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Published in:
Proceedings of the 2004 International Symposium on Spread Spectrum Techniques and Applications

Publication date:
2004

Document Version
Publisher's PDF, also known as Version of record

Measurements of Indoor 16×32 Wideband MIMO Channels at 5.8 GHz

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***Abstract*— A wideband 16×32 multiple-input multiple-output (MIMO) channel sounder has been developed for the 5.8 GHz band. This paper reports on a series of measurements with the purpose of investigating both temporal and spatial aspects of channel changes in a number of widely different indoor environments. The measurements are carried out using two planar arrays of monopoles. The results include statistics on capacity, coherence bandwidth, and Doppler spreading for the various measurement scenarios.**

I. Introduction

Future wireless communications devices is expected to offer bit rates of several hundred Mbit/s. This will require high spectral efficiencies of the transmission systems because the radio spectrum available for each pair of transceivers is limited. Systems using MIMO transmission techniques are promising in this aspect and has been studied intensely recently [1], [2].

In communications using MIMO channels multiple antennas are used simultaneously at both the transmitter (Tx) and the receiver (Rx) so that many mobile channels are used, thereby utilizing the multipath propagation that often takes place in the mobile radio channel. Depending on the channel properties the capacity of a MIMO system may be much higher than for a system with only one antenna at each end and using the same bandwidth. However, the capacity of MIMO systems are highly dependent on the mobile channel properties [3], [4].

The focus of this work is MIMO transmission to and from mobile devices in an indoor environment where a large capacity is expected because of a generally high degree of signal scattering and lack of line of sight (LOS) in many cases. The mobile device may be a laptop or similar with sufficient space for many antennas and the device may be moving or remain stationary for periods of time. Hence, a variety of different channels may be experienced with varying degrees of stationarity, dispersion, *etc.* In order to predict the feasibility of such a system accurate knowledge of the channel is essential.

The current paper reports on results obtained from measurements with a 100 MHz wideband MIMO channel sounder for the 5.8 GHz band. Using 16 parallel transmitters and 4 parallel receiver branches combined with fast switching, the sounder is capable of measuring a 16×32 MIMO channel where all the individual channels are measured virtually simultaneously (within about 572 μs for the current setup).

The measurements are carried out in various indoor environments with focus both on temporal as well as spatial aspects of channel changes. Results are given in terms of capacity statistics, the coherence bandwidths, and Doppler bandwidths.

II. Measurement System

The measured data used in this work are obtained using a 16×32 MIMO channel sounder based on the correlation principle. An overview of the sounder is given in Fig. 1.

The sounding bandwidth is about 100 MHz which is obtained by transmitting the pseudo noise (PN) sequence at a chip rate of 100 MHz using binary phase shift keying (BPSK). The carrier frequency is 5.8 GHz.

Each of the 16 transmitters simultaneously output a PN sequence using a 1 W power amplifier. The system is designed to be flexible so that any set of PN-sequences can be used, as required by the type of measurements. In the current work an m-sequence of length 1023 is used for all the transmitters, where each transmitter has a unique code offset so that the different channels can be separated in the receiver.

All frequency sources in both the transmitter and receiver are phase locked to rubidium frequency standards, so that complex impulse responses can be measured.

The receiver has four parallel branches each with a separate automatic gain control (AGC) circuit and sampler. Four channels are measured truly in parallel and via switching this is repeated 8 times to obtain the 32 receive channels. For the current setup with a 1023 chip PN sequence, measurement of the 32 channels takes about 572 μs, using four times averaging of each measurement in order to improve the dynamic range. Assuming a maximum speed of 1 m/s of a receiver or transmitter moving in an indoor environment, the total measurement time corresponds to about $\lambda/90$, where λ is the wavelength.

Measurements can be carried out in two different modes. In continuous mode the measurements are made at a given rate in time, *e.g.*, every 10 ms, or at equidistant positions, *e.g.*, for each $\lambda/3$, as given by a tachometer. In high Doppler rate environments it may be desirable to carry out the measurements in burst mode where measurements are made, *e.g.*, for each $\lambda/3$ inside a burst, which is followed by a pause, after which a new burst of measurements is made, *etc.* The measurements part of the current work are made in the continuous mode with channel measurements made at a rate of 60 Hz, or about every 17 ms.

