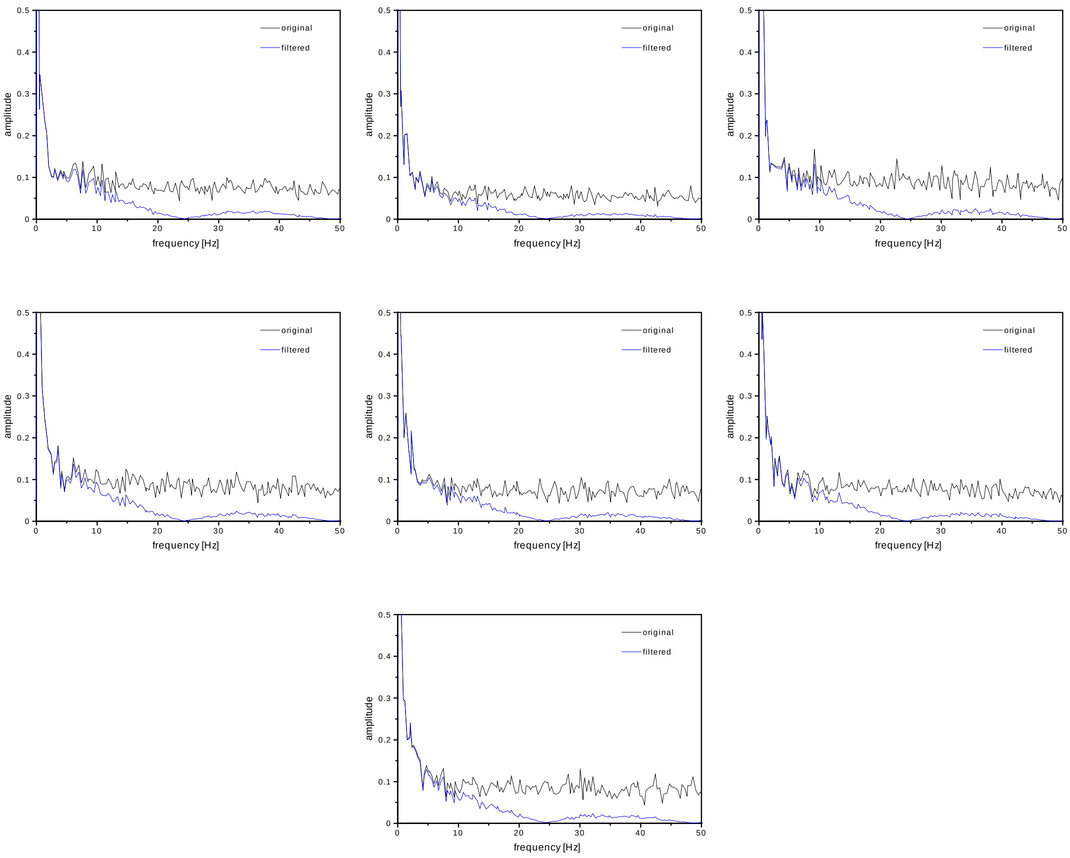


Figure 3.40: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Carpark.

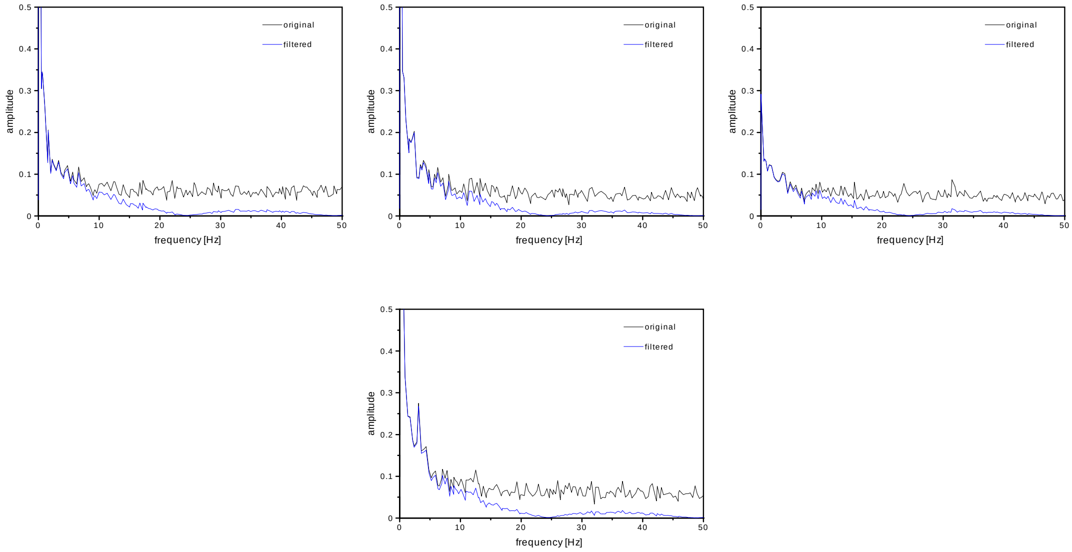


Figure 3.41: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Maths.

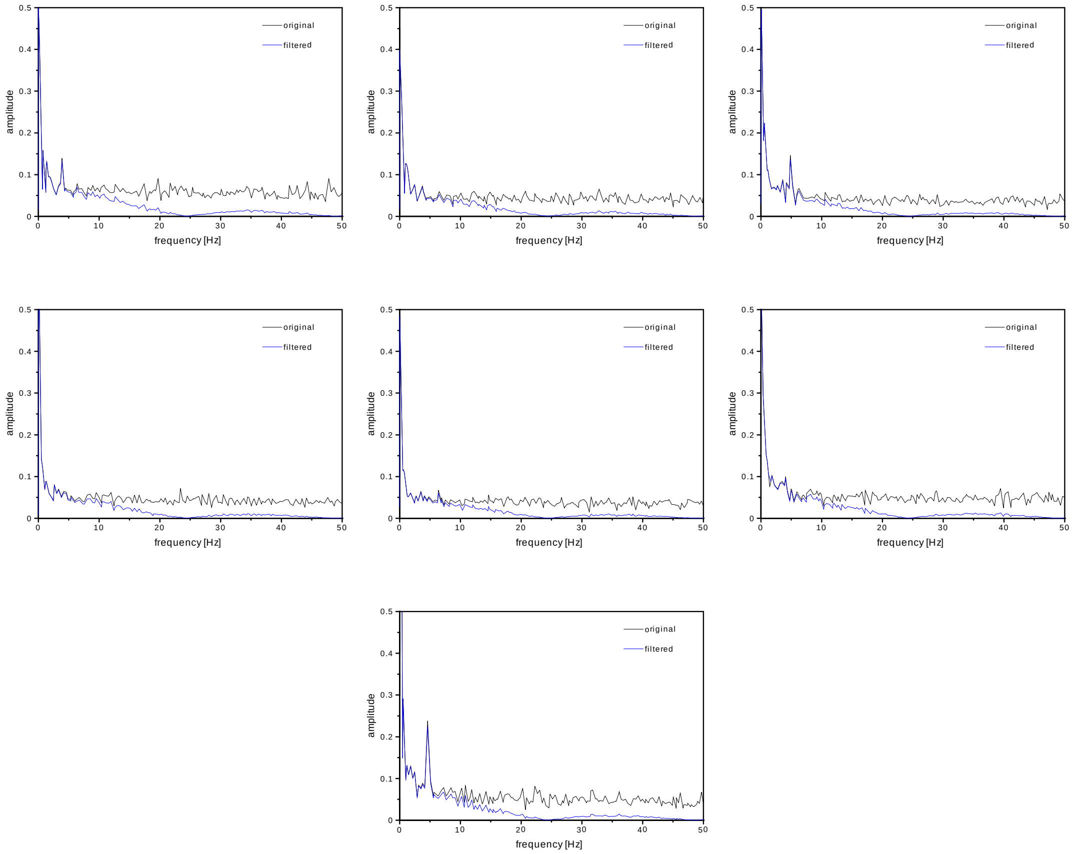


Figure 3.42: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Mensa.

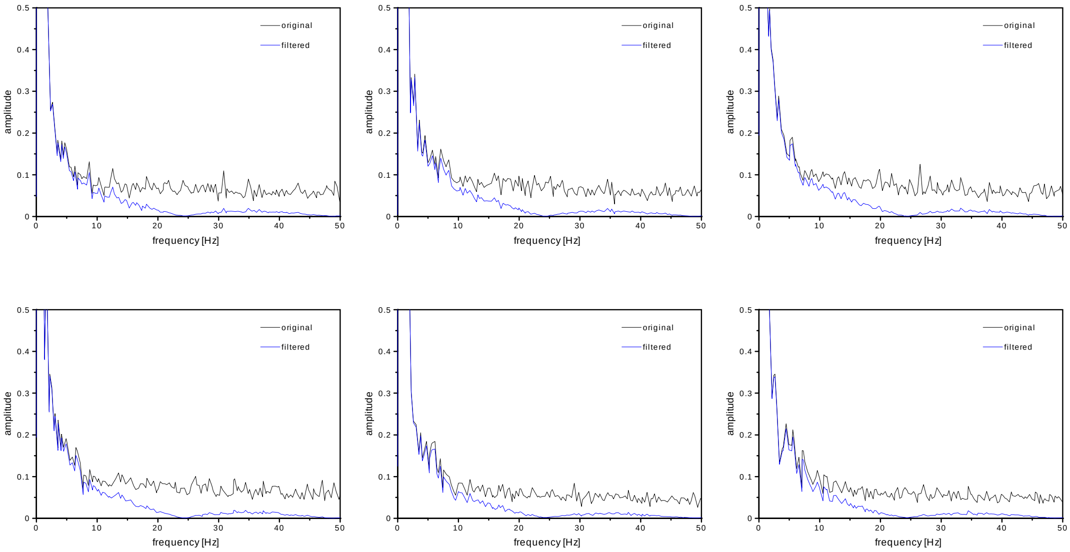


Figure 3.43: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Road.

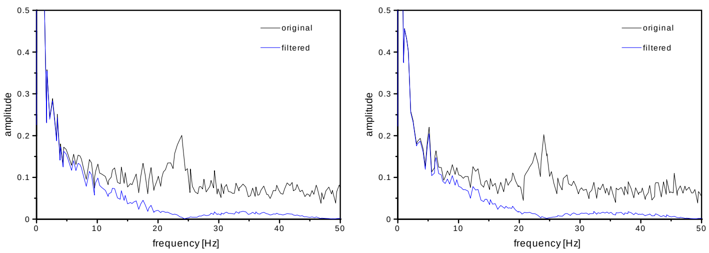


Figure 3.44: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Stadium1.

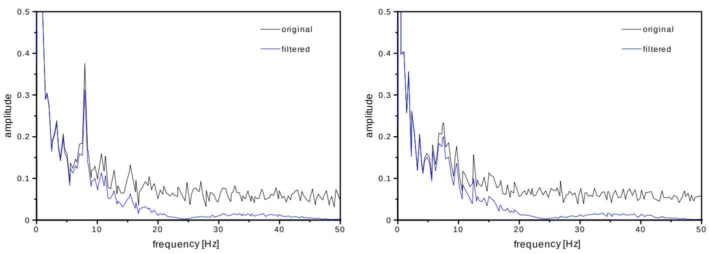


Figure 3.45: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Stadium2.

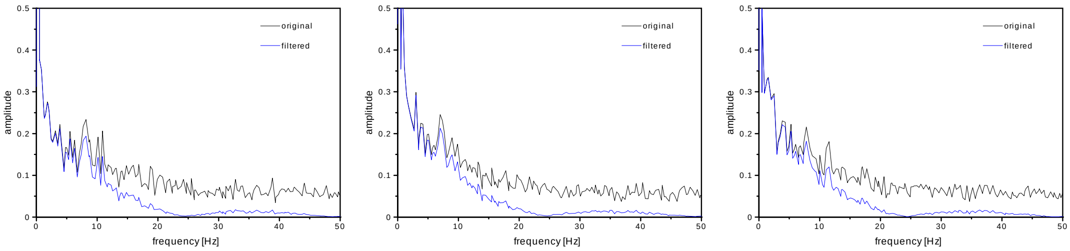
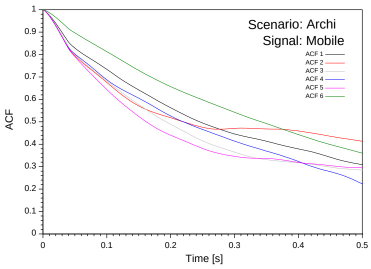


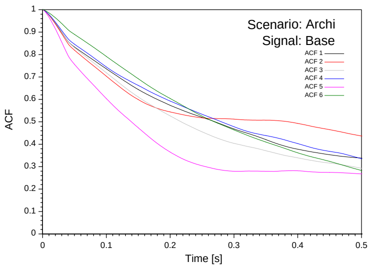
Figure 3.46: FFT of the received signal before and after time domain filtering for all measurement runs of the scenario Walk.

3.5 Autocorrelation

In this section the autocorrelation functions of all scenarios are shown for both the Base and the Mobile. The different dynamic of the channels is clearly visible, e. g., the slower fading scenario Walk (Figure 3.55) has a much slower decreasing auto-correlation function than the scenario Road (Figure 3.52).

