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Over-the-air demonstration of spatial multiplexing at high data rates using real-time base-band processing

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Abstract. Over-the-air transmission experiments with a real-time MIMO test-bed are reported. We describe in principle a hardware architecture for spatial multiplexing at high data rates, discuss in detail the implementation on a hybrid FPGA/DSP platform and show measured bit error rates from indoor transmission experiments. Per-antenna rate control and joint transmission are enabled as well using an ideal feed-back link. A functional test of these new techniques is described while detailed transmission experiments are still ongoing.

1 Introduction

Some years ago, basic requirements were outlined for a new air interface which may become effective after the year 2010. A striking challenge is the need to deliver 10 times the data rate at similar costs [1].

There are spectrum, hardware and infrastructure costs in cellular radio systems. It is another issue to reduce the infrastructure costs, but there may be a trade-off between spectrum and hardware costs using multiple antennas both at the base station and at the mobile terminal forming a multiple-input multiple-output (MIMO) system [2, 3]. Various measurements have revealed the potential of MIMO to increase the spectrum efficiency at the same transmitter (Tx) power (see e.g. [4, 5, 6]). To bring these new MIMO techniques into application, the hardware effort must be evaluated, based on implementation trials.

Here we report on a real-time MIMO test-bed where the data rate is limited only by the coherence bandwidth of the indoor propagation channel and not by the digital signal processing as in an earlier implementation [7]. We report on over-the-air transmission experiments in an indoor environment and show some new features as per-antenna rate control and joint transmission.

The prototype described here has recently been shown at the *IEEE Globecom* conference in San Francisco in December 2003.

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2 The real-time MIMO testbed

The real-time MIMO test-bed was developed in the German *HyEff* project. The intention is to show the feasibility of MIMO in real-time at first in a single carrier link, based on the well-known flat fading algorithms, and to speed-up the signal processing substantially so that the system becomes limited by the coherence bandwidth of typical indoor channels. Various hardware architectures were evaluated therefore and a promising approach is implemented and fully operational now.

In particular, we use field-programmable gate arrays (FPGAs) instead of digital signal processors (DSPs) as in [7], for the real-time processing of the base-band signals. The reason therefore is the need to process multiple data streams in a single unit. The limited number of in- and output ports of current DSPs may not allow multiple high data rate streams in parallel. For the most simple MIMO algorithms, as the minimum mean-square error (MMSE) detector, all required components for the real-time processing of the received base-band signals can be integrated on current FPGAs. However, each component must carefully be programmed in VHDL, to allow a proper timing control. [(Calculation of beam steering weights, power allocation and bit loading vector). The typical MIMO algorithms are implemented on a standard DSP.] It is also used to control the system.

The complete system is shown in principle in Fig. 1. It comprises of a transmitter (Tx) unit with 4 antennas and a receiver (Rx) unit with 5 antennas. Digital processing of the discrete-time base-band signals is done using an FPGA both at the Tx and at the Rx, and at the Rx it is complemented by a DSP. The link is currently unidirectional and so a feed-back link from the Rx to the Tx is realized by cable. Since the current implementation focuses on the real-time processing, the frame and symbol synchronization are realized by cables as well.

2.1 Transmitter

The home-made 5.2 GHz Txs perform direct up-conversion using four IQ mixers each followed by +20 dBm power amplifiers (see Fig. 2).

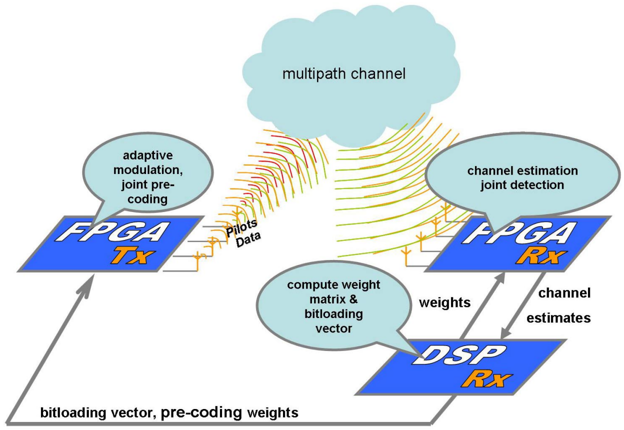

Fig. 1. Principle of the real-time MIMO testbed.

