MIMO System Setup and Parameter Estimation

Jeroen Warnas, Xiaoying Shao, Roel Schiphorst and Cornelis H. Slump

***Abstract*—There is a rat race in wireless communication to achieve higher spectral efficiency. One technique to achieve this is the use of multiple antenna systems i.e. MIMO systems. In this paper we describe a wireless 4x4 Multiple Input Multiple Output (MIMO) testbed in the 2.2 GHz band including results from live experiments. MIMO systems have several advantages compared to SISO (Single Input Single Output) systems. The most important ones are higher reliability and/or higher throughput per Herz. In this testbed we used the 802.11a OFDM Wireless LAN standard as a basis for the MIMO system. The experiments have been conducted at 2.2 GHz carrier using 5 MHz bandwidth. These can be divided into several topics: antenna spacing experiments, effects for increasing antennas, AD accuracy and performance for different antenna topologies. Moreover, the performance of several MIMO decoding algorithms have been evaluated. These include the Zero Forcing (ZF), Minimum Mean Square Error (MMSE) and Vertical Bell labs LAyered Space Time (VBLAST).**

I. INTRODUCTION

THE trend for ever increasing data communications has been set in the past decade and isn't about to stop. The amount of data that can be sent through a channel with a predefined bandwidth is, however, limited. Expanding the bandwidth to ensure more capacity would be a logical choice, yet this is not always possible and in the end it isn't a sustainable solution. Most of today's communication systems use Single Input Single Output (SISO) topology, which uses the channel capacity once. It has been shown in [1] that, using multiple transmit and receive antennas, it is possible to significantly increase the capacity of the channel.

Many literature can be found about MIMO theory [2]. In this paper we validate this theory by the results of live experiments in a 4x4 MIMO testbed in the 2.2 GHz band. The measurements were made in an indoor lab. First, the MIMO basics are discussed, which is followed by a description of the system setup of the MIMO testbed. This is followed by an experiments section, where the results are listed and evaluated. The paper ends with conclusions.

II. MIMO BASICS

In a MIMO system there are a multiple transmit (N_t) and receive antennas (N_r) as depicted in figure 1. The data to be transmitted is divided into (N_t) sub streams, which are encoded individually and fed into its respective transmitter. All the transmitters send their data at exactly the same time, transmitting an (N_t) sized vector of symbols.

Each of the transmitted symbols are OFDM modulated using QPSK or QAM constellations on the sub carriers. In this paper a linear model of the MIMO system will be considered. The MIMO system can be described by:

The authors are with the University of Twente, Enschede, the Netherlands (e-mail x.shao@ewi.utwente.nl, r.schiphorst@ewi.utwente.nl and c.h.slump@ewi.utwente.nl).

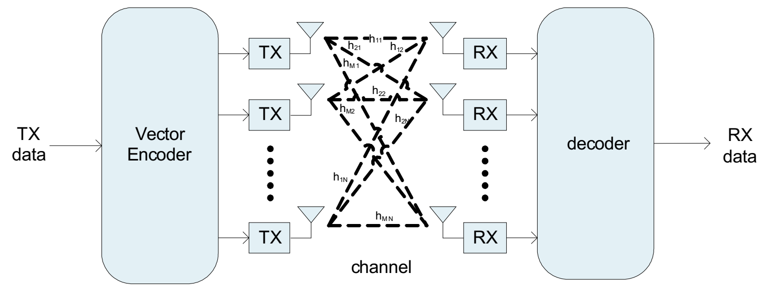

Fig. 1. MIMO communication system

$$\vec{y} = \mathbf{H}\vec{x} + \vec{n} \tag{1}$$

Where $\vec{x}$ denotes the N_t sized transmit vector with symbols drawn from the chosen constellation. The $\mathbf{H}$ matrix is an N_t x N_r sized independent identically distributed (iid) zero mean random complex variable with unit variance, which represents a Rayleigh fading channel. The channel is assumed to be flat fading. The noise vector $\vec{n}$ is a N_t sized iid zero-mean complex Gaussian noise vector. Finally $\vec{(y)}$ denotes the N_r sized received vector. The channel model is assumed to be time invariant for a chosen period.