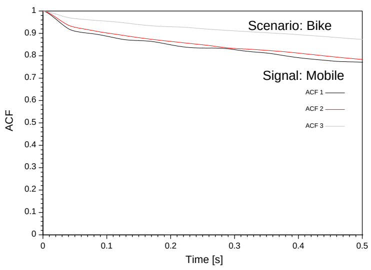


(a) Mobile

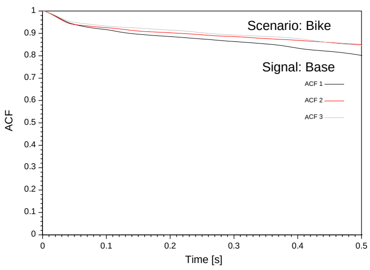


(b) Base

Figure 3.47: Autocorrelation function of Archi

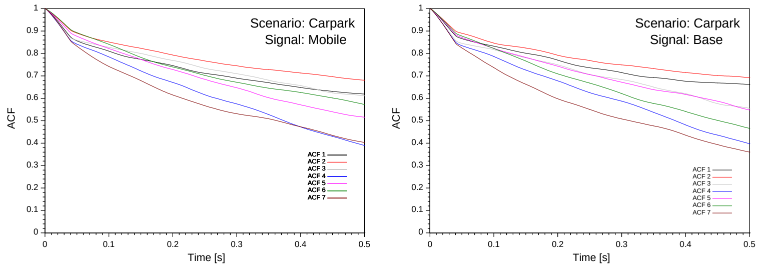


(a) Mobile



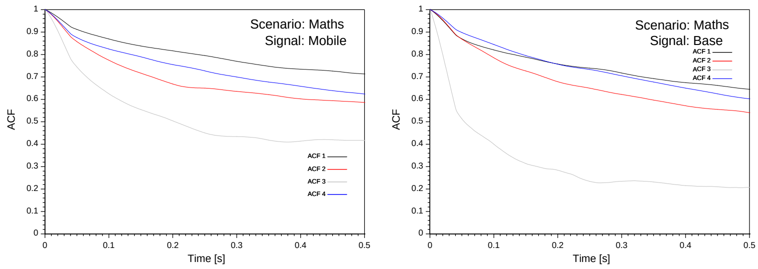
(b) Base

Figure 3.48: Autocorrelation function of Bike



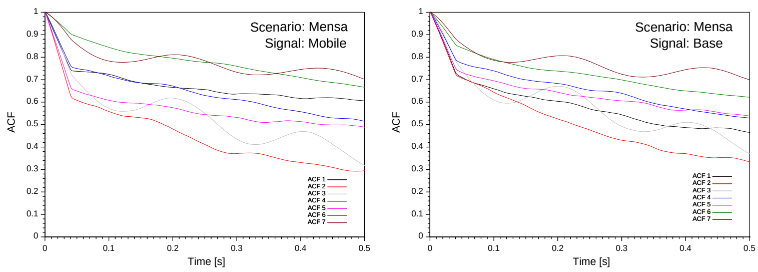
(a) Mobile (b) Base

Figure 3.49: Autocorrelation function of Carpark



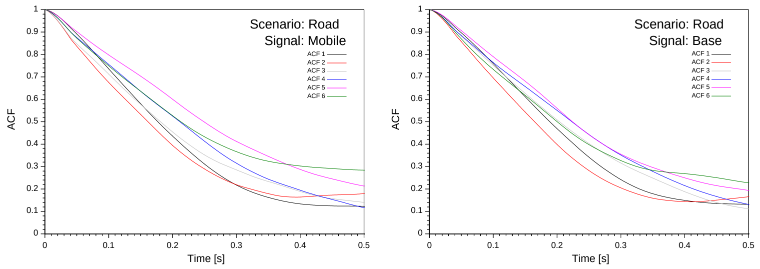
(a) Mobile (b) Base

Figure 3.50: Autocorrelation function of Maths



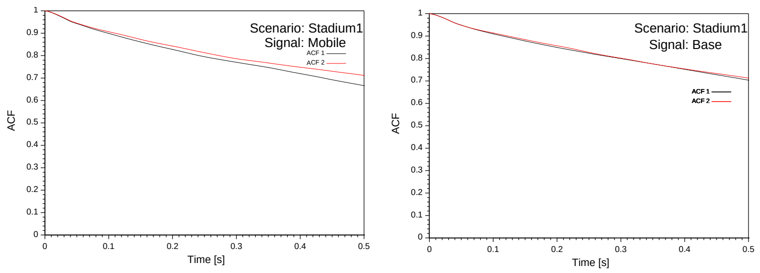
(a) Mobile (b) Base

Figure 3.51: Autocorrelation function of Mensa



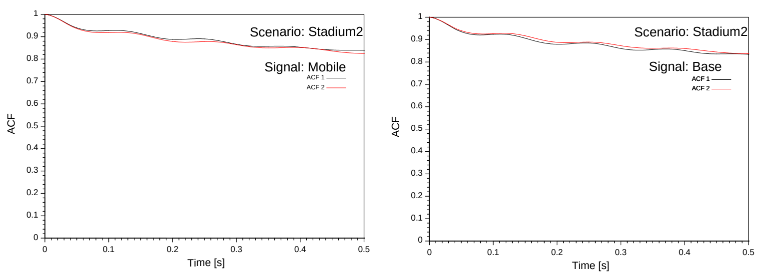
(a) Mobile (b) Base

Figure 3.52: Autocorrelation function of Road



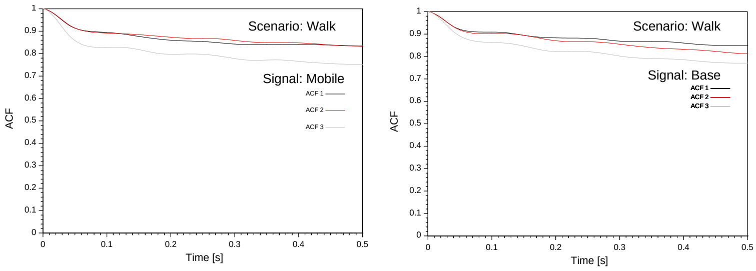
(a) Mobile (b) Base

Figure 3.53: Autocorrelation function of Stadium1



(a) Mobile (b) Base

Figure 3.54: Autocorrelation function of Stadium2



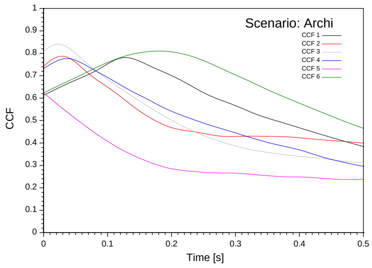
(a) Mobile

(b) Base

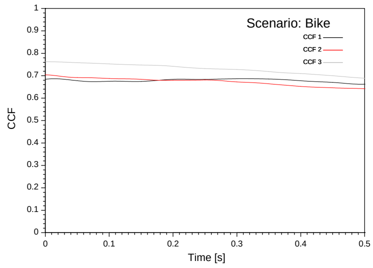
Figure 3.55: Autocorrelation function of Walk

3.6 Cross-correlation

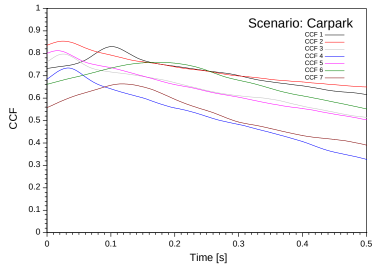
In this section we show the results of the cross-correlation analysis between the received signal at the Mobile and Base. From these results we expect to conclude about the reciprocity of the channel, i. e., whether it really behaves similarly in both directions. Figure 3.56 shows the cross-correlation functions of all measured scenarios.



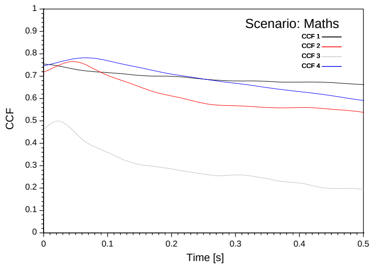
(a) Archi



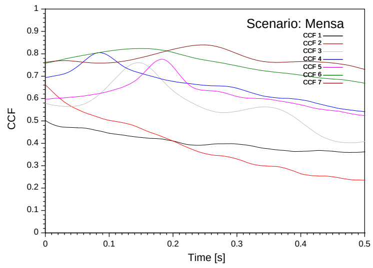
(b) Bike



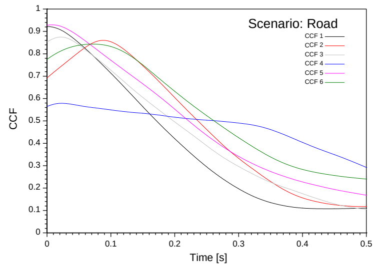
(c) Carpark



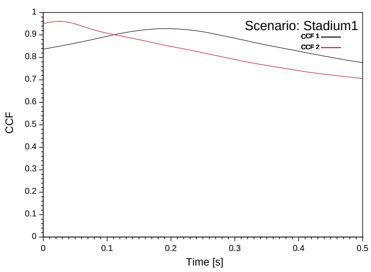
(d) Maths



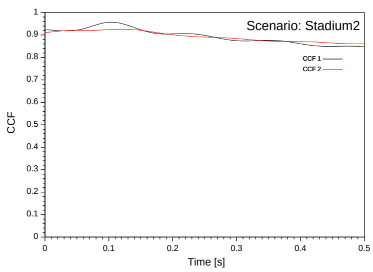
(e) Mensa



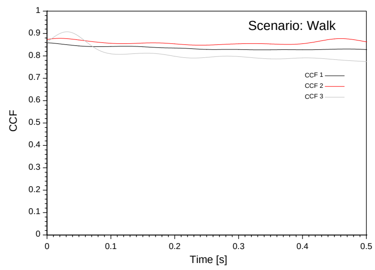
(f) Road



(g) Stadium1



(h) Stadium2



(i) Walk

Figure 3.56: Autocorrelations function of all scenarios

Additionally, Figure 3.57 shows the cumulative distribution function (CDF) of the cross-correlation coefficient r (Equation 3.1) of all scenarios. This coefficient was calculated within a sliding window of 1 sec. It shows the linear correlation of two signal series [3]. A correlation coefficient of 1 means a high correlation, 0 no correlation and -1 reciprocal correlation.

$$r = \frac{\frac{1}{N}\sum_{i=0}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\frac{1}{N-1}\sum_{i=0}^{N}(x_i - \bar{x})^2}\sqrt{\frac{1}{N-1}\sum_{i=0}^{N}(y_i - \bar{y})^2}} \qquad (3.1)$$

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

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, confirming what we could already see in the figures in Section 3.1 comparing the behaviour of the received signal in both directions.

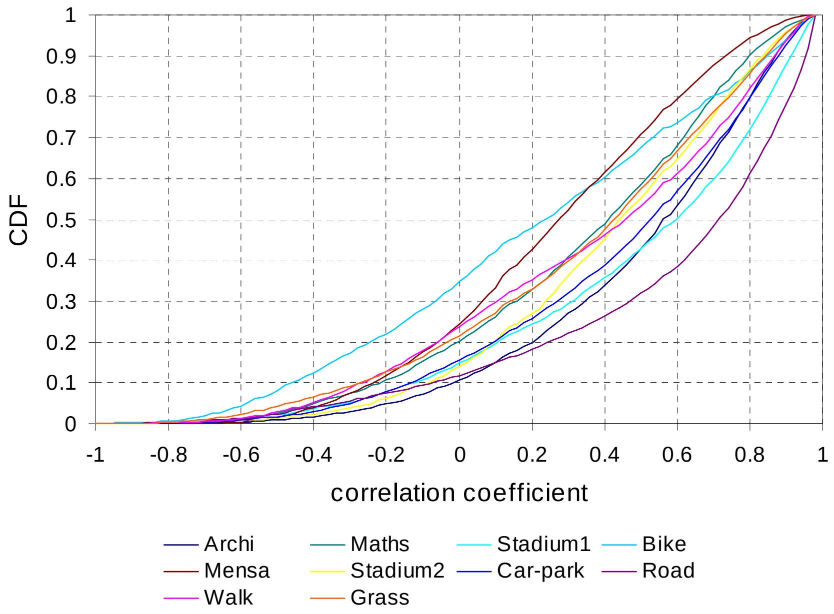


Figure 3.57: Cross-correlation coefficient of all scenarios

Chapter 4

Conclusions

We measured the signal received by two computers communicating over wireless LAN in several environments with varied mobility conditions and show the results in this report.

We can draw some conclusions from the inspection of the time behaviour of the measured received signal.

- When no computer is moving, but movement of objects around the propagation path exists, the received signal has fades.
- When the moving objects are cars, we identify a multipath fading pattern.
- When the moving objects are people, the signal suffers only shadowing and from random noise.
- Fades are deeper in narrow rooms with many possible reflected propagation paths.

These results were expected and cen be explained by the radio wave propagation phenomena.

An analysis of the correlation of the measured data obtained for both communication directions shows 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. These results validate the assumption that the wireless channel is mostly reciprocal.

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

Bibliography

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

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

[3] Rainer Schlittgen and Bernd H. J. Streitberg. *Zeitreihenanalyse.* R. Oldenbourg, 1999.

Appendix A

First-order Statistics for 500 ms

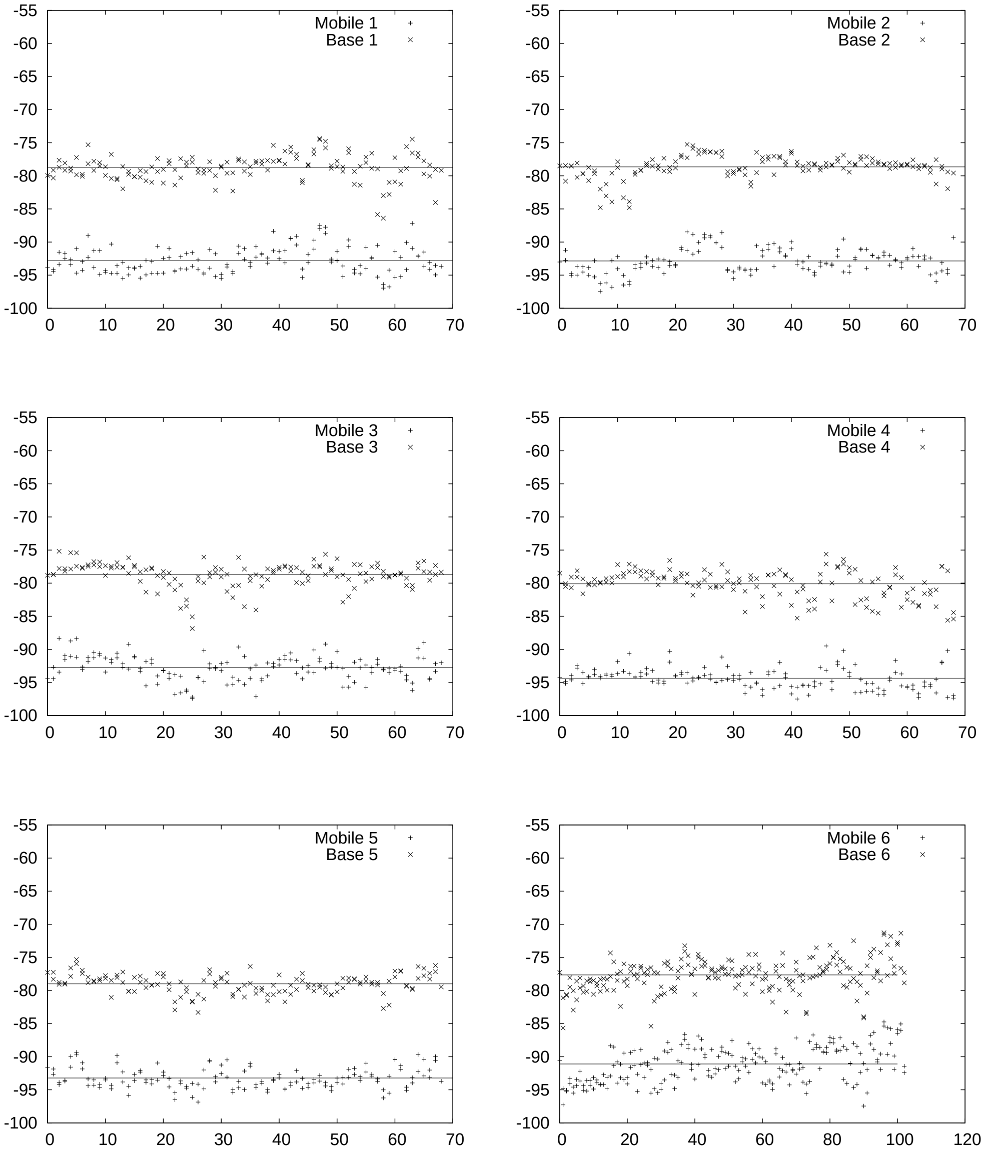


Figure A.1: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Archi (straight lines are the mean values over the whole run).

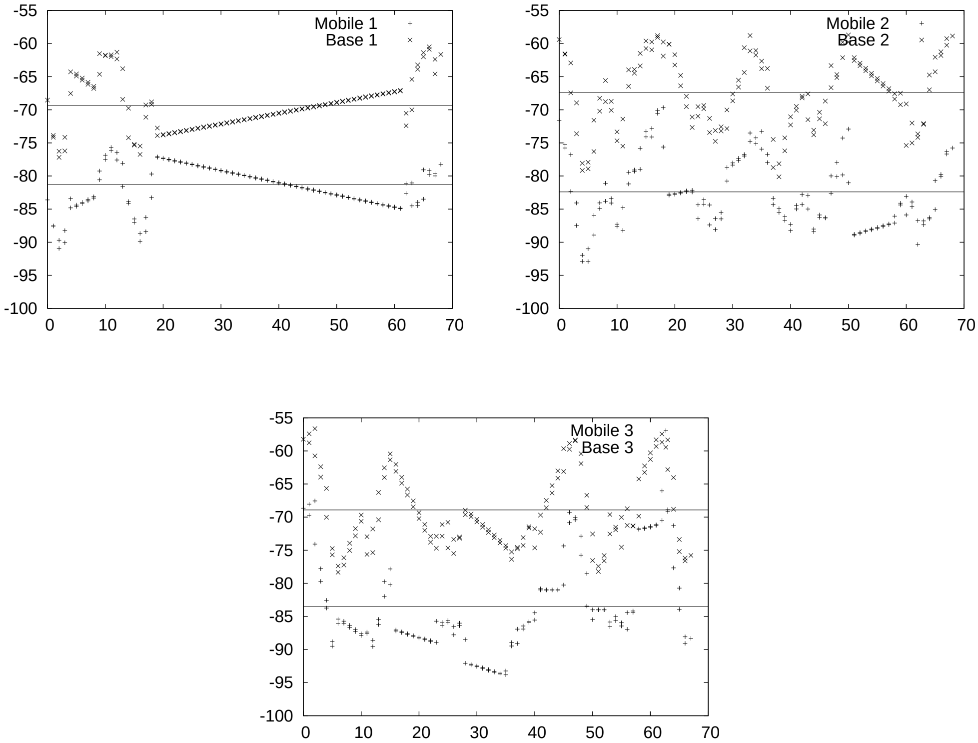


Figure A.2: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Bike (straight lines are the mean values over the whole run).