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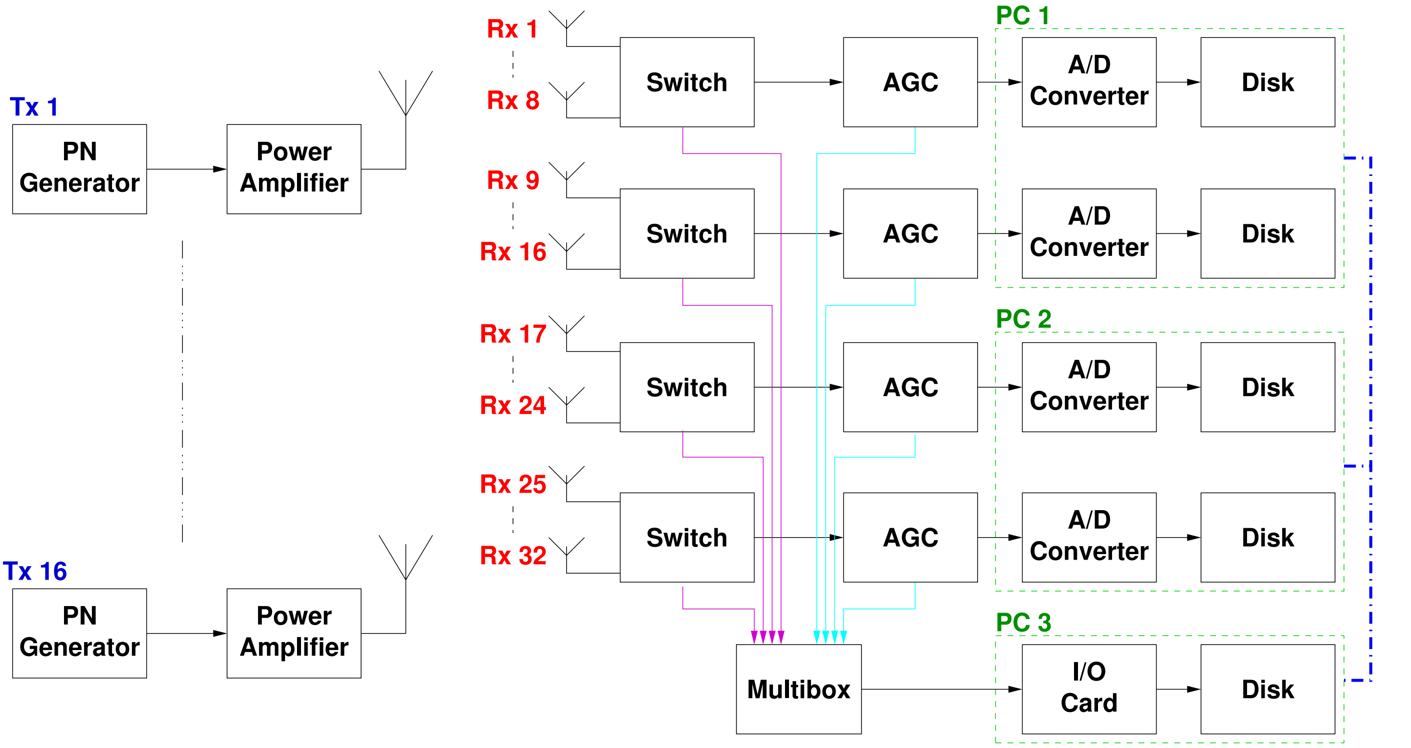

Fig. 1. Overview of 16×32 MIMO channel sounder.

The received signals are sampled at an intermediate frequency (IF) at a rate of 400 MHz and moved to a buffer in local RAM. From the buffer the data is stored on disk for later processing after the measurements. In the post-processing the samples are converted to complex low pass representation and correlated with the PN sequence in order to obtain the complex impulse responses (CIRs). Using a series of back-to-back measurements the system response is removed from the measured data.

The measurements discussed subsequently were obtained with a planar array of monopole antennas at the Rx arranged in a 8×12 rectangular grid where the two outermost rows on all sides are dummy elements so that the array effectively is 4×8. The monopole antennas are about 0.3λ in length and spaced about 0.5λ apart. Fig. 2 shows the Rx antenna. The Tx array is similar in construction but instead is a 8×8 grid where the active elements are in a 4×4 grid.

The Rx array is mounted on a sledge controlled by a step motor so that the array can be moved in a linear fashion during the measurements. The height of the array is 94 cm above the floor. In the current measurement campaign the movement of the the sledge from one end to the other was set to 1 m, which takes 30 s. Given the above mentioned measurement rate of 60 Hz, a single measurement run consists of 1800 samples of the 16×32 CIRs.

