THE VIENNA MIMO TESTBED: EVALUATION OF FUTURE MOBILE COMMUNICATION TECHNIQUES

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In order to evaluate current and upcoming mobile communications standards and to investigate new transmission as well as receiver techniques in a real-world environment, a very flexible testbed was set up at the Vienna University of Technology, comprised of multiple base stations, each equipped with several antennas. After providing an overview of this testbed and its capabilities, different kinds of measurements and their underlying methodologies are described in the context of 3GPP Long Term Evolution (LTE) transmissions. These are, on the one hand, point-to-point LTE Multiple-Input Multiple-Output (MIMO) throughput measurements, employing a single base station and, on the other hand, modern interference alignment measurements, utilizing up to three base stations simultaneously.

Introduction

The decades after Marconi's invention were filled with wireless experiments. Although we understand many physical phenomena of wireless propagations today much better than in the past, the channel models we use still capture only a part of the complex physical process. Nevertheless, in the last two decades, it has become a common method to entirely skip experimental validation and trust existing channel models when designing mobile communication systems. As the complexity of mobile communication standards also increases, simulation methods appear to be the Holy Grail to solve open design questions. While these methods deliver quantitative results in acceptable time, many important issues are simplified or not modeled at all, trading off timely results for accuracy. Converting new algorithmic ideas into hardware on the other hand is quite time consuming and often lacks flexibility so that experimental evaluation remains no longer an attractive choice. We show that with our testbed approach, we essentially combine the advantages of both worlds: design flexibility and timeliness under true physical conditions.

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In this article, we explain briefly our testbed approach[1] and our optimized measurement methodology that allows the deducing of results based on a minimal number of sampling points in the following section, "The Vienna MIMO Testbed: A Marriage of Hardware and Software." Experimental examples based on 3GPP Long Term Evolution (LTE) are then provided in the section "LTE Measurements," and finally experimental results for the interference alignment (IA) transmission scheme[2] are presented in the section "Interference Alignment Measurements." The article briefly sums up the findings with a "Conclusion" section.

The Vienna MIMO Testbed: A Marriage of Hardware and Software

The Vienna MIMO testbed consists of various hardware components that couple data generating and capturing PCs, radio frequency front ends, antennas, and a suite of software tools, the so-called Vienna LTE Simulators.[3][4][5] While the LTE simulators help in designing optimal algorithms, the same signals can be fed into the testbed in order to transmit them over the air. The captured data are then input to the receiver part of the simulators and can be evaluated offline later on. It is important to note that the Vienna MIMO testbed is not limited to LTE transmissions. The LTE simulator can be easily replaced by software implementations of any desired communication system that meets the constraints of the testbed.

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Hardware

Figure 1 exhibits the main hardware components required to convert *a priori* generated data into electromagnetic waves, transmitting them over the air and finally capturing them before storing them in digital form for further evaluation. The major hardware components are:

- Three rooftop transmitters supporting four antennas each. The digital signal samples are converted with a precision of 16 bits and are transmitted with adjustable power within a continuous range of about −35 dBm to 35 dBm per antenna.
- One indoor receiver with four channels that converts the received signals with a precision of 16 bits before the raw signal samples are saved to hard disk. The receive antennas are mounted on a positioning table, which allows for measurements at different positions within an area of about 1 m × 1 m.
- The carrier frequency, the sample clock, and the trigger signals are generated separately at each station utilizing GPS synchronized rubidium frequency standards. The synchronization of the triggers is based on exchanging timestamps in the form of UDP packets over a trigger network.[6] The precision of this trigger mechanism does not require any further

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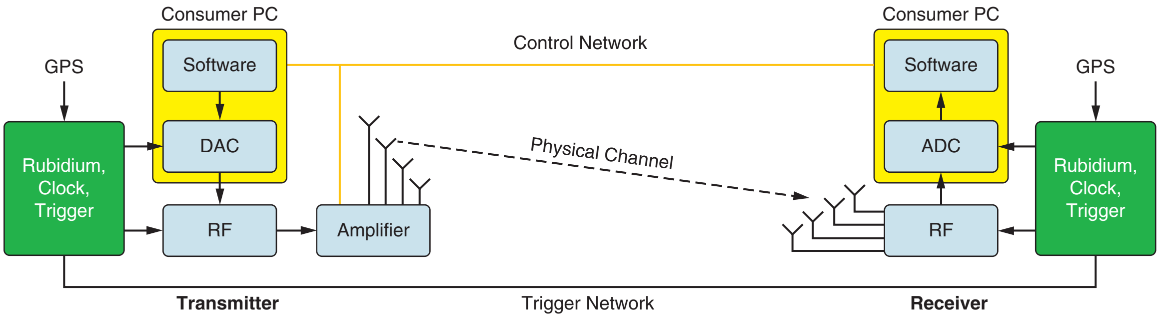