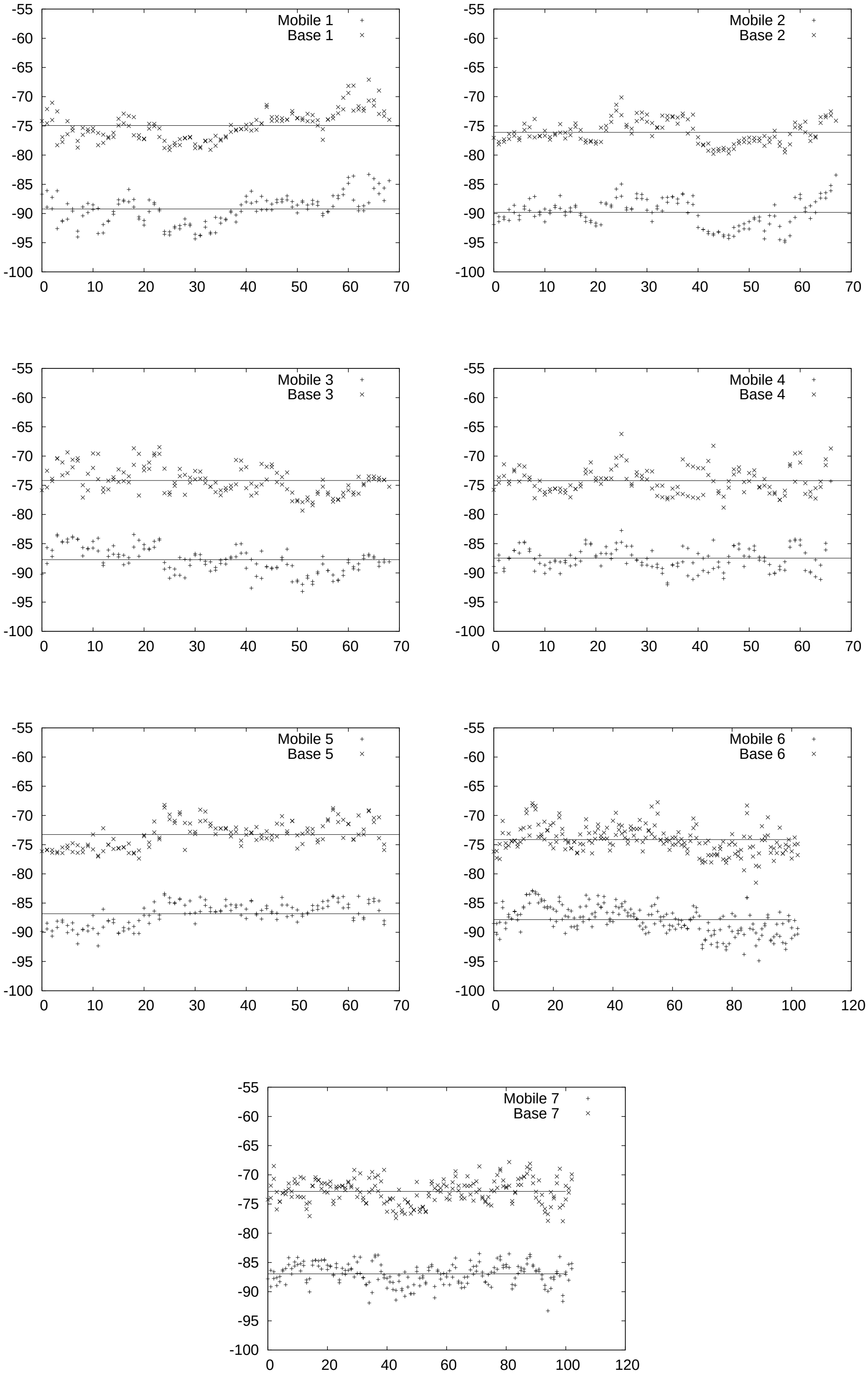


Figure A.3: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Carpark (straight lines are the mean values over the whole run).

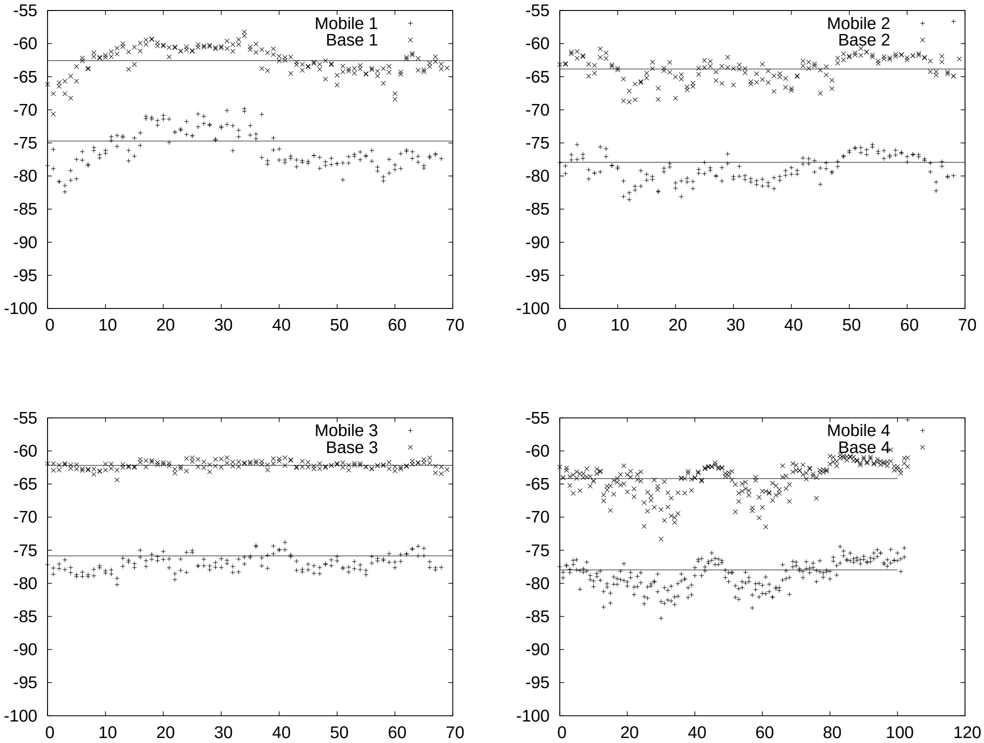


Figure A.4: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Maths (straight lines are the mean values over the whole run).

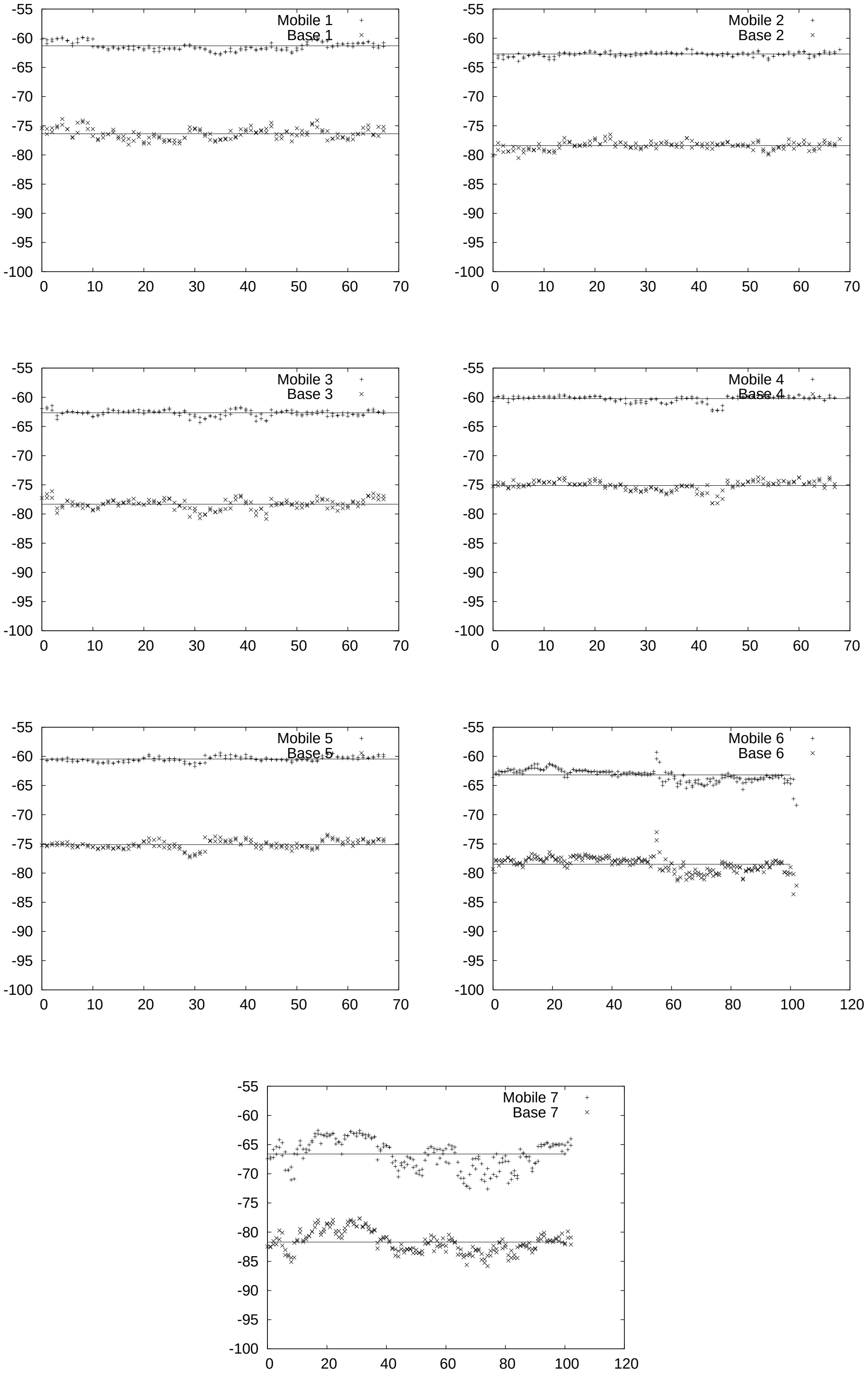


Figure A.5: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Mensa (straight lines are the mean values over the whole run).

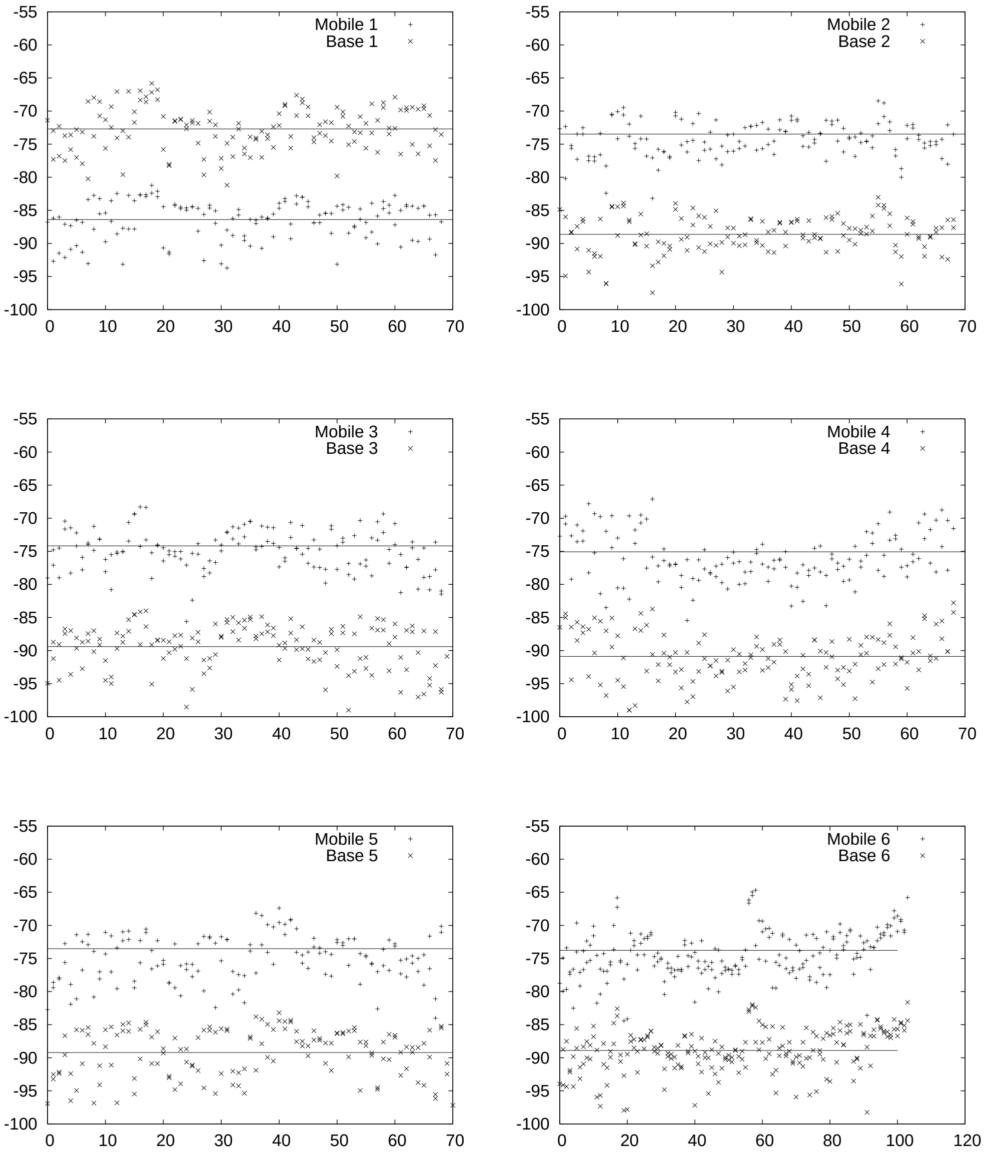


Figure A.6: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Road (straight lines are the mean values over the whole run).

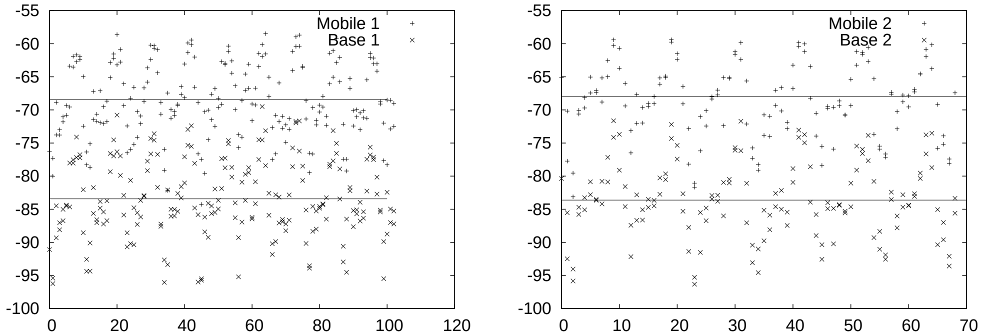


Figure A.7: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Stadium1 (straight lines are the mean values over the whole run).