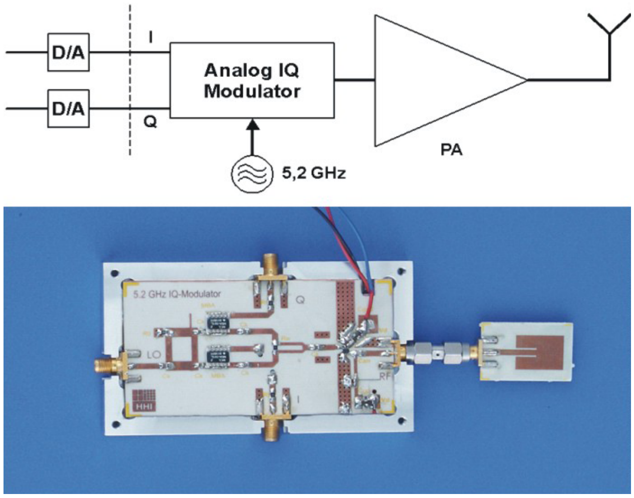

Fig. 2. One of the four 5.2 GHz transmitters.

The pilot and data signal generation, the modulation as well as the joint pre-processing using a matrix-vector multiplication unit are all realized in a XILINX XC2V8000 (see Fig. 3). The 12-bit output signals were DA converted and used to modulate the carrier (see Fig. 3).

Each of the 8 (4 times I and Q each) periodically generated signals consists of a pilot and a data block. A different 127-bit Gold sequence is used as a pilot in each signal to identify at the Rx each I and Q branch from each Tx antenna. Relatively long pilots are used to get sufficiently precise channel estimates for the linear joint transmission experiments. The requirements therefore are investigated in [8]. Each pilot is followed by a different pseudo-random data block with 1024 symbols on each stream. The joint symbol clock for all data streams is variable and so the transmission can be adapted to the coherence bandwidth in the channel. The modulation is set independently on each I and Q branch for each antenna with up to 16 PAM levels. The modulation is individually controlled using a binary vector provided externally by the DSP via cable. Note that a branch may be switched off if

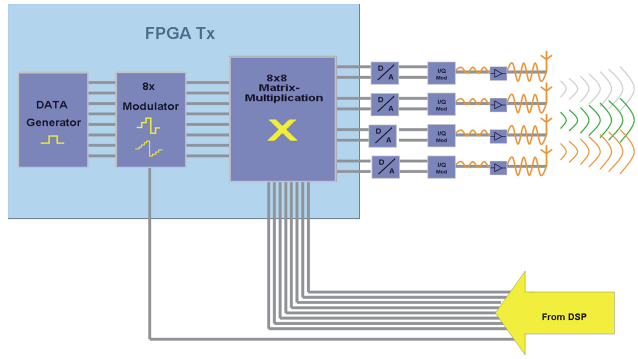

Fig. 3. Transmitter setup.

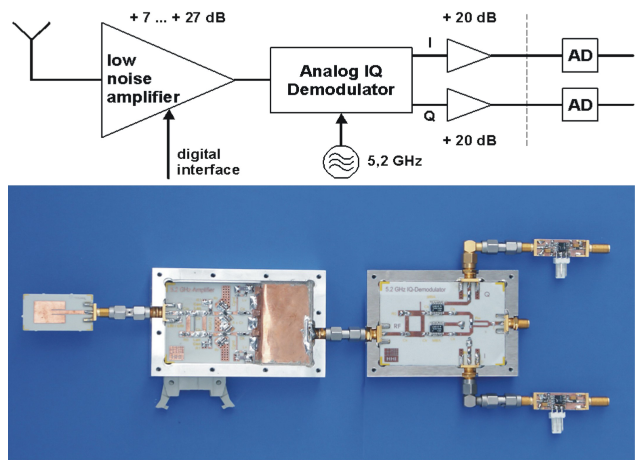

Fig. 4. One of the five 5.2 GHz receivers.

desired. Also the weights for the joint transmission can be controlled by the DSP via the feed-back link.

2.2 Receiver

The received signals from 5 antennas are amplified in a digitally controlled low-noise amplifier and directly down-converted in a home-made analogue IQ demodulator (see Fig. 4). The base-band signals are again amplified and digitized with 12-bit at a 25 MHz sampling rate.[1]

An overview of the Rx setup is shown in Fig. 5. It comprises of the channel estimation circuit, the channel tracking by the DSP, the joint detector, the multiple demodulators and the unit for the bit error rate (BER) measurements.

2.3 Channel estimation

80 correlation circuits (CC) using the known pilot sequences are implemented in the Rx FPGA (XILINX XC2V6000).