The capacity of the MIMO channel can be derived from the SISO capacity introduced by Shannon. When using the random iid matrix $\mathbf{H}$ the capacity of the channel is an expected value.

$$C = E\left[log_2 det(I_{N_r} + \frac{E_t}{\sigma_n^2 + N_t})\mathbf{H}\mathbf{H}^H\right] \tag{2}$$

This formula is very hard to analyze analytically for $N_r, N_t > (1,1)$. To be able to get a view at the theoretic channel the capacity formula found by [3] is used.

$$C = \int_0^\infty log_2(1+\frac{E_t\lambda}{N_t})\sum_{k=0}^{m-1}\frac{k!}{(k+n-m)!}[L_k^{(n-m)}(\lambda)]^2\lambda^{n-m}e^{-\lambda}d\lambda \tag{3}$$

in which L_k is the k_{th} order Laguerre polynomial. This formula has been evaluated for several antenna configurations and signal-to-noise ratios. This has been chosen to function as our reference for the MIMO capacity.

III. SYSTEM SETUP

In the testbed, the transmitted data is generated offline using a C++ program. If the samples are computed, they are stored in memory and the transmitter software is able to feed the data, via a PCI board (ADLINK PCI 7300), to a custom designed digital to analog conversion board. The maximum throughput

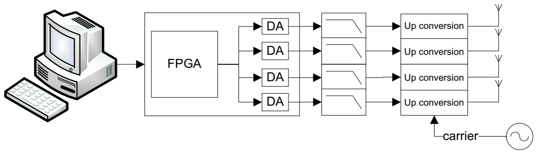

Fig. 2. MIMO transmitter hardware

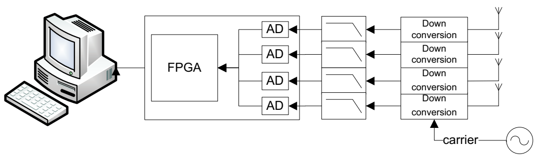

Fig. 3. MIMO receiver hardware

to the DA board is 20 MSPS. As the hardware supports a maximum of four transmit/recieve antennas the bandwidth of the system is chosen to be 5 MHz. A schematic representation of the transmitter is shown in figure 2.

The analog RF front-end contains a DA convertor (Analog Devices AD9761), a 6th order low pass analog transmit filter and a modulator (Analog Devices AD8347) to mix the signal to RF. To boost the range of the testbed its output can be connected to a 20 dB amplifier.

The receiver has a similar topology as can be seen in figure 3. The receiver has an 8th order analog low pass filter to minimize distortions from other adjacent transmitters.

The MIMO system is based on OFDM as it is a good and complexity-friendly modulation scheme for fading channels. The channel itself is estimated using least-squares estimation. The general synchronization structure is uses the Schmidl and Cox algorithm [4]. Where the optimal symbol timing, d_{opt}, is estimated by maximizing the function:

$$M(d) = \frac{|P(d)|^2}{(R(d))^2} \tag{4}$$

Where the correlation between the halves *r* is given to be.

$$R(d) = \sum_{m=0}^{L-1} r^*_{d+m} r_{d+m+L} \tag{5}$$

and the power of the second half of the system is given as

$$P(d) = \sum_{m=0}^{L-1} |r_{d+m+L}|^2 \tag{6}$$

When d_{opt} has been found the next formula provides carrier offset estimation.

$$\hat{\phi} = arg(R(d_{opt})) \tag{7}$$

The SNR is estimated by comparing a part of transmitter silence to a known transmission. The parameters of the system are summed in table I.

In the testbed we've used four different algorithms to decode a received transmission. A very simple zero forcing (ZF) method, a minimum means square error (MMSE) method and both those methods using the Vertical Bell Labs LAyered Space Time (VBLAST) algorithm [1]. The ZF method has been chosen for its simplicity and easiness to implement. The MMSE algorithm needs an estimation of the SNR and should provide better performance in higher SNR ratios than ZF. The VBLAST algorithm has been chosen as a representative of the iteratively solving algorithms. It is also fairly straightforward to implement and has clear and measurable advantages over the non-iterative methods [2]. It should also be noted that these experiments do not have any error correcting codes embedded. The Symbol Error Rate (SER) are raw and could be significantly improved with error correcting methods, obviously at the loss of data rate.