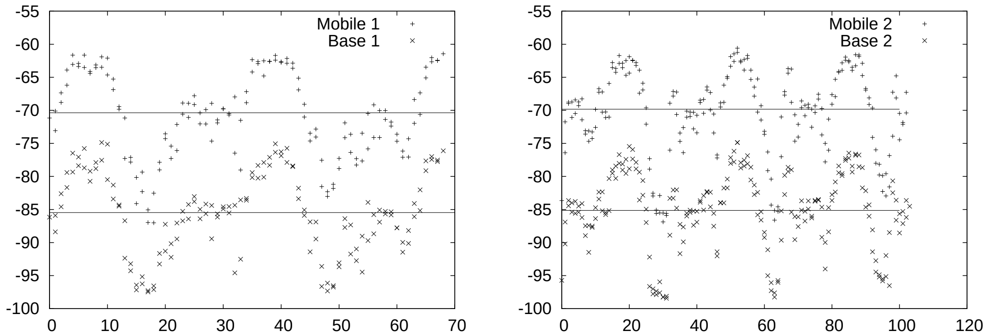


Figure A.8: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Stadium2 (straight lines are the mean values over the whole run).

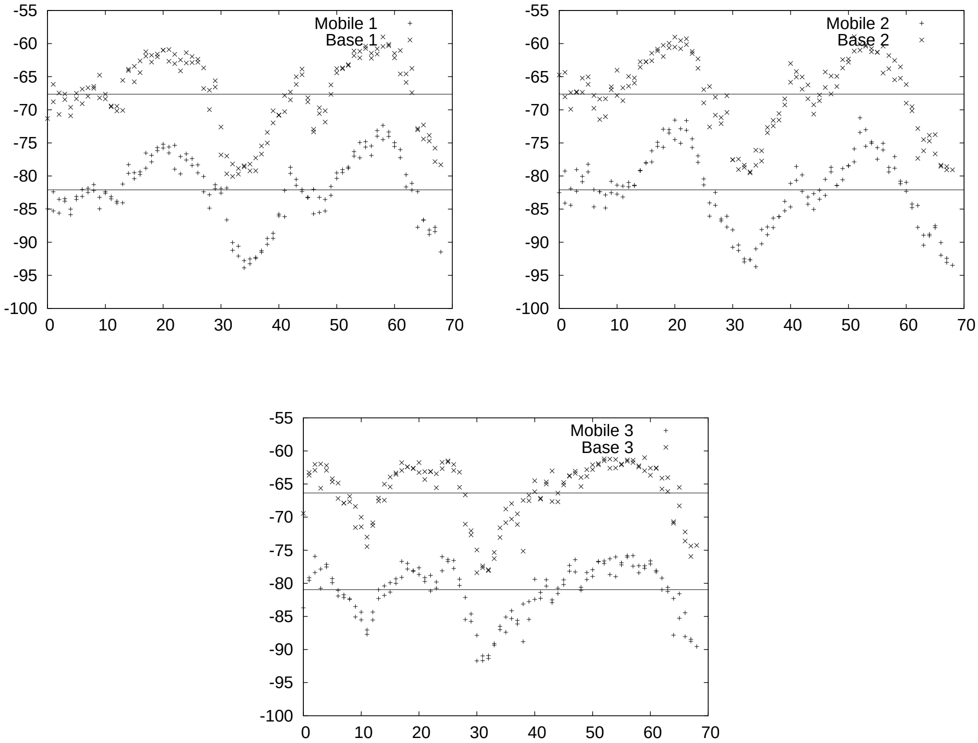


Figure A.9: Mean value of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Walk (straight lines are the mean values over the whole run).

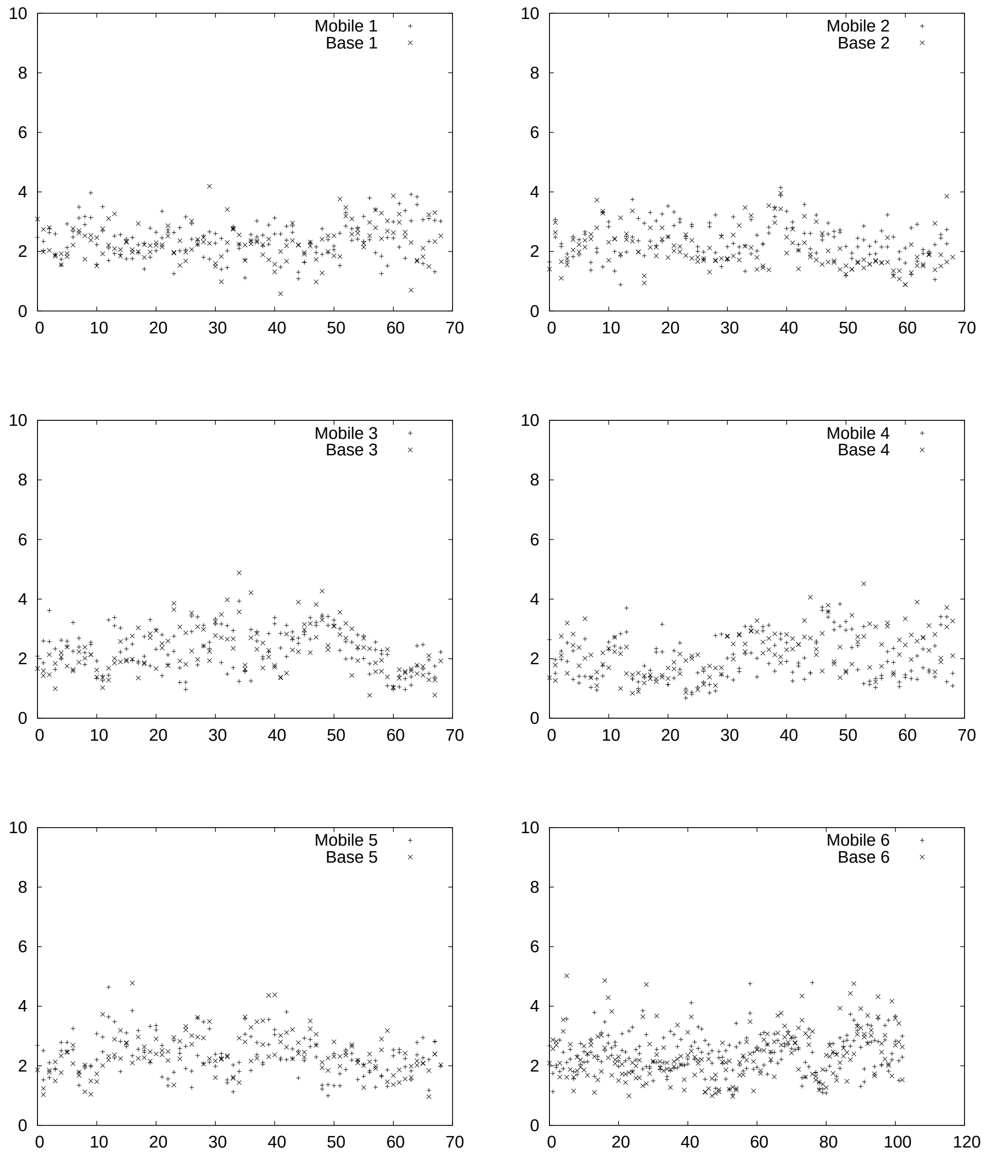


Figure A.10: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Archi (straight lines are the mean values over the whole run).

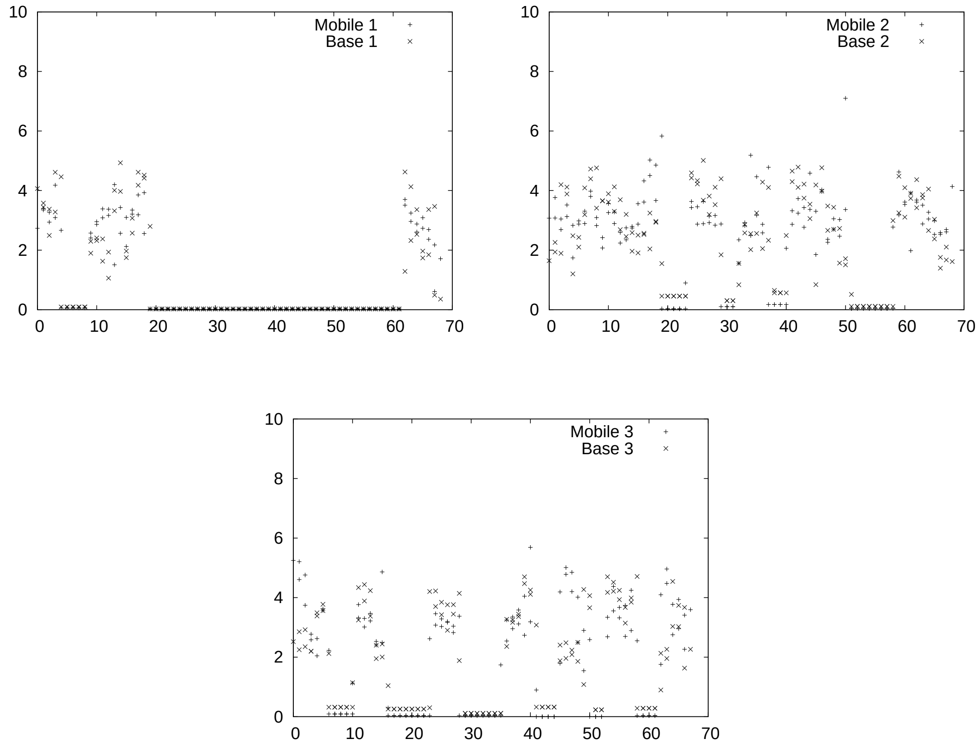


Figure A.11: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Bike (straight lines are the mean values over the whole run).

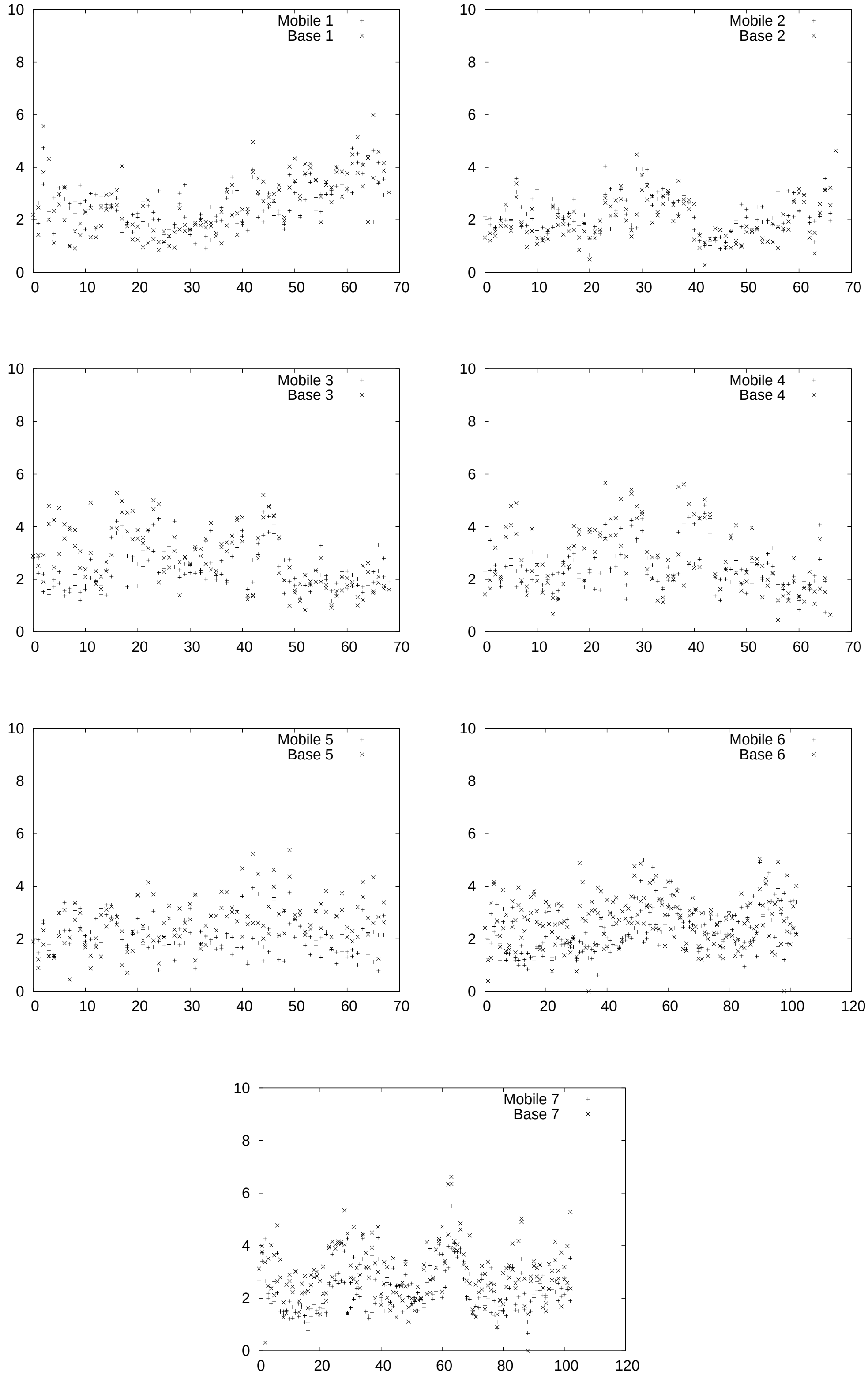


Figure A.12: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Carpark (straight lines are the mean values over the whole run).

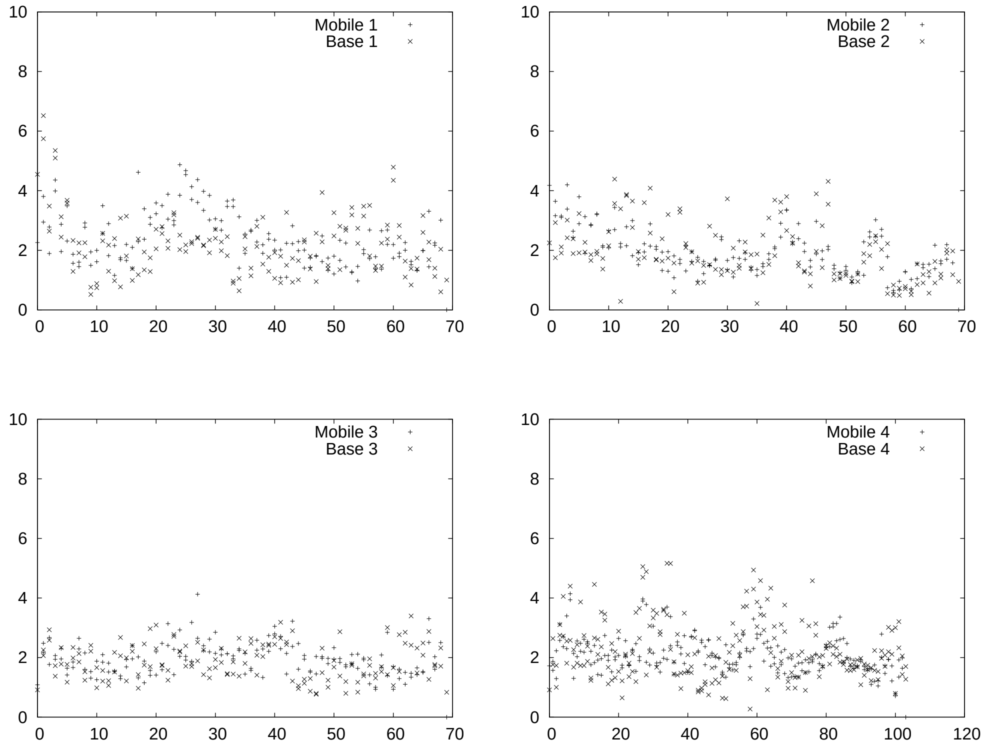


Figure A.13: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Maths (straight lines are the mean values over the whole run).