III. Measurement Scenarios

All the measurements were made within the same modern four story (including basement) office building. The building

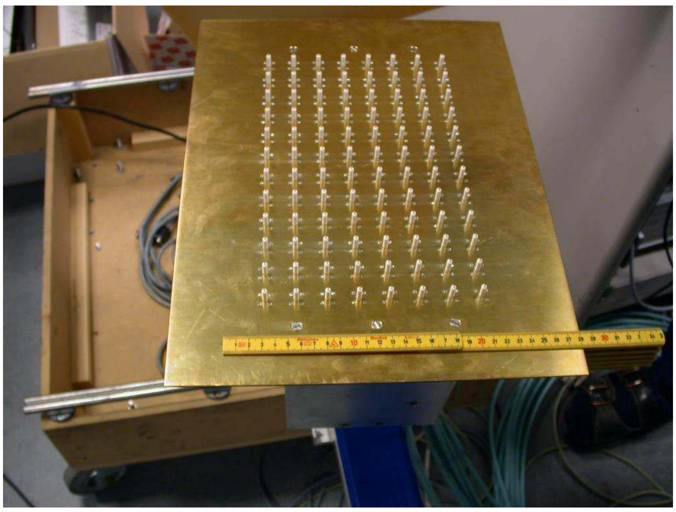

Fig. 2. The Rx antenna array.

is primarily made of reinforced concrete with an outer brick wall and with most inner partitions made in light plaster board construction. The floors/ceilings of each level are also made of concrete. Two types of measurements were made,

Fixed transceiver: In this type of measurements both the Tx and Rx remained in the same position while the measurements were carried out. This means that any variation in the channel are due to people passing by, doors opening/closing, *etc.*, and thus may be named temporal channel variations.

Moving transceiver: In this case the Tx remained fixed but the Rx was moved on the sledge as described in Sec. II. Both temporal channel variations due to changes in the environment and spatial channel variations due to the moving Rx are experienced.

The following widely different scenarios have been selected. In each case both the fixed transceiver and moving transceiver types of measurements were made in a number of different transceiver positions. The scenarios are chosen to mimic a point-to-point communications link between two terminals or a base station to mobile kind of communication link.

Note that due to time limitations only a subset of the full set of measurements have been processed for this paper, all of the moving transceiver type.

A. Open Lab

In this measurement series both transceivers are located inside a large room, containing much furniture and equipment, including bookshelves and room partitioning that may block the LOS between the Tx and Rx. In addition people activity can be expected in this room. For all of these measurements the Tx array was fixed on a wooden mast, with the monopoles vertically oriented and with the ground plane topmost at a height of about 2.2 m above the floor. The Tx antenna was located at one end of the main part of the lab, which has dimensions of about 13 m$\times$ 7 m.

The Rx antenna array was in the following places:

Lab_s4: In a room adjacent to the main room, opposite the Tx antenna, non-line of sight (NLOS) condition

Lab_s5: In the main room about 8 m away from the Tx antenna, partly in NLOS condition

Lab_s6: Immediately below the Tx antenna, LOS condition

Lab_s7: In a small storage room across corridor from main room, at the same end as the Tx, but behind light walls/doors. NLOS condition.

For the remaining measurements the Tx antenna array was positioned on a table with the monopoles vertically oriented and the ground plane at a height of 88 cm above the floor.

B. Basement

In this case both the Tx and the Rx are located inside the same large room on the basement floor. This is a storage room which has concrete floor, ceiling and walls where the ceiling is cluttered with various pipes, lamps, *etc.*. The room joins a corridor in one side. For the measurements selected for the current work the Tx is located in a the south-east corner of the room and the Rx is at three different positions in the corridor:

Basement_s18: Rx at south-west, near NLOS condition.

Basement_s19: Rx at north-west, LOS condition.

Basement_s21: Rx in corridor north of room, NLOS condition.

C. Building Level Crossing

For these measurements the Tx array is on the 1st floor and the Rx is on the 2nd floor. In this situation most of the energy can be expected to propagate via corridors and staircases. The two floors are connected to a main entrance hall which covers the full height of the building.

Level_s14: The Rx is inside office next to the 2nd floor corridor.

Level_s15: The Rx is in the 2nd floor corridor.

Level_s16: The Rx is in the 2nd floor corridor, close to main hall.

D. Office to Office

In this scenario both the Tx and Rx arrays are located inside small offices next to the 2nd floor corridor.

Off2Off_s11: The offices are on opposite sides of the corridor with about 10 m between the offices, but with NLOS, due to a bend of the corridor.

Off2Off_s12: The offices are on the same sides of the corridor with one office between.