Parameter	Value
Maximum number of transmitters	4
Maximum number of receivers	4
Sampling rate	5 Msps for I and Q per channel
Carrier central frequency	2.2 GHz
Length of cyclic prefix	16 samples
Data carrying subcarriers	48
Pilots carrying subcarriers	4
Subcarrier spacing	78.125 KHz
Guard band width	860 KHz

TABLE I
SYSTEM PARAMETERS OF THE MIMO TESTBED

IV. EXPERIMENTS

The following experiments have been carried out with the MIMO testbed. A meaningful measure of the channel itself needs to be introduced. There are several ways measure the performance of the channel. First the SER is a good indicate of how well the channel has performed. It however does not say anything about the channel itself. Therefore the capacity formula (equation 2) is used to evaluate wireless channel.

The channels have been tested over 100 frames which each have 52 values (i.e. sub carriers) for each used OFDM subcarrier. This means the channel capacity will be calculated over 5200 channel model **H** matrices. The capacity will be used as an indication of the performance of the channel. The following experiments have been done on our testbed.

- *Antenna spacing* The position of the antennas in the system have an influence on its performance. The highest capacity is obtained when all the antennas get their data from different paths, when all the antennas receive exactly the same data MIMO decoding isn't possible. The independence of the received signal is correlated with the distance between the antennas. In this experiment the influence of the space between the antennas is measured and analyzed.
- *Effects for increasing antennas* The capacity of a MIMO communication system should increase linearly with the number of antennas. In this section an experiment has been done to verify this behavior.
- *Simulated loss of AD accuracy* In this experiment performance of the system is set out to the available information in bits. As the hardware cannot easily be adapted the loss of AD accuracy has been simulated by discarding the a number of the least significant bits.

Parameter	Value
Maximum number of transmitters	2
Maximum number of receivers	2
Constellation	QPSK
Sampling rate	5 Msps
Carrier central frequency	2.2 GHz

TABLE II
PARAMETERS OF THE ANTENNA SPACING EXPERIMENT

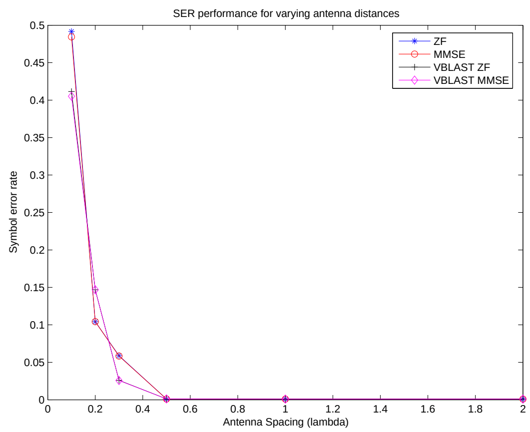

Fig. 4. SER performance for different antenna spacings

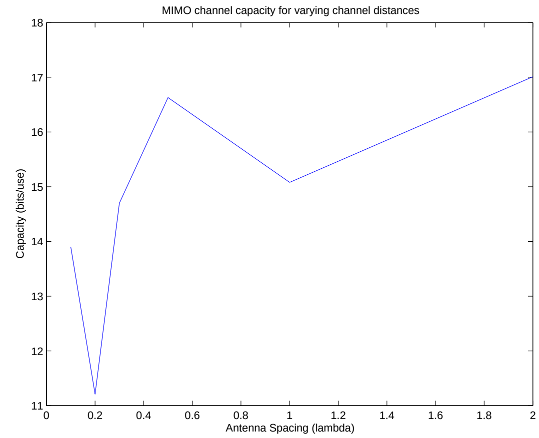

Fig. 5. Capacity versus different antenna spacings

Parameter	Value
Maximum number of transmitters	1,2,3,4
Maximum number of receivers	1,2,3,4
Constellation	QPSK
Sampling rate	5 Msps
Carrier central frequency	2.2 GHz

TABLE III
PARAMETERS FOR THE EFFECTS OF INCREASING ANTENNAS EXPERIMENT

- *Performance for different antenna topologies* In this section the results for several antenna topologies will be presented.