[1]The analogue RF design creates an IQ imbalance comparable to commercial products but taken into account in the entire MIMO signal processing concept. In principle, we treat the complex-valued MIMO base-band system with 4 Txs and 5 Rxs as a real-valued system having 8 Txs and 10 Rxs.

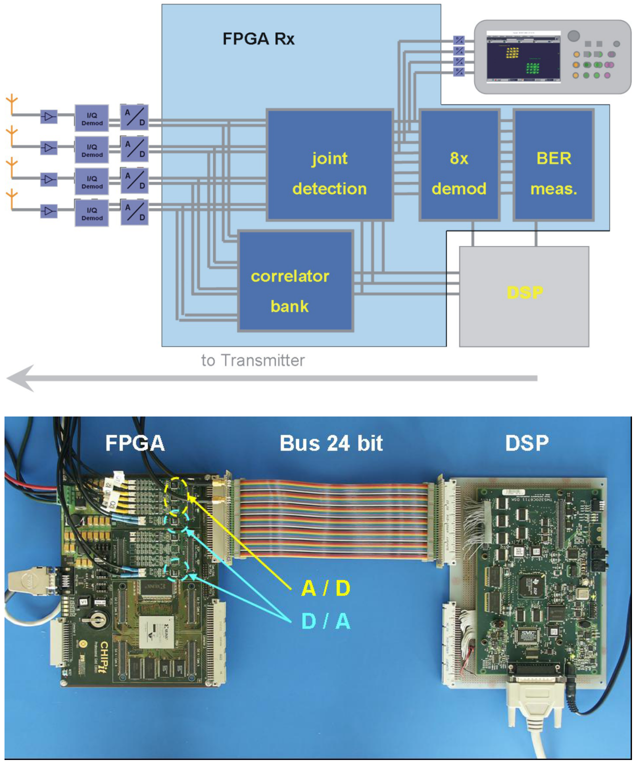

Fig. 5. Top: Receiver setup. Bottom: A/D converters are on top of the FPGA (left). A DSP (right) is connected via a parallel bus.

Since binary sequences are used, the CCs need no multiplication. The next bit in the sequence may eventually change the sign of the signal to be accumulated and then the CC switches from addition and subtraction. One such CC requires 23 out of 33.792 slices in the FPGA and so the entire channel estimation needs less than 6% of the total resources. The noise variance for the MMSE detector is estimated in an off-line measurement.

The new channel estimates are immediately available after the last bit in the sequence and stored in registers. These registers are read-out by the DSP (Texas Instruments 6713). The read/write operations of the DSP are fully asynchronous to the frame structure, enabled by back-up register pages. For a few ns after a new estimate is finished, the estimation results are transferred to these registers and access from the DSP is not permitted.

2.4 Channel tracking

The DSP is then used to calculate the coefficients of a linear MMSE filter which are then sent back to the weight registers for the joint detection in the FPGA. To achieve a higher mobility, it is critical in general to adjust the coefficients in the MMSE detector sufficiently fast. The most time consuming part of the weight calculation is a matrix inversion initially implemented in the DSP using C based on Greville's method [9]. One such inversion takes some ms depending on the antenna configuration. For multy carrier systems, the total time must be in the order of a ms carrier, as well. A detailed analysis revealed that the same task can in principle be sped up by a factor of 50 or so by better using the special matrix-vector skills of the DSP. In this way, the value for one inversion could reach some 10 μs with the same DSP and so the channel tracking rate would become sufficiently fast for indoor and pedestrian applications. Another way might be the interpolation of the inverse matrices between adjacent carriers. But our simulations indicate that the numbers of inversions can noticeably be reduced so only in the case of rather large coherence bandwidths.

Fig. 6. Over-the-air transmission experiments shown at the Globecom 2003 conference. The Tx unit is located in the centre with the antennas in the top left corner. The receive antennas are top right and the Rx unit is left from the scope tower.

2.5 Joint detection

A matrix-vector multiplication unit is implemented and used as a MMSE filter in the Rx FPGA to separate the spatially multiplexed data streams. The unit consumes 80 out of the 144 dedicated multipliers and operates synchronous to the sampling clock (25 Mio. matrix-vector multiplications per second).

2.6 Demodulation

The separated streams are individually demodulated using individual hard decisions in each I and Q branch according to the modulation format set by the DSP at the Tx, and the recovered data are compared inside the FPGA with the transmitted data. There are counters for the bit- and frame error rate in each stream which can be read out by the DSP and displayed on a screen or stored to the hard disk. The entire set-up as presented at the Globecom 2003 is shown in Fig. 6.