IV. PROCESSING

The data obtained from the different measurement scenarios is processed in the same way in order to allow for a direct comparison. The processing of the measured data covers the following main topics.

The theoretical capacity of the different MIMO channels is of prime interest since this reveals the possible benefits of using multiple transceiver channels. For the narrowband case and assuming no knowledge of the channel at the Tx the capacity is given by

$$C = \log_2 \left[\det \left(\mathbf{I}_M + \frac{\rho}{N} \mathbf{H}\mathbf{H}^H \right) \right]$$

where $\mathbf{I}_M$ is the identity matrix of size $M \times M$, M and N is the number of Rx and Tx antennas, respectively [2]. The channel matrix is denoted by $\mathbf{H}$ and the signal to noise ratio (SNR) by ρ.

Due to the random nature of the channel matrix the capacity distribution is obtained for each of the measured scenarios from which statistics such as mean and outage capacities can be derived. The capacity of the channel has been reported in some cases to increase when the channels have time dispersion, as compared to flat fading channels [5]. In this work the capacity is evaluated using averaging over of the capacities obtained in different frequency bands, about 2 MHz wide [6].

In order to utilize any extra diversity provided by a frequency selective channel the transceivers have to include some kind of equalizer, thus increasing complexity and introducing a tradeoff between complexity and capacity. The coherence bandwidth can be used as a measure of how large a bandwidth can be considered flat fading, and hence the upper limit of how many bits/s a given system can achieve. The coherence bandwidth is therefore estimated from the measured data.

Another important issue is how long time channel can be considered static, since this dictates how often channel has to be estimated in the transceivers using the channel. A useful measure for this is the Doppler spread of the channel, which is therefore estimated from the measured data.

V. Results

An overview of the results obtained for the different measurement scenarios are given in Tab. I.

The minimum delay and excess delay values are obtained using the power delay profile (PDP) and a dynamic range of 30 dB, below which any measured value is considered noise. Also the Doppler bandwidths are estimated using a 30 dB dynamic range form the peak of the spectrum. The coherence bandwidth was estimated using a correlation level of 0.7, and using sub-channels in the frequency domain of 2.0 MHz. Linear interpolation of the correlation curve was employed to obtain coherence bandwidths at fractions of the sub-channel bandwidth. All the values in Tab. I are obtained from a single Tx/Rx antenna combination.

Generally, it can be said that the minimum and excess delays as well as power levels are explainable from the building geometry.

Regarding the Doppler bandwidth, most of the values are within a few Hertz, where it is noted that the estimated values should be taken with some caution, since the Doppler spectra used for obtaining the values are quite noisy. However, the estimated values are comparable to the expected Doppler bandwidths since the Rx antenna array is moving at a speed of about $1/30$ m/s corresponding to a max Doppler of ± 0.6 Hz. Thus, it can be concluded that on average the activity of people, equipment, *etc.* does not increase the Doppler bandwidth much. Note, however, that this is an average figure. The channel was sampled at the much higher rate of 60 Hz in order to characterize the fast changes of the channel, such as when people walk by or doors are opening/closing *etc.*

It is interesting to note that the coherence bandwidth varies considerably depending on the environment. For example, the bandwidth for Level_s15 is more than tree times larger than that of Level_s16, even if both the measurements involve a building level crossing, and hence could be assumed to be of similar nature.

Statistics for the estimated channel capacities are shown in Tab. II, all obtained for an SNR of 10 dB. One thing to notice is that the 10% and 90% percentiles are usually within 5 bit/s/Hz and hence the available channel capacity is quite stable within a local environment.

Considerable differences in capacities are observed comparing for example the Basement_18 measurement with Lab_s4 where median capacities of 32 bit/s/Hz and 51 bit/s/Hz are obtained, respectively. The difference may be explained from the rather short CIR in the Basement_18 case compared to the much longer CIR for the NLOS case of Lab_s4. The capacities obtained may be compared to the capacity of a

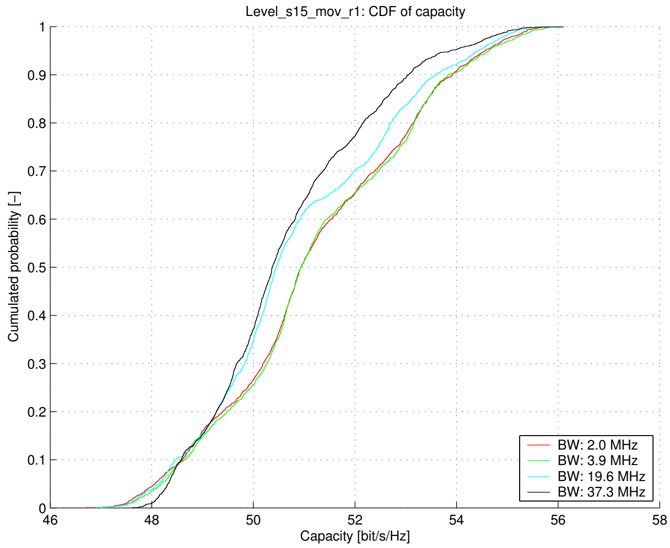

Fig. 3. CDF for capacity of Level_s15.