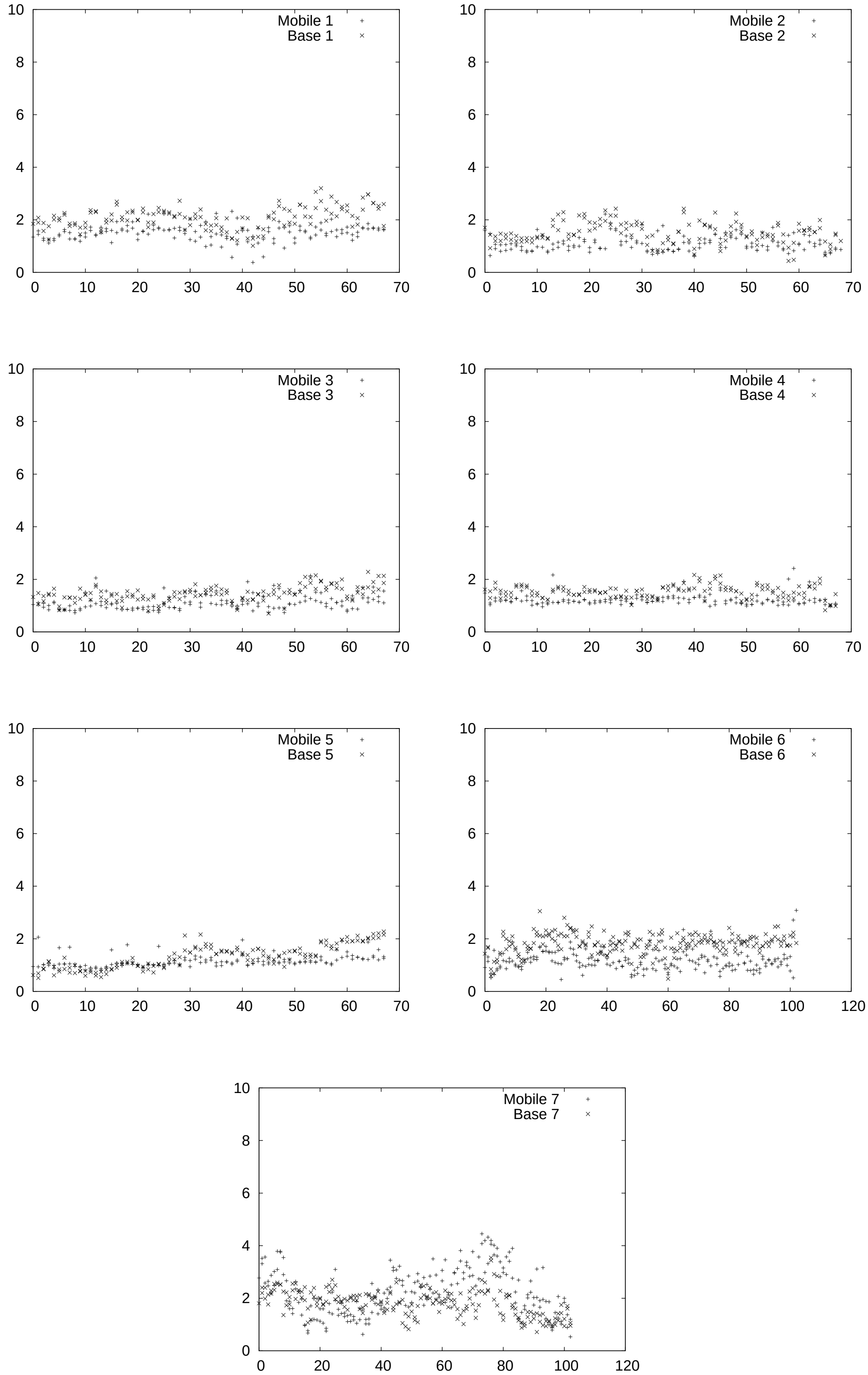


Figure A.14: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Mensa (straight lines are the mean values over the whole run).

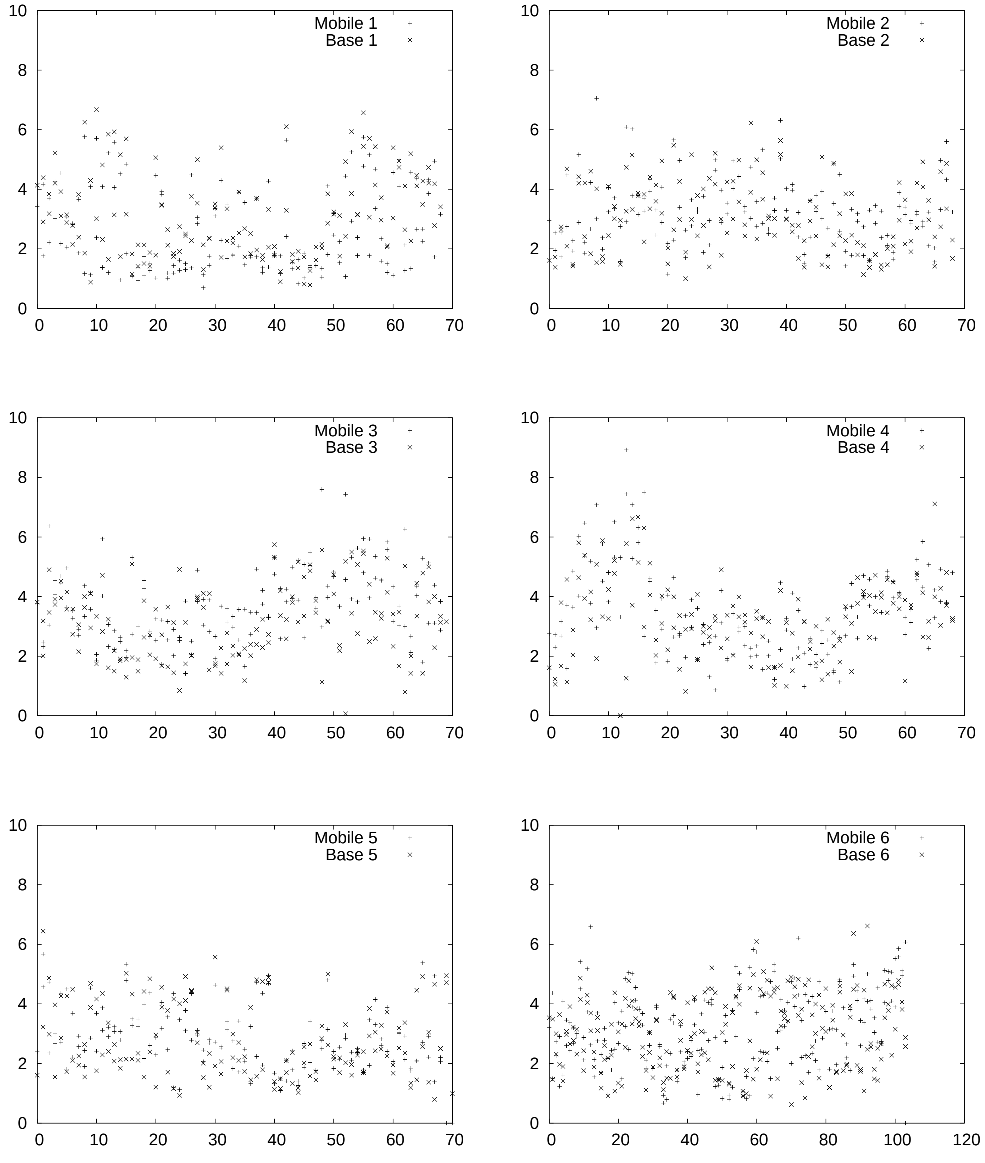


Figure A.15: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Road (straight lines are the mean values over the whole run).

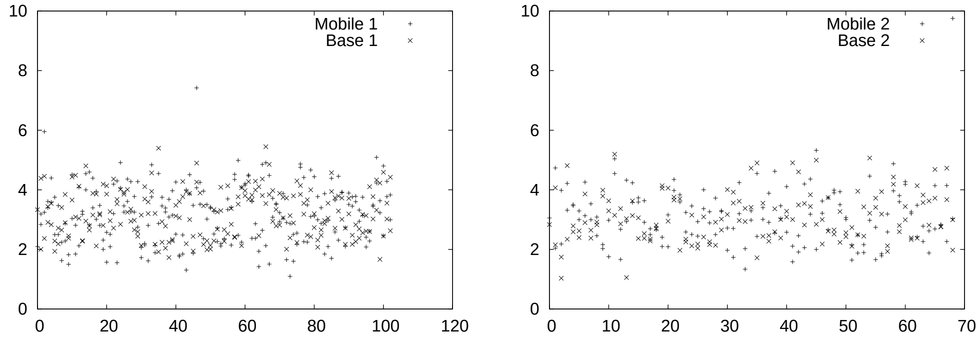


Figure A.16: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Stadium1 (straight lines are the mean values over the whole run).

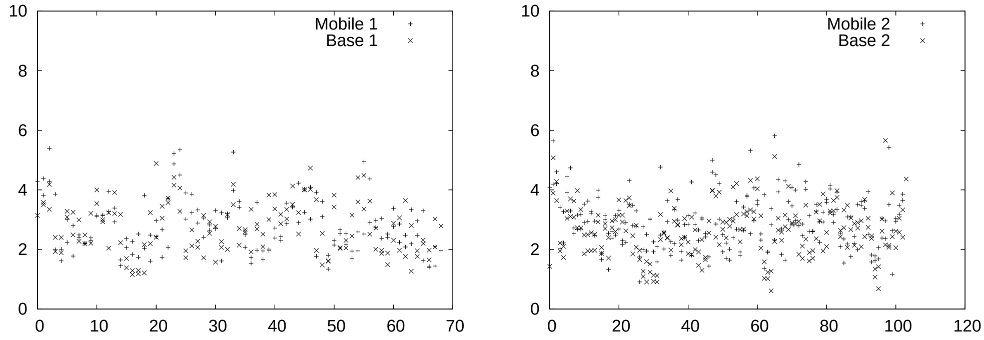


Figure A.17: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Stadium2 (straight lines are the mean values over the whole run).

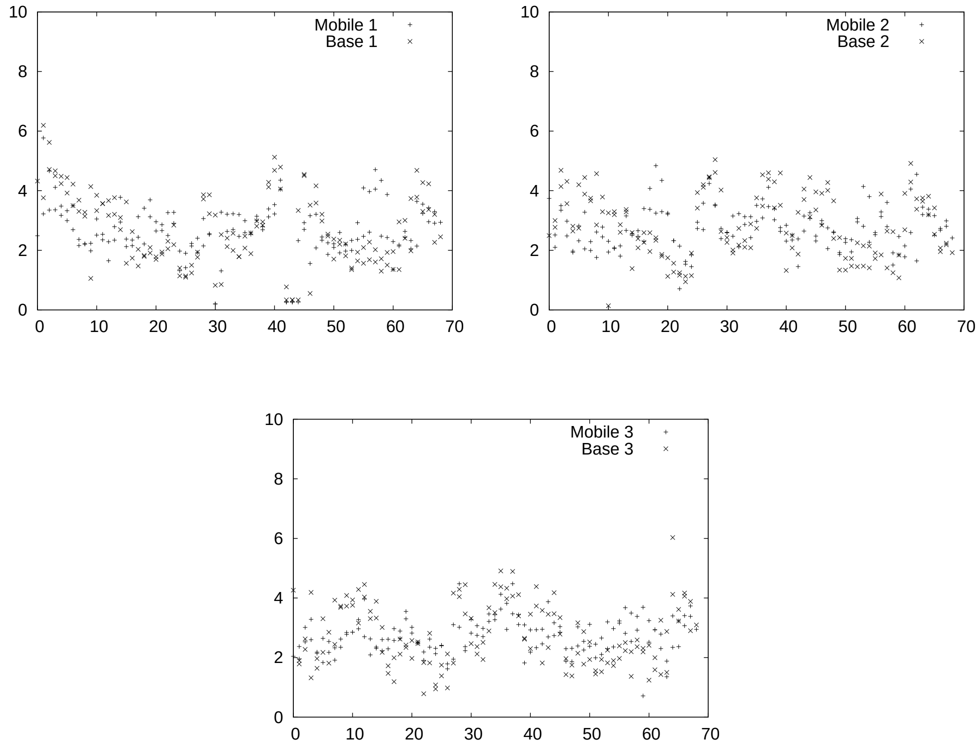


Figure A.18: Standard deviation of the received signal over 500 samples (500 ms) for all measurement runs of the scenario Walk (straight lines are the mean values over the whole run).

Appendix B

First-order Statistics for 100 ms

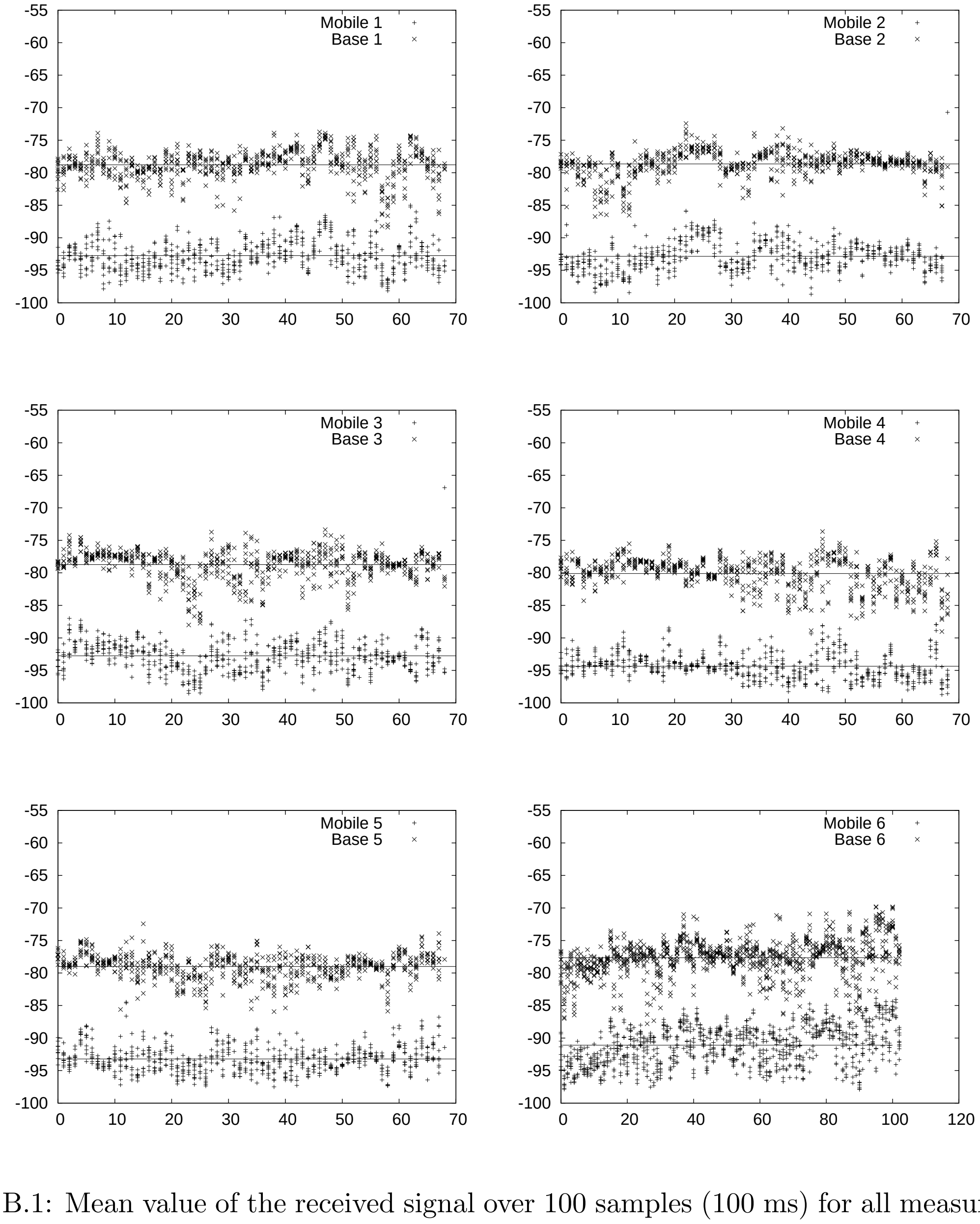


Figure B.1: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Archi (straight lines are the mean values over the whole run).