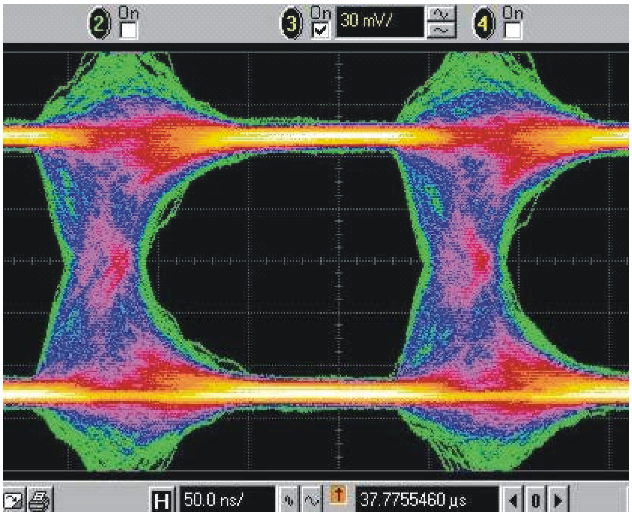

Fig. 7. Eye pattern after the separation of streams in a single I branch with 3 Tx and 4 Rx at 5 million symbol vectors per second (QPSK modulation on all streams, 30 Mbit/s).

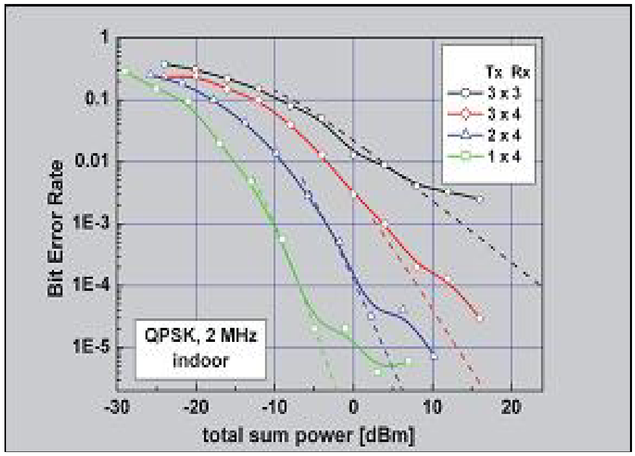

Fig. 8. Fixed rate experimental results of the mean uncoded bit error rates in an indoor scenario. The increase of the diversity is clearly evident when more receivers than transmitters are used.

3 Functional test

The eye pattern in a single I branch after the transmission with 3 Tx and 4 Rx over a 3 m distance in an indoor environment and the subsequent MIMO detection is shown in Fig. 7 at a modulation rate of 5 Mio. symbol vectors per second. The temporal dispersion in the multi-path indoor channel sets an upper limit to the maximal clock rate. It leads to the exponential fall after the start of the bit as observed in Fig. 7. Note that there is additional jitter of about 40 ns which corresponds to the 25 MHz sampling rate.

So our set-up is limited by the coherence bandwidth of the channel and not by the signal processing. Further increase of the symbol vector rate is possible in principle by increasing the sampling rate and the clock of the joint dection unit, but it requires the use of multi-carrier techniques as OFDM.

More efficient iterative MIMO detection schemes as V-BLAST were not yet implemented. Unlike in DSPs, a dedicated processing and memory architecture is required for real-time operation. Even if this might be possible in principle, the effort to implement these algorithms on the register transfer level is not negligible.

4 Transmission experiments

4.1 Fixed rate results

For the transmission experiments, up to 4 Tx and 5 Rx antennas were used in an indoor scenario. In order to realize a sufficient channel statistics, the transmitter is placed on a wagon and moved along a 5 m line through the room, which measures about 90 full carrier wavelength at 5.2 GHz. To measure the average bit error rate (BER), the bit errors are accumulated over the whole run. But at low speed it is possible to investigate the instantaneous BER as well. In the results shown in Fig. 8, the transmitter power is held fixed in each run, and a separate run was made for each power value. The Rx antennas were always more than 2 m away from the Tx and even though the line-of-sight (LOS) was free at most locations, the variation of the mean Rx power is within a few dB, due to the rich multi-path propagation. It leads to a more or less homogeneous power distribution in the entire room [6]. So this variation is left included in the results.