A. Antenna spacing

According to theory and simulation the distance between the antennas has a large influence on the performance of the system. For MIMO to work well the antenna's reception should be as independent as possible compared to the other receiving antennas. A rule-of thumb is to separate the antennas at least half a wavelength λ for independent reception. To verify this behavior the system has been measured in a 2 by 2 MIMO system with fixed distance between the transmit antennas. The distance between the two receiving antennas has been varied in several steps from 0.1 λ to 2 λ.

The parameters in table II have been used during this experiment.

First, a look is taken at the SER performance of the system. Figure 4 gives the Symbol error rate versus the the antenna spacing measured in λ. This measurement was made with an average SNR of 22.9 dB.

The figure shows clearly that the positioning of the antennas has a huge effect on the performance of the system. Below 0.5 λ the SER is relatively high. When the antenna spacing reaches 0.5 λ the SER falls. This complies with the theory that the space between the receiving antennas should at least 0.5 λ.

Now lets take a look at the capacity of the channel. An increase is expected as the antennas as the spacing between the antenna increases and become more and more independent.

Figure 5 shows on average an increase of capacity for larger antenna spacing. This increase however isn't nearly as significant as the change is SER. One would assume that the channel capacity for the 0.1 λ spacing would be smaller than at 0.2 λ spacing. This suggests that the capacity formula is not valid for small antenna spacings.

We also performed similar experiments at different locations. The overall picture shows that the antenna spacing has to be larger that 0.5 λ. The antenna spacing for the system has been chosen to be 1 λ at the transmitter and 2 λ at the receiver to optimize measurement results.

B. Effects for increasing antennas

In these test the performance of the different decoding methods are tested for an increasing number of antennas. Table III gives the parameters used for this experiment.

In simulation the decoding methods react differently to increasing number of antennas. The VBLAST based algorithms SER remained more or less constant as the non iterative ZF and MMSE algorithms kept increasing. This is a known phenomenon in MIMO [2] and this experiment was done to verify if its behavior.

The antennas configuration have not been changed or moved during this experiment. Thus all antennas were present in all individual experiments regardless of the number of antennas used. This option was chosen over changing the setup for each measurement, changing the setup will result in moving the antennas. The influence caused by moving the setup of the channel resulting from moving the antennas is deemed to be larger than the influence of the static antennas when unused. Every time another antenna was used the transmitted power was divided equally over all transmitters and the total power was kept as constant as possible. As the power in the testbed can only be attenuated in steps of 3 dB the N_t = 3 by N_r

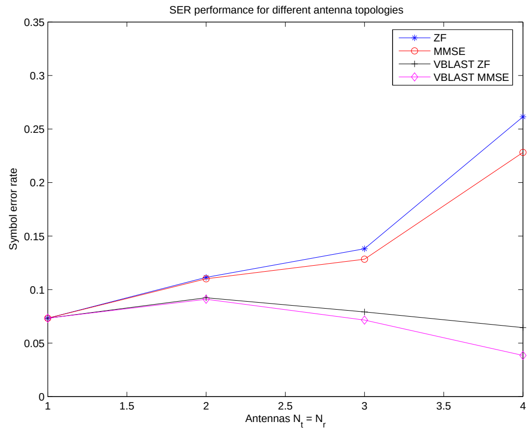

Fig. 6. SER versus the number of transmit antennas, $N_t = N_r$

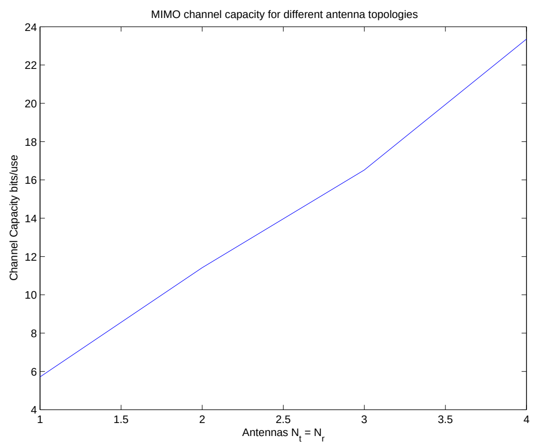

Fig. 7. Capacity versus the number of transmit antennas, $N_t = N_r$

= 3 measurement has been made on the same attenuation of the 4x4 system, this means it had less transmit power. The average SNR was measured to be near 19 dB.