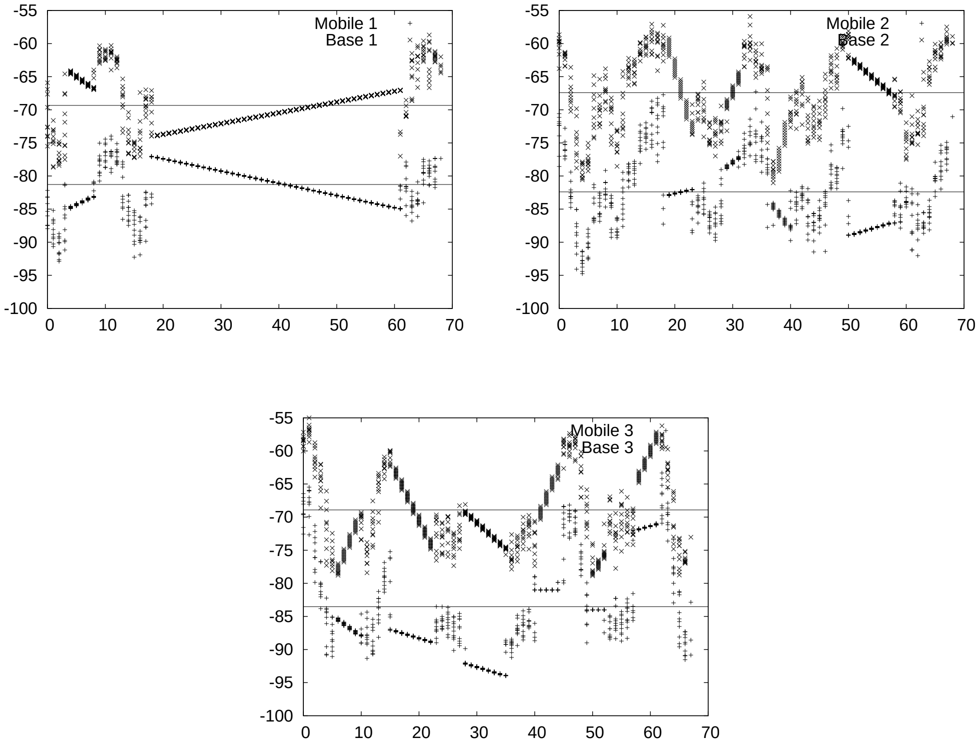


Figure B.2: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Bike (straight lines are the mean values over the whole run).

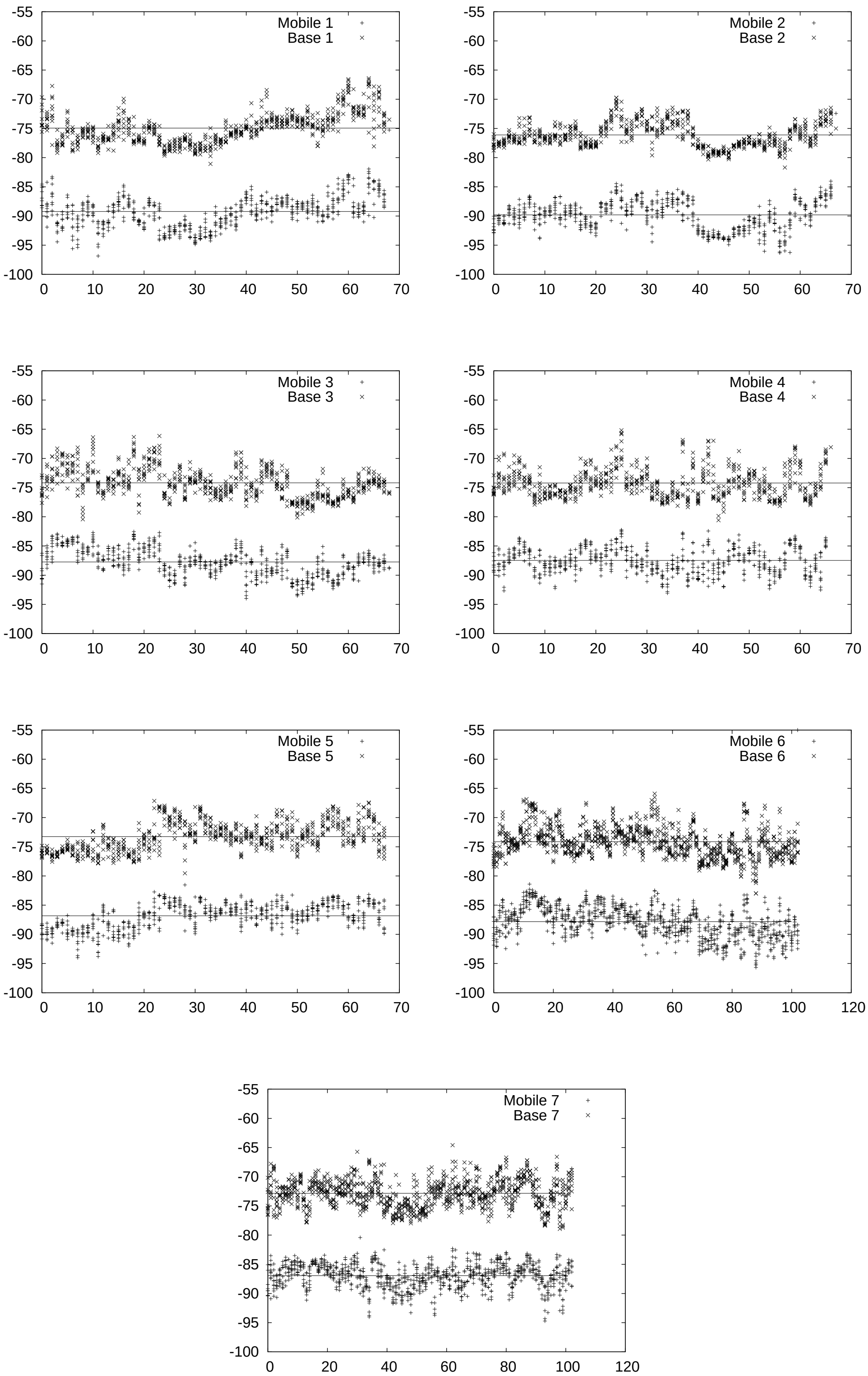


Figure B.3: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Carpark (straight lines are the mean values over the whole run).

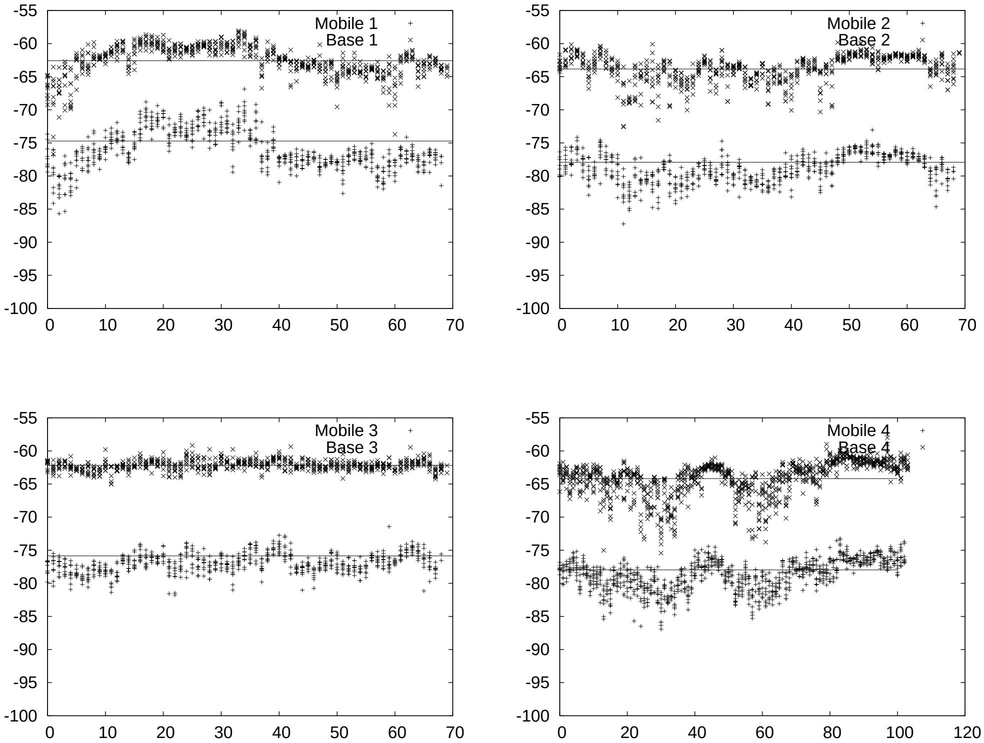


Figure B.4: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Maths (straight lines are the mean values over the whole run).

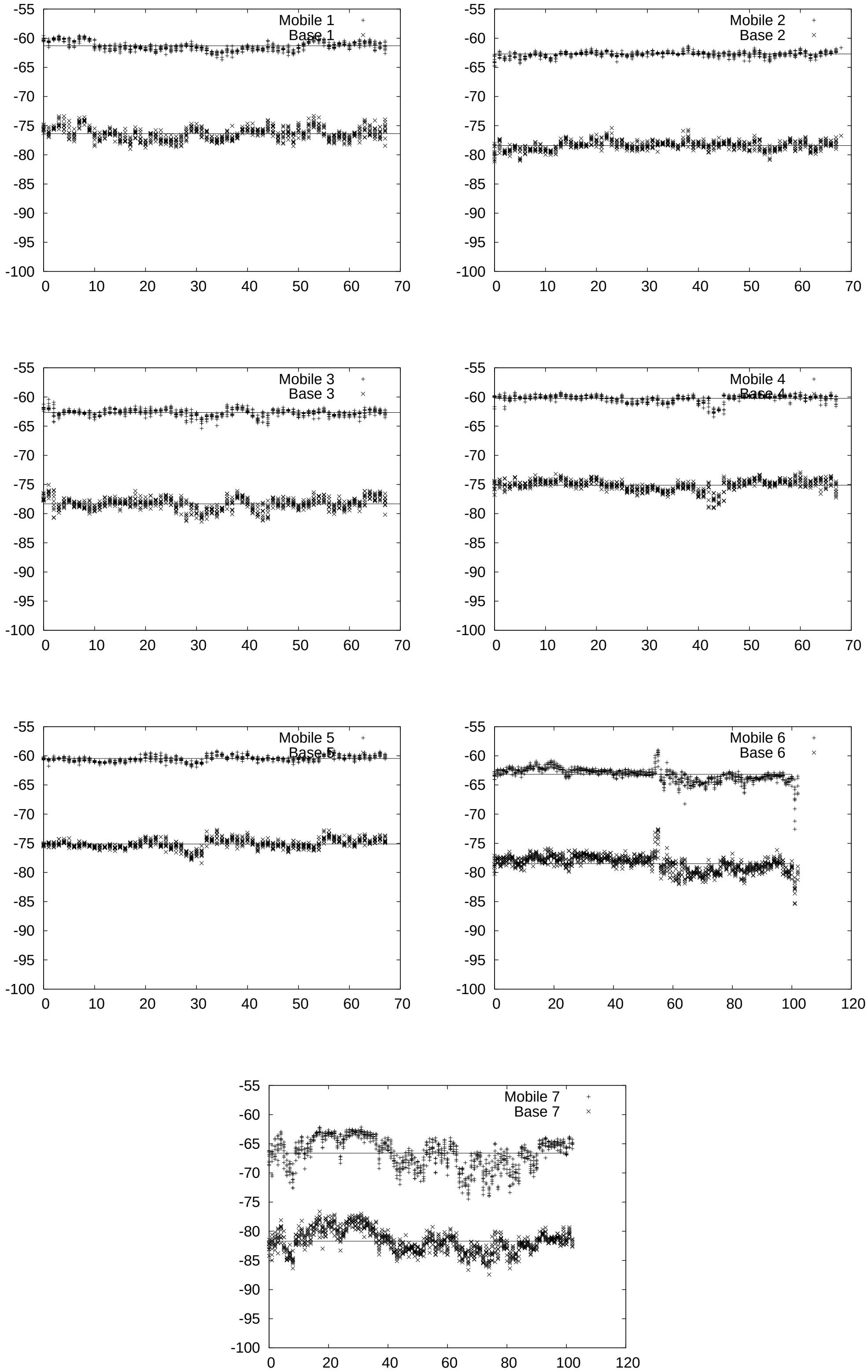


Figure B.5: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Mensa (straight lines are the mean values over the whole run).

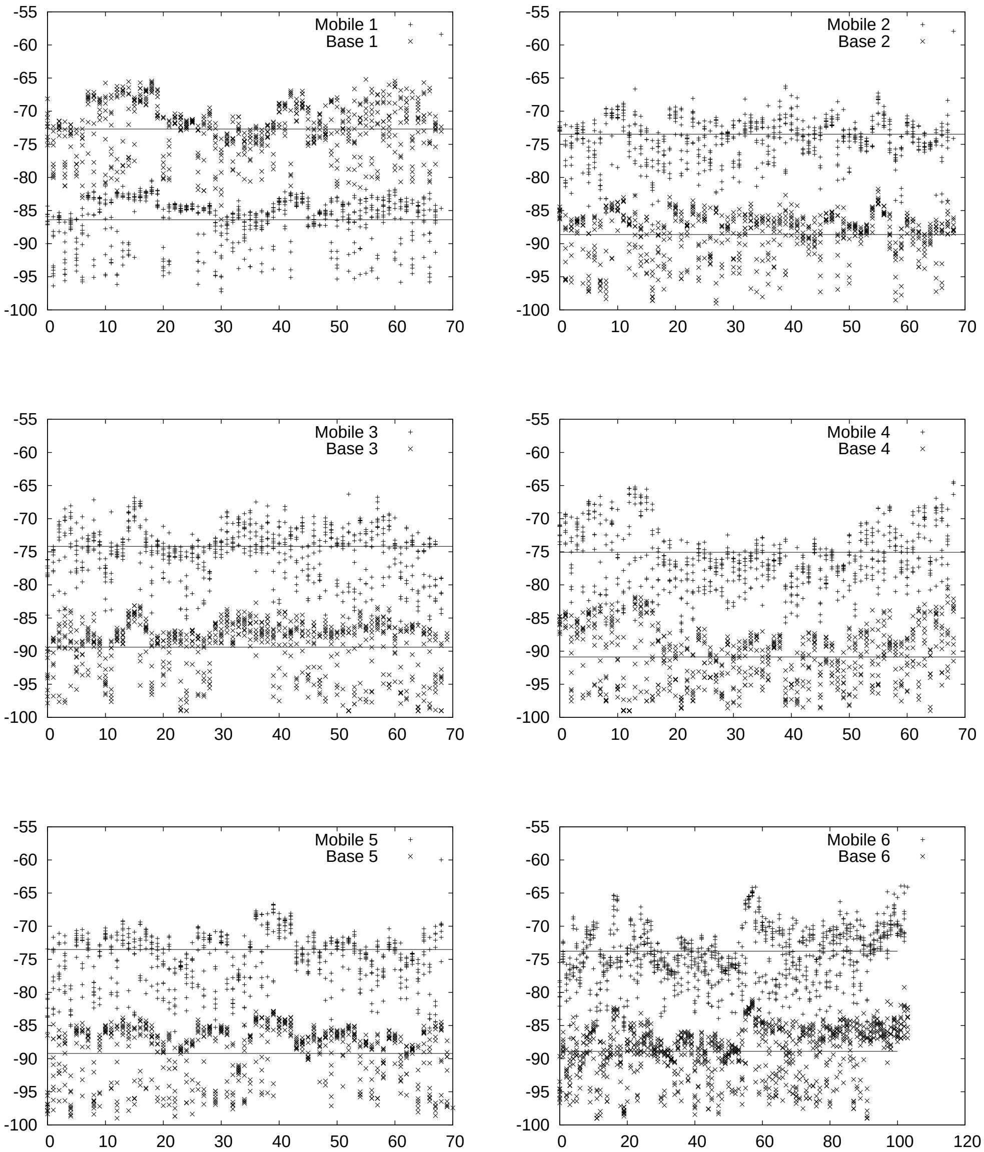


Figure B.6: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Road (straight lines are the mean values over the whole run).