When changing the number of Tx and Rx antennas, the influence of the diversity is clearly obvious from the results in Fig. 8. It is observed that the diversity order increases as N_{Rx}-N_{Tx}+1 as predicted for the MMSE detector at large SNR. So the transmission becomes the more reliable the larger the difference between the numbers of receivers N_{Rx} and transmitters N_{Tx} is. The dashed lines correspond to the theory curves and they agree fairly well with the measured data.

Note that there is always an error floor at high Tx powers due to the frequency-selective nature of the channel (It disappears when the symbol rate is reduced). The position of these floors agrees very well with the theoretical analysis in [10]. In particular, the floor reduces when the diversity order increases. These floors indicate again that now we need multi-carrier techniques to further increase the symbol vector rate.

4.2 Variable rate results

Per-antenna rate control (PARC, [11]) is proposed for MIMO links to approach the channel capacity. With optimal but very complex schemes, as maximum likelihood detection, the PARC is just required to achieve this goal. But with the reduced complexity schemes, the PARC may be required also to save a reliable communication over the MIMO channel. Note that the MIMO channel matrix may eventually become close to singular. With reduced complexity schemes, a sudden increase of the noise after the MIMO detector can then be observed increasing the bit error rate. At first one

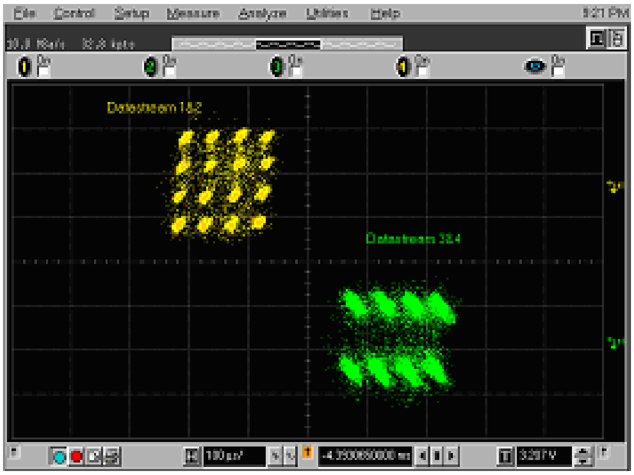

Fig. 9. Variable rate results with 4 Tx and 5 Rx antennas. A snapshot from the modulation of the third and fourth antenna signals is shown after the MMSE filter. While the former uses the same modulation in the I and Q branches, the signal on the fourth antenna is more favourably transmitted when 4 and 2 levels are used in the I and Q branches, respectively.

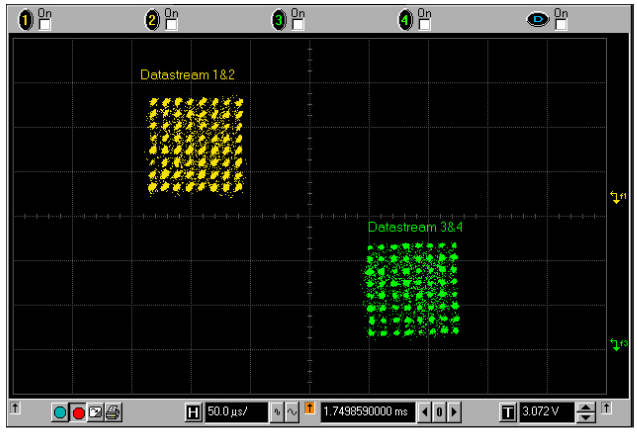

Fig. 10. Two user's signals after jointly pre-processing them based on adaptive channel inversion and transmitting the resulting signals with 4 antennas at the base station. These signals shown were immediately tapped after the AD conversion at the receivers indicating no noticeable cross-talk.

might attribute these events to some instability in the signal processing. But as soon as the PARC is switched on, this apparent instability is no longer noticeable, and the system is operational in a more stable mode.

The PARC is implemented as follows in our test-bed. As mentioned above, there are IQ-imbalances due to the RF design and so the noise in the I and Q branches corresponding to a given Tx antenna may be different after the separation of the data streams with the real-valued MMSE detector[2]. So it is natural to use multi-level modulation in each I and Q branch and steer the number of bits per branch individually. This allows a smooth link adaptation in steps of 1 bps/Hz. The demodulator design is more simple due to the individual 1-D decisions, compared to the 2-D decisions normally required, at least for 8-PSK, 32- and 128-QAM.