Figure 1: Testbed setup showing GPS-controlled rubidium clocks at both ends of the transmission chain (Source: Vienna University of Technology, 2014)

post-synchronization at the receiver. It is sufficient to measure the delay once and time-shift all signals according to the measured delay.

- A dedicated fiber-optic network is utilized to exchange synchronization commands as well as feedback information and general control commands.

The current setup supports a transmission bandwidth of up to 20 MHz at a center frequency of 2.503 GHz.

LTE Simulators

Along with the hardware setup, a suite of software-based simulators are employed. Currently we support:

- The Vienna LTE-A Downlink Link Level Simulator (DL-LL)
- The Vienna LTE Uplink Link Level Simulator (UL-LL)
- The Vienna LTE Downlink System Level Simulator (DL-SL)

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Our simulators together with published results were released under an open license agreement, free of charge for academic research. Over the years, many thousand users have formed a Web-based exchange forum where open problems were posed and solutions discussed. Due to these efforts in reproducibility, our simulators not only increased in functionality but also gained substantial quality. Many companies are now also using the simulators because they offer a convenient platform to exchange results between partners. The DL-SL simulator is only listed here to provide a complete list; this simulator uses link-level abstractions and supports simulations with hundreds of users since such complexity would not lead to acceptable run times in link-level precision. Both link-level simulators can be used to generate inputs to the testbed and testbed outputs can be fed back into them, hence providing an LTE-compliant transmission chain whose data can be directed to the transmit antennas and captured at the receive antennas instead of running transmissions over simulated channels such as ITU or Winner. Although the transmission only allows a burst mode, we can continuously generate such data bursts and mimic accurately continuous transmissions. The received symbols are time-stamped and can later be fed back into the simulator chain for evaluation. By this we can directly compare simulations with measured results based on identical transmit data and identical receiver algorithms, allowing very rigorous research results.

Measurement Methodology

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In typical measurements, the transmission of desired signals, or rather signals generated according to parameters of interest, is repeated with different values of transmit power in order to obtain results for a certain range of receive signal-to-noise ratios (SNR). Furthermore, the transmission of such signals at all values of transmit power is repeated at different receive antenna positions in order to average over small-scale fading scenarios. As a rule of thumb, in a typical scenario approximately 30 measurements of different receive antenna positions are necessary to get sound results for an LTE signal with a bandwidth of 10 MHz. In order to check whether we have measured enough channel realizations, we always include BCa bootstrap confidence intervals in our results (see the following section and Caban et al.[7]). While this process is usually the same for different kinds of measurements, they may differ in the way transmit signals are generated.

As illustrated in Figure 2, two different methodologies are utilized as detailed in the following:

- *Brute force measurements:* All signals of interest are pre-generated, transmitted over the physical channel, and saved as raw signal samples to hard disk. The received signals are then evaluated offline. This approach is only feasible as long as the time duration of all the different transmit signals is small compared to the channel variations so that successively transmitted data sets appear to be transmitted over the same channel.
- *Measurements with feedback:* The transmit signals are generated on the fly utilizing channel state information obtained via a preceding transmission of training symbols. While the processing and evaluation of the actual data symbols can be computed offline, the demodulation of the training symbols, evaluation, and decision about the generation of the next transmit signal has to be performed in (quasi-) real time.