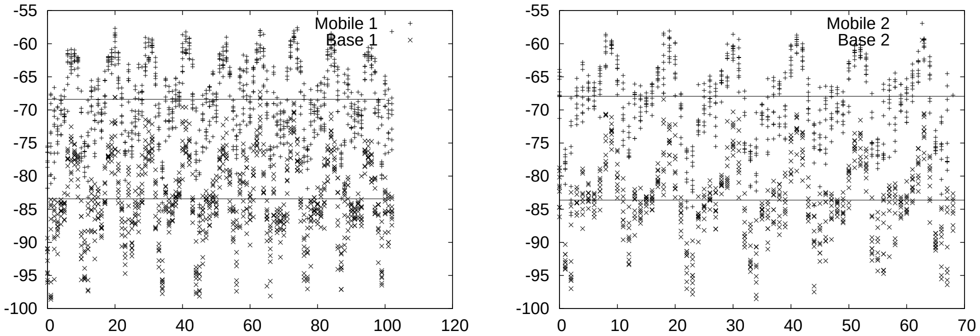


Figure B.7: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Stadium1 (straight lines are the mean values over the whole run).

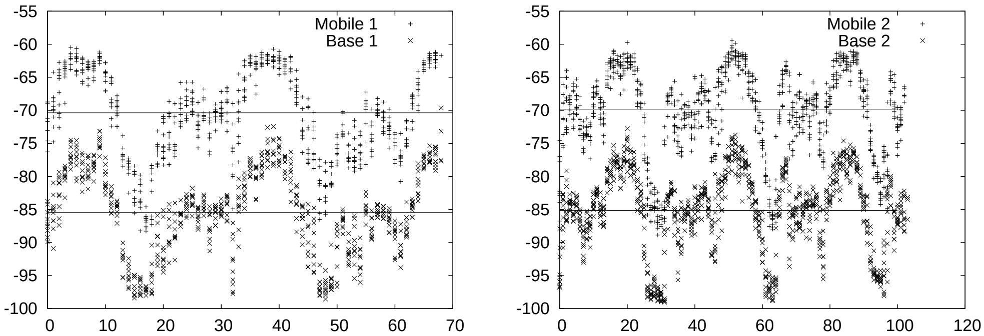


Figure B.8: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Stadium2 (straight lines are the mean values over the whole run).

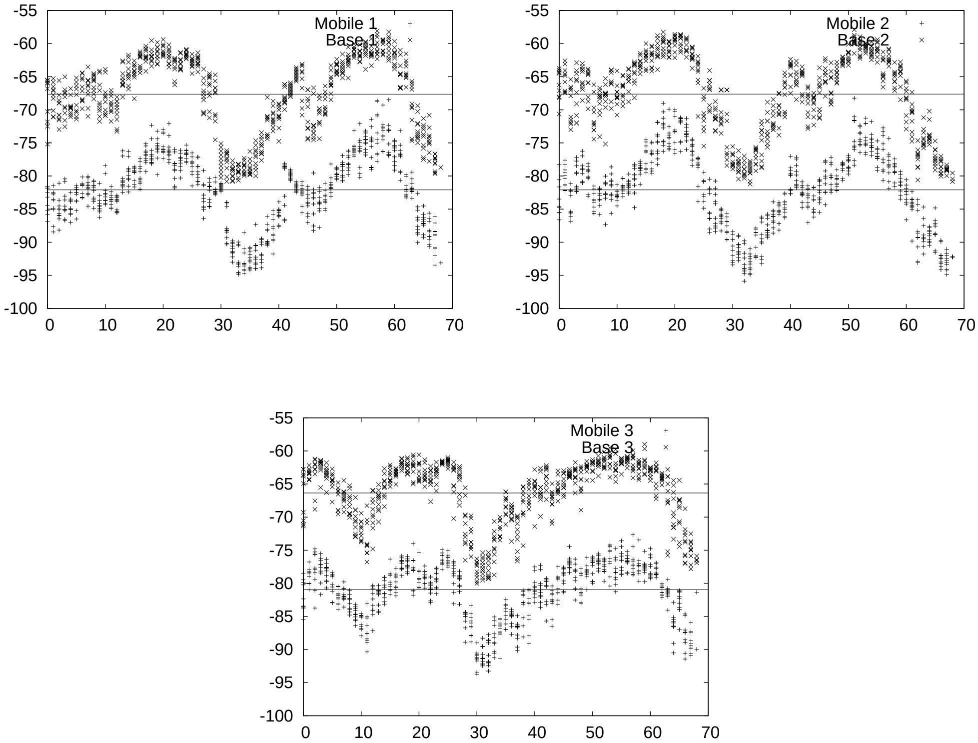


Figure B.9: Mean value of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Walk (straight lines are the mean values over the whole run).

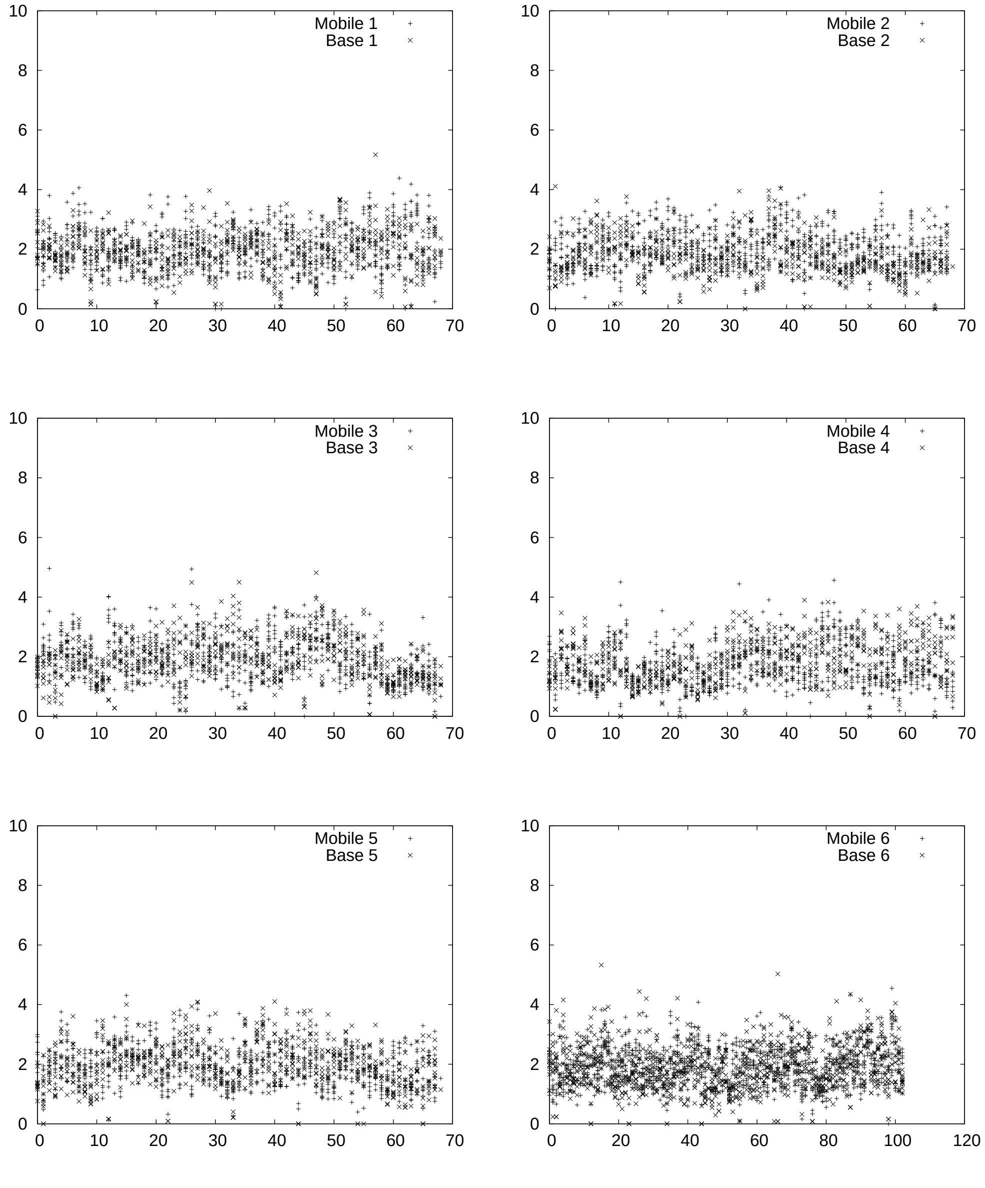


Figure B.10: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Archi (straight lines are the mean values over the whole run).

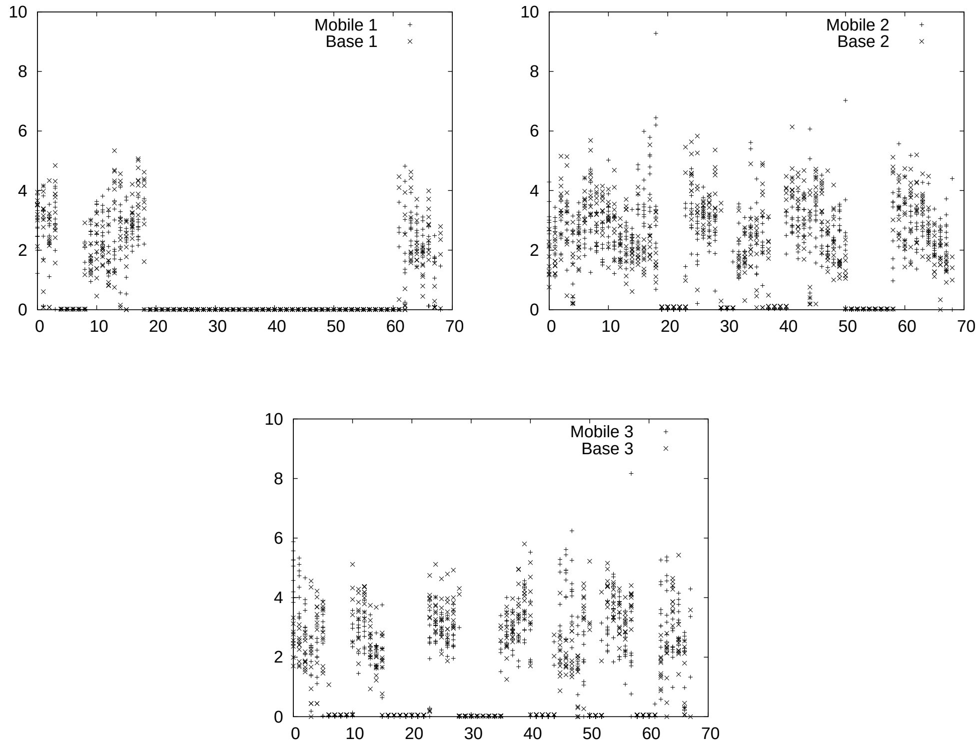


Figure B.11: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Bike (straight lines are the mean values over the whole run).

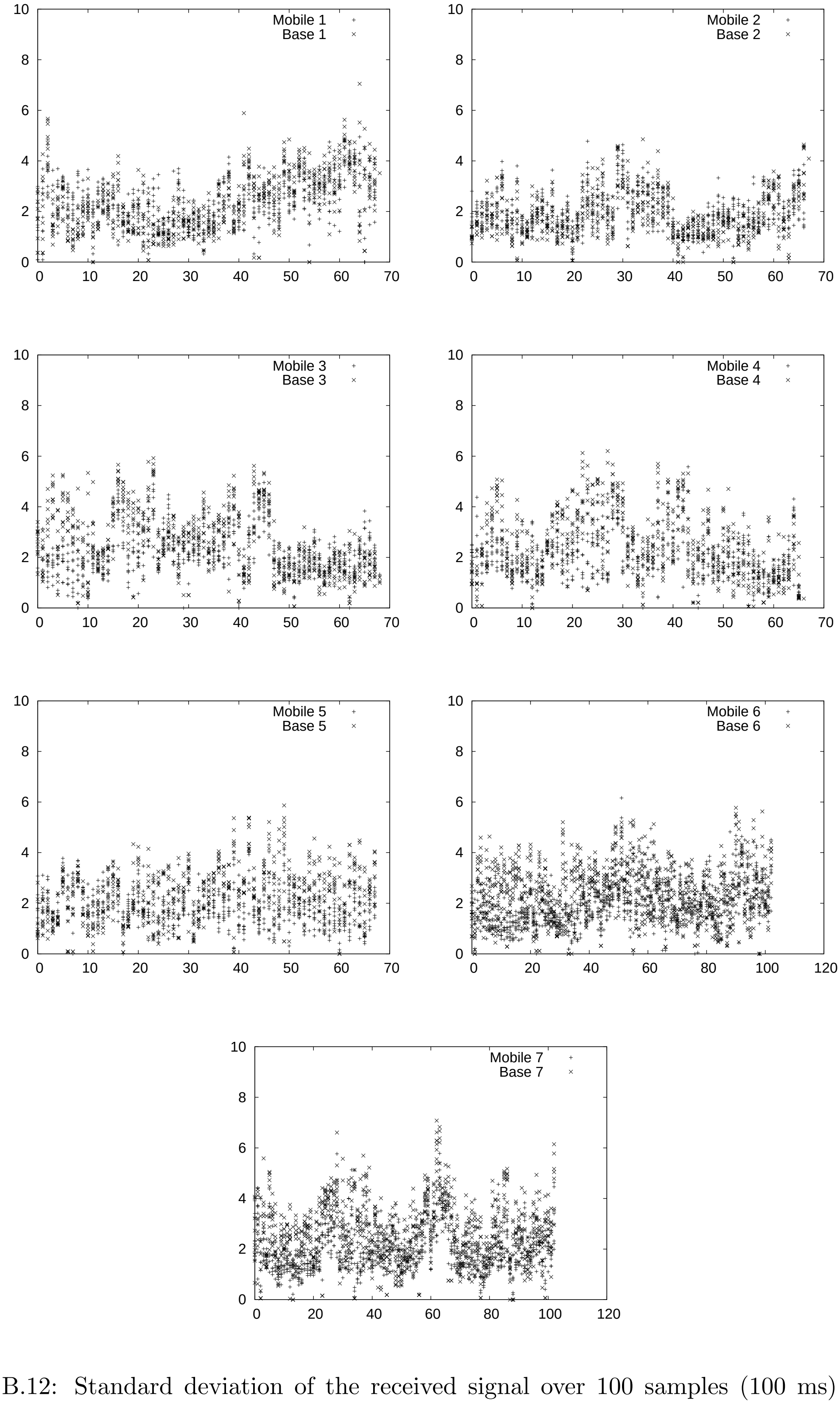


Figure B.12: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Carpark (straight lines are the mean values over the whole run).