The PARC implementation is based on the signal to noise and interference ration (SINR) in each branch after the joint MMSE filter. The SINR is a side result from calculating the filter coefficients in the DSP. In order to guarantee a certain quality of service in each branch, i.e. a certain BER, the effective SNR is compared to a list of pre-defined values required for that BER and then the modulation is set so that the currently available SNR satisfies the requirement. If data streams are not used, the weights are again obtained using the reduced channel matrix.

A typical IQ diagram of two separated antenna signals after the MMSE filter is shown in Fig. 9. The mixed-mode modulation formats observed in the oscilloscope screen-shot are used by the scheduling algorithm on occasion. Note that the noise is anisotropic in the IQ diagram of the particular antenna, where the scheduling algorithm has decided to use a mixed modulation.

In the indoor set-up with 4 Tx and 5 Rx antennas and at high SNR, the scheduling algorithm occasionally decides in favour of 256-QAM constellation in favourable channels. But the BER in these streams is too large due to the non-linearity of the IQ mixers at the Tx. After a careful adjustment of the local oscillator power and the modulation amplitudes, error-free detection of 64-QAM module signals is possible. So with 4 Tx antennas the maximal spectral efficiency is 24 bps/Hz. Depending on both the channel condition and the SNR, typical values range between 10 and 20 bps/Hz corresponding to data rates between 50 and 100 Mbit/s at 5 Mio. symbol vectors per second.

Note that the adaptation tends to switch off one or more antenna signals at low SNR, while the remaining streams may be transmitted at higher-level modulation formats.

Altogether we have observed that the PARC makes the MIMO communication with simple detection schemes more reliable and it should be used when the channel changes slowly enough to provide feed-back, as in indoor or pedestrian applications. With respect to the signal processing effort we feel that introducing the individual rate control for the parallel streams at the transmitter may be more efficient than using a more complex detection scheme at the receiver. Such pre-adaptation at the transmitter may be a distinct feature in future wireless systems since it reduces the signal processing effort significantly while it maintains a high quality of service.

4.3 Joint transmission using adaptive channel inversion

In the down-link of mobile communication systems, it is desirable to jointly pre-process the data for multiple users and transmit them at the same time at the same frequency using

[2] This is observed also in the estimated real-valued channel matrices. Without IQ imbalance, there are always pais of singular values which are degenerate. Including the imbalance, they are no longer degenerate.

multiple antennas at the base station. Of course, such a joint transmission (JT) needs channel side information at the transmitter, which can be realized via a feed-back link or by exploiting the channel reciprocity available in TDD systems up to moderate mobility. The most simple way to realize JT is to multiply the transmitted data streams with the pseudo-inverse of the channel matrix and in this way the striking new feature of JT can best be explained.

In particular, the JT separates the data streams in advance so that each user receives only the desired signal, while the signals of all other users are forced to zero. But this forcing of zeros is costly in terms of the Tx power. When the channel matrices become close to singular on occasion, the Tx power tends to infinity. These outage events are less likely when more base station antennas than users are in the system. But a scheduling approach to achieve this at least temporarily may be useful as well. If the channel becomes singular, there are rather frequently just one or two users for which the zero-forcing criterion substantially increases the transmitter power. By interrupting the link to those users and transmitting with the whole power to the other users for a while, on average a higher throughput can be achieved for all users. This is called adaptive channel inversion (ACI) and investigated [12, 13]. In particular it was found that the channel capacity can so be achieved, at least for small SNR, while for high SNR there is some penalty.

Using the perfect feed-back link in our test-bed, we have realized the JT based on ACI. A screenshot in Fig. 10 shows the base-band signals from two Rx antennas immediately after the AD conversion. Obviously there is no more cross-talk among the user's signals noticeable, as desired. At least when the users move slowly, the 64-QAM signals can be detected without joint signal processing at the two receivers. Consequently, the two streams can be assigned to two separate users.

5 Conclusions

In conclusion, we have described a software-reconfigurable real-time test-bed for MIMO transmission at high data rates in which the speed of the signal processing is limited only by the coherence bandwidth in the channel. Using the well-known flat-fading linear MMSE algorithm with 4 transmitters and 5 receivers, over-the-air data transmission was demonstrated in the up-link. We have shown that per-antenna rate control may significantly improve the stability of the MIMO radio link. It avoids already in advance the frequent outage events occurring after reduced-complexity MIMO detection schemes. For the down-link, joint transmission experiments using adaptive channel inversion have been described as well, still based on a perfect feed-back link. Future work is directed to the demonstration of JT in time-division duplex mode based on the channel reciprocity and to the implementation of MIMO-OFDM to further increase the symbol vector rate.

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