simulated Gaussian channel, where all the sub-channels are uncorrelated. In this case 98% of the capacities are in the range 62–66 bit/s/Hz.

The coherence bandwidths shown in Tab. I are all higher than 5 MHz which is consistent with the obtained capacity results for the 2.0 MHz and 3.9 MHz bandwidths, in general showing a negligible capacity increase when using the larger bandwidth. Hence not much frequency diversity is available. Increasing the bandwidth further to 37.3 MHz also provides no convincing improvements, despite that the coherence bandwidth is always smaller. However, the reason for this may be lack of sufficient channel samples or non-stationary channel behavior, as evidenced by a ‘bumpy’ cumulative distribution function (CDF). An example of this is given in Fig. 3.

VI. Conclusions

The objective of this work was to estimate the capacity of indoor 16×32 indoor MIMO channels taking into account both temporal and spatial channel changes.

Statistics of the obtained capacities show that for each environment 80% of the measured capacities are generally within about 5 bit/s/Hz, but the capacity may vary considerably depending on the type of environment. The median capacities thus are in the range 32–51 bit/s/Hz.

The Doppler bandwidth was found in all cases to be within about ± 2 Hz, which is comparable to the expected ± 0.6 Hz due to the known Rx speed. The added Doppler may be attributed to other changes in the channel, such as people walking by, *etc.*

The coherence bandwidths of the channels were found to be in the range 5–28 MHz, depending on the type of environment. It was generally not possible to increase the capacity of the channels using wideband transmission, even assuming bandwidths exceeding the coherence bandwidths considerably.

Measurement	Min. delay [ns]	Excess delay [ns]	Avg. power [dB]	Doppler, (min ; max) [Hz]	Coherence BW [MHz]
Lab_s4	15	210	−103.3	(−0.7 ; 0.9)	5
Lab_s5	10	170	−98.5	(−2.0 ; 1.4)	9
Lab_s6	25	135	−96.6	(−0.6 ; 1.4)	8
Lab_s7	15	155	−95.4	(−0.7 ; 0.8)	9
Off2Off_s11	60	305	−112.9	(−0.9 ; 1.3)	5
Off2Off_s13	55	135	−94.1	(−0.6 ; 0.9)	11
Level_s14	60	140	−107.0	(−0.6 ; 0.6)	21
Level_s15	60	125	−101.7	(−0.8 ; 0.6)	19
Level_s16	55	230	−107.6	(−1.6 ; 0.9)	5
Basement_s18	65	105	−91.5	(−0.3 ; 0.7)	21
Basement_s19	70	110	−90.1	(−0.6 ; 0.1)	28
Basement_s21	100	195	−110.8	(−0.4 ; 0.8)	7

TABLE I

BASIC STATISTICS FOR THE VARIOUS MEASUREMENT LOCATIONS.

Measurement	2.0 MHz			3.9 MHz			37.3 MHz		
	10 %	50 %	90 %	10 %	50 %	90 %	10 %	50 %	90 %
Lab_s4	49	51	53	49	51	53	49	51	53
Lab_s5	44	48	49	45	48	49	46	48	50
Lab_s6	38	39	41	38	39	41	37	39	41
Lab_s7	41	43	45	41	43	45	41	42	44
Off2Off_s11	47	50	51	47	49	51	47	50	51
Off2Off_s13	49	51	53	49	51	53	50	51	53
Level_s14	34	37	40	34	37	40	34	38	40
Level_s15	49	51	54	49	51	54	49	50	53
Level_s16	45	48	50	45	48	51	44	48	51
Basement_s18	30	32	35	30	32	35	30	32	35
Basement_s19	38	40	42	38	40	42	38	39	41
Basement_s21	34	37	40	34	38	40	34	38	40

TABLE II

PERCENTILES OF THE CAPACITY AVERAGED OVER DIFFERENT FREQUENCY BANDS.

This may be due to insufficient number of channel samples or non-stationary channels during the measurements.

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