In figure 6 the SER performance of the different decoding schemes is shown. The ZF and MMSE algorithms both have a clear increasing SER with an increasing number of antennas. The VBLAST based version's performance remains more or less the same. It seems as both the VBLAST are performing a bit better with increasing antenna, this could also be caused to the positioning of the antennas i.e. the measurement uncertainty.

The iterative methods show their advantage over the non-iterative methods. This experiment verifies the predicted behavior of the simulations. The capacity should also increase with multiple antennas. Using the earlier presented equation for MIMO capacity its result has been plotted in figure 7

From the picture, it can be seen that there is a clear linear correlation between the capacity and the number of antennas. This means the capacity of the channel increases linearly with the number of antennas used as predicted by [3].

C. Simulated loss of AD converter accuracy

The system uses a 10-bit AD converter to convert the analog baseband channel to the digital domain. In this experiment,

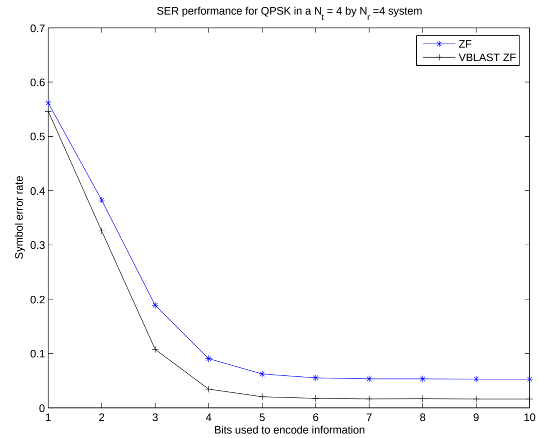

Fig. 8. SER versus the number of bits used for decoding for a 4 by 4 topology using QPSK

the minimal AD resolution is determined before severe performance degradation occurs.

The loss of "AD converter accuracy" has been simulated by discarding the least significant bit that particular time. In these experiment only the zero forcing based algorithm is used. The software measures the SNR on the basis of the received signal, the discarding of the bits will influence this measurement in a way that cannot easily be compensated.

In figure 8 the number of bits used to decode the signal set out to the SER performance. A measurement has been selected that has a relatively small SER with full ADC resolution. As would be expected the figure shows that most significant bits carry the most information, in this case the five most significant bits could be used to decode the received data without much performance degradation.

D. Performance for different antenna topologies

In the final experiment, the performance of several antenna topologies is evaluated in different positions. All the experiments have been conducted in a $N_{tx} = N_{rx}$ antenna configuration. In this section we will look at $N_{tx} = N_{rx} = 2, 4$.

As the antennas changed in distance and orientation from each other during the measurements have resulted in different SER and different signal to noise rations. Lets start with the 2x2 topology: these measurements are sorted on SNR performance and plotted in figure 9.

Surprisingly some of the estimated values are below the simulated MMSE VBLAST line. Although this is unexpected it is not impossible, the line is based on the *average* of several thousand measurements. These random models range from very bad to very good and the average has been shown. It is well possible that the single measurements made on this particular time happens to have a good MIMO channel.

Along with the SER the channel capacity has been measured and is plotted in figure 10.

In the plot the formula gives an increased capacity for higher SNR, this however is not reflected in the SER of the system which remains relatively flat. One possibility is that although the channel capacity is increased the software does not seem to