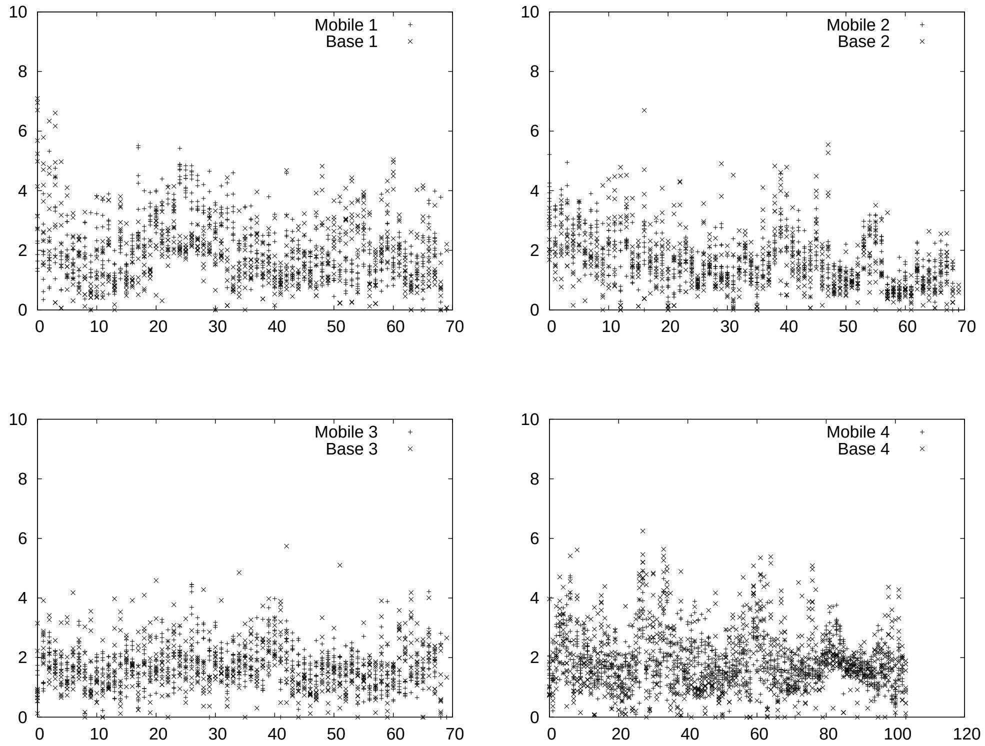


Figure B.13: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Maths (straight lines are the mean values over the whole run).

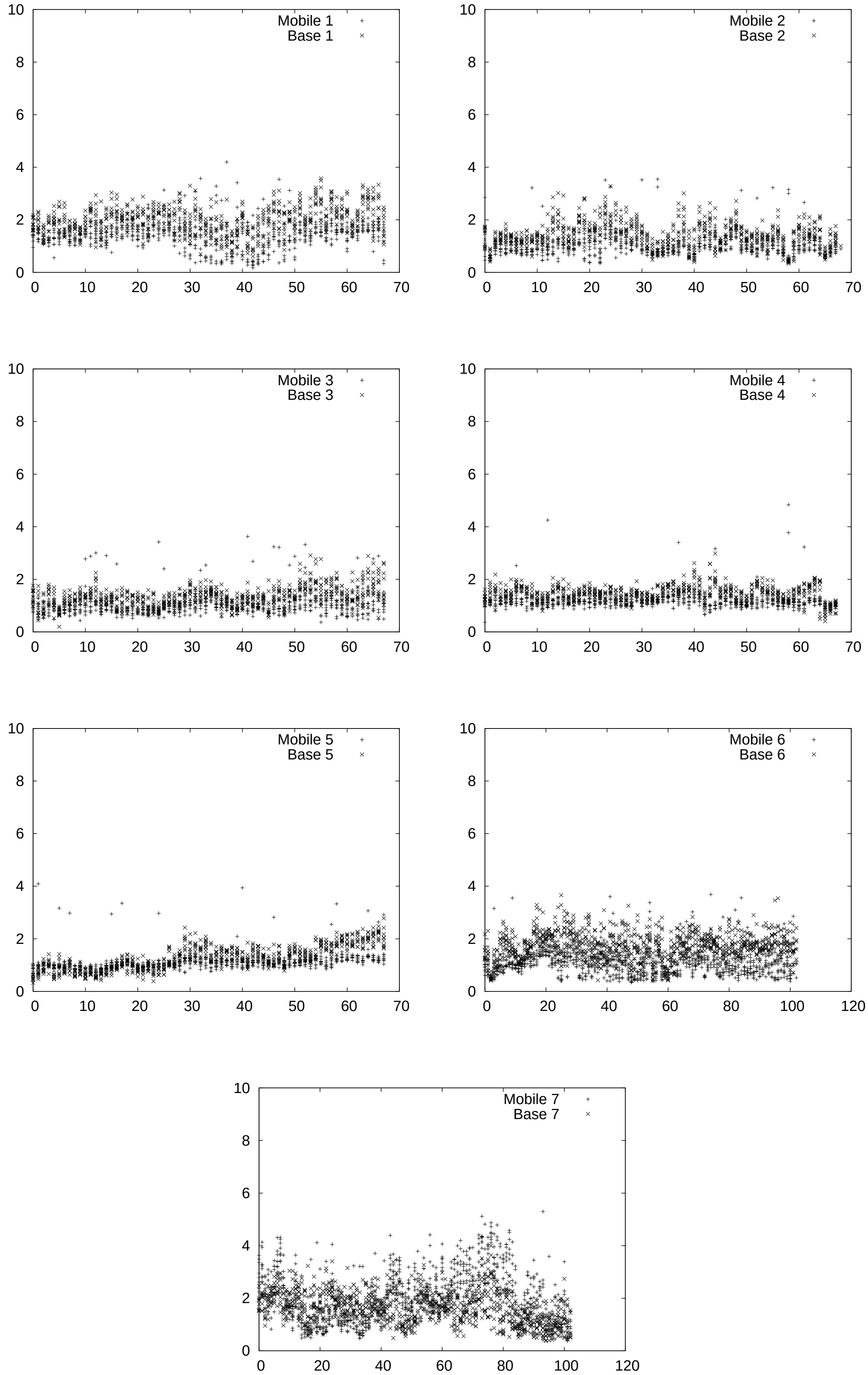


Figure B.14: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Mensa (straight lines are the mean values over the whole run).

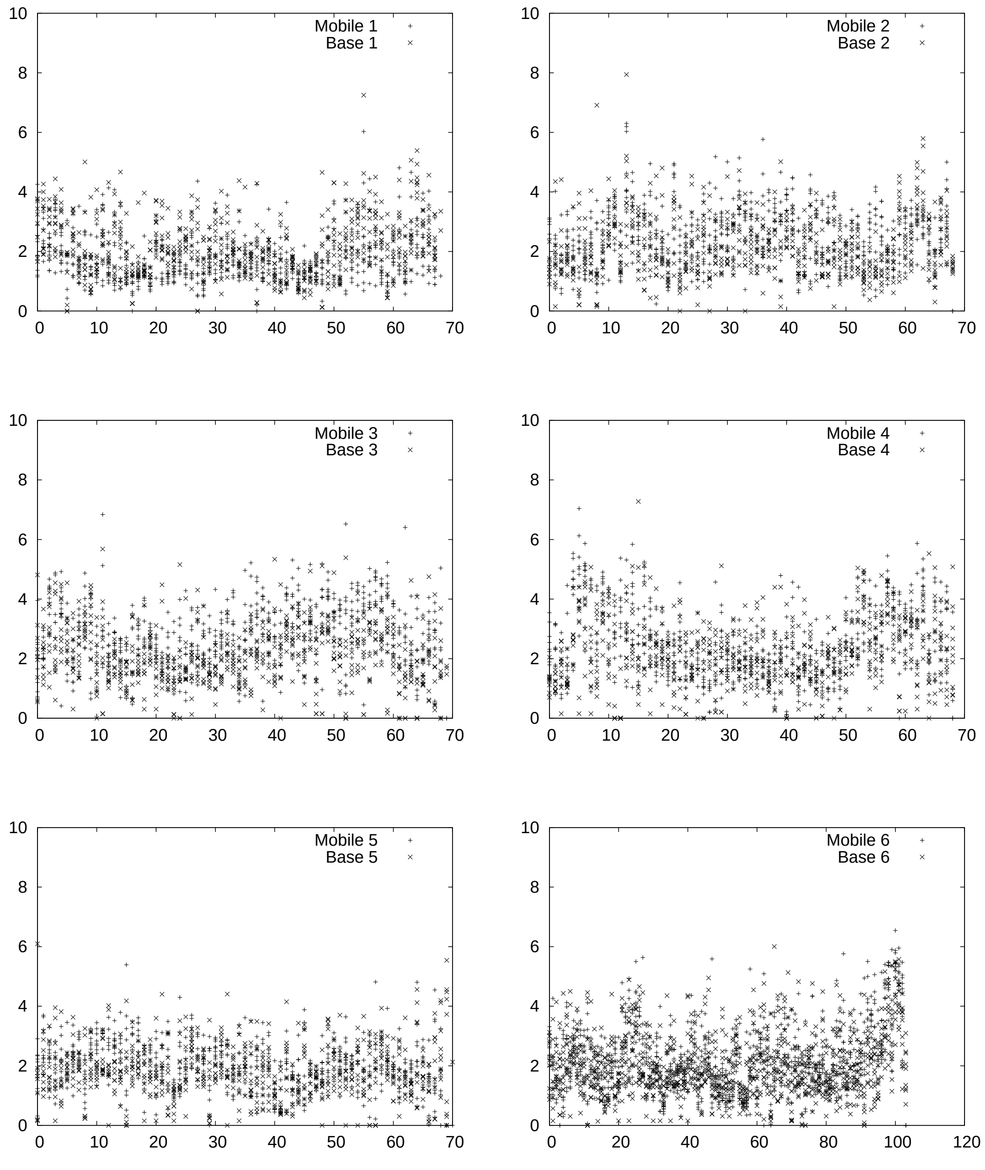


Figure B.15: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Road (straight lines are the mean values over the whole run).

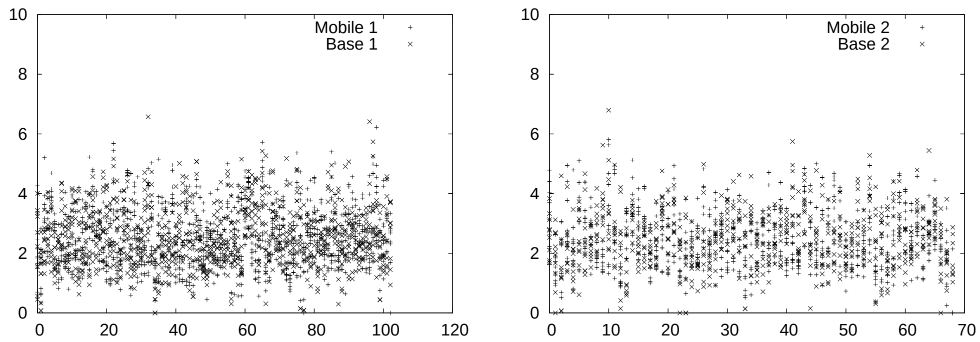


Figure B.16: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Stadium1 (straight lines are the mean values over the whole run).

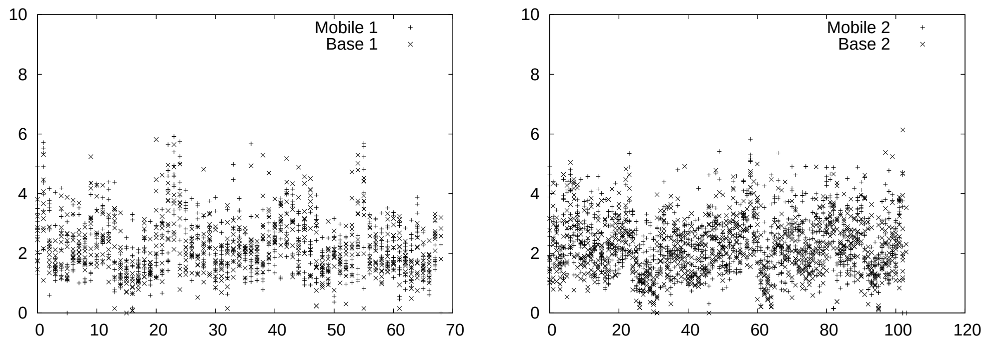


Figure B.17: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Stadium2 (straight lines are the mean values over the whole run).

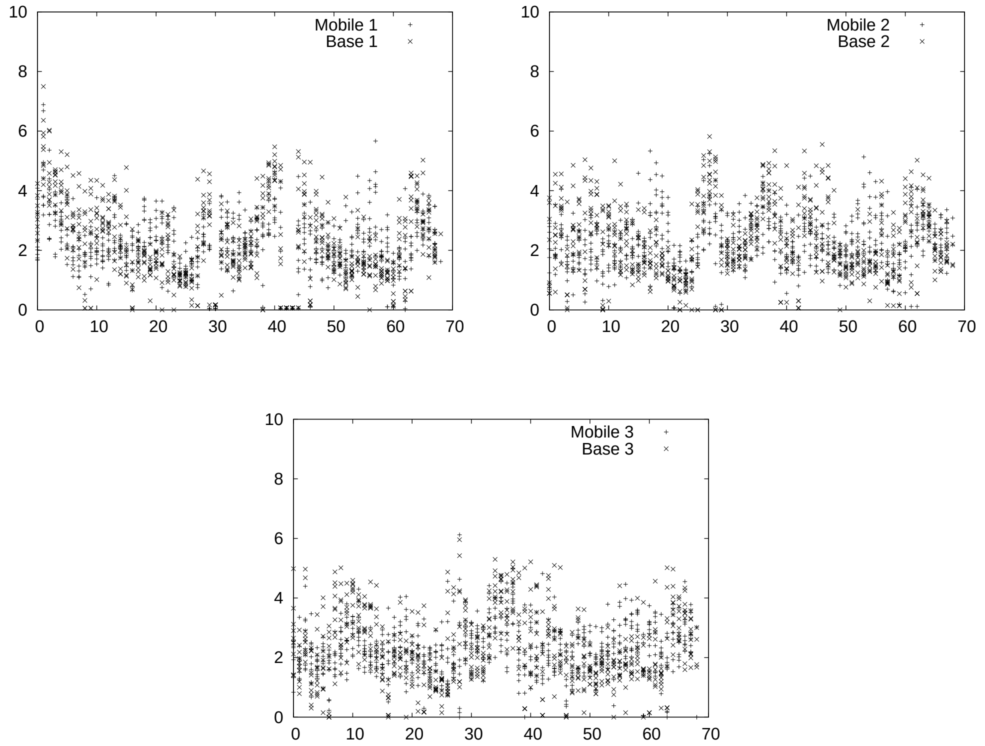


Figure B.18: Standard deviation of the received signal over 100 samples (100 ms) for all measurement runs of the scenario Walk (straight lines are the mean values over the whole run).