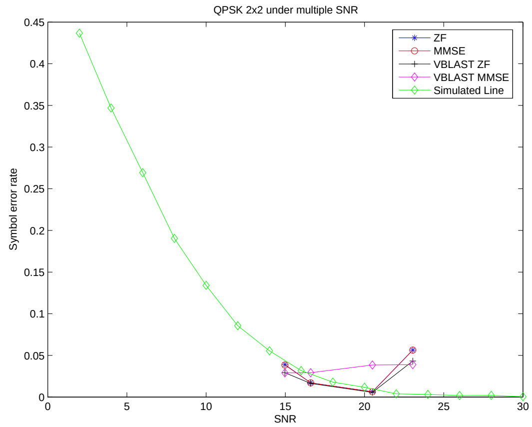

Fig. 9. SER versus SNR for a 2x2 MIMO system

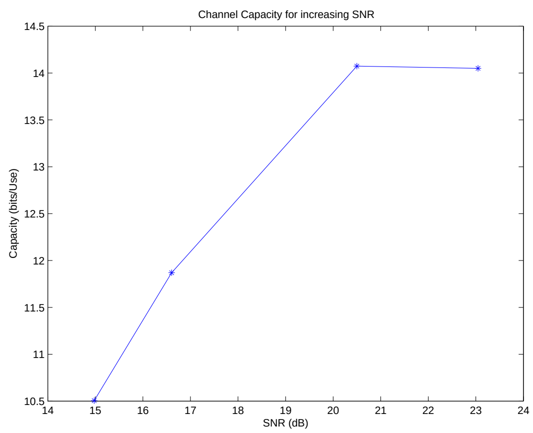

Fig. 10. Capacity versus SNR for a 2x2 MIMO system

be able to put it to good use. On the other hand the reliability of the capacity formula used in this fashion is not known. The measurement could just be the inaccuracy of the introduced method.

In the next figures, the 4x4 topology has been evaluated. Figure 11 shows a number of measurements made at various locations. The smooth line again is the simulated performance of the software. The second measurement was with a Line Of Sight between several antennas, which immediately is reflected in the SER. So MIMO systems require non-Line of Sight for optimal capacity/bit rate.

As with the other experiments the capacity for each of the measurements has been calculated and has been plotted in figure 12. Again the capacity increases along with the SNR. Note that although the SER of the second measurement is high, the capacity is in line with the others.

V. Conclusions and Future Work

In this paper we have described a 4x4 MIMO testbed in the 2.2 GHz. Moreover, a series of experiments have been conducted to verify MIMO theory with live measurements. The results verifies the predicted behavior from theory and simulation. Among others it is shown that the capacity grows linearly with the number of antennas.

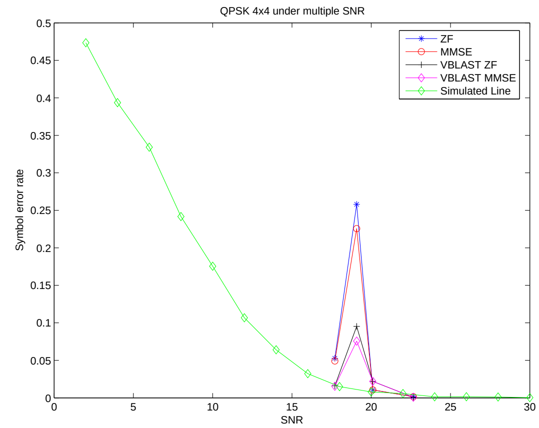

Fig. 11. SER versus SNR for a 4x4 MIMO system

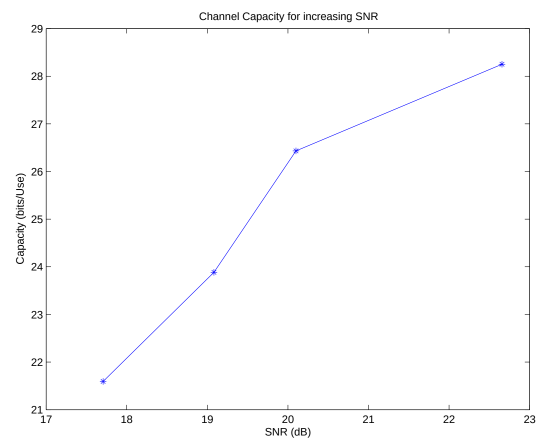

Fig. 12. Capacity versus SNR for a 4x4 MIMO system

In the future, we will incorporate error correction in the testbed. This will give more insignt in the measured channel capacity. Moreover, we will upgrade the testbed with more digital signal capacity (i.e. FPGAs) to allow real-time processing of the received signal.

References

[1] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-blast: An architecture for realizing very high data rates over the rich-scattering wireless channel," 1998, pp. 295–300.

[2] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, June 2005. [Online]. Available: http://www.amazon.ca/exec/obidos/redirect?tag=citeulike09-20\&path=ASIN/0521845270

[3] E. Telatar, "Capacity of multi-antenna gaussian channels," pp. 585–595, 1999. [Online]. Available: http://citeseer.ist.psu.edu/346880.html

[4] A. Berno, "Time and frequency synchronization algorithms for HIPERLAN/2," Master's thesis, University of Padova, October 2001.