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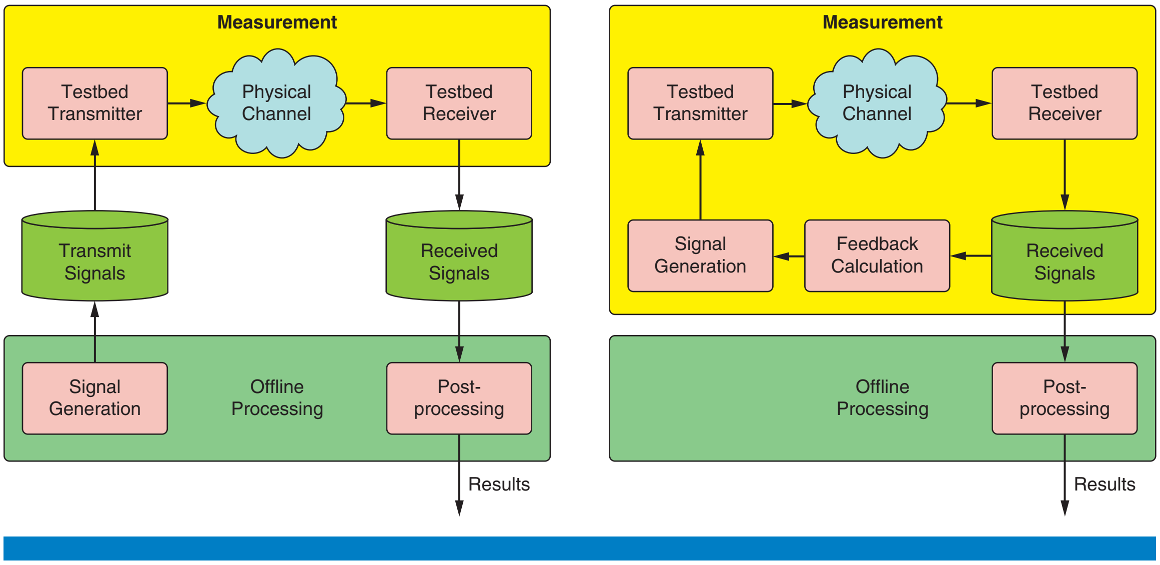

Figure 2: Measurement process without (left) and with feedback (right) (Source: Vienna University of Technology, 2014)

While brute force measurements typically take longer than the feedback approach and the number of different signals that need to be evaluated is much higher, results obtained by brute force measurements are typically more detailed and are certainly not contaminated by the quality of the feedback function. If the number of different transmit signals is not too large, a combination of both methodologies is possible. All signals of interest are pre-generated, but only those a feedback function decides for are transmitted. This approach reduces the number of signals that have to be evaluated and signals do not have to be generated during the measurement. Nevertheless, it should be noted that if the number of possible transmit signals is rather large or infinite (for example, zero-forcing Multi-User MIMO mode), only a feedback approach is feasible.

LTE Measurements

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While LTE cellular systems are already being rolled out and operated in many countries around the world, there are still unresolved issues in transmission technology. Focusing on point-to-point single-user LTE transmissions, there exist many open questions that can be best tackled by LTE measurements:

- Comparison of different kinds of receivers (receiver algorithms)
- Performance of novel and modified transmission schemes following the LTE standard
- Performance measurements at extreme channels (for example, very high speed) for which channel models are very crude or even nonexistent
- Comparison of different penetration scenarios or different antenna configurations

In the following, we present two measurements comparing on the one hand two different transmit antenna configurations and two different scenarios on the other hand. For both measurements the brute force approach using the DL-LL simulator as software implementation of the base station and the user equipment was used. We chose the open loop spatial multiplexing transmission mode where no feedback of the preferred precoder is performed. Thus the number of different transmit signals is small enough to apply the brute force approach.

A Comparison of Different Antenna Configurations

We were interested in evaluating the influence of the transmit antenna configuration on the performance of the LTE MIMO downlink. Possible configurations for the case of two transmit antennas are cross-polarized antennas, as they are used in today's base station antennas, and equally polarized antennas. For the measurements presented below, we utilized an off-the-shelf double cross-polarized sector antenna (Kathrein 800 10543) whose four antenna elements were used for implementing both a cross-polarized antenna pair and two equally polarized antennas with a spacing of 1.24 wavelengths (see legend of Figure 3).

"…spatial multiplexing outperforms single-stream transmission only above a certain average SNR we observe that a cross-polarized configuration outperforms an equally polarized configuration."

Figure 3 shows the measured throughput of the LTE open-loop downlink. In the left plot the results are shown over measured average SNR for a fixed transmission rank (1 or 2) where for single-stream transmission (rank 1) both antenna configurations performed similarly. The results for two spatial streams (rank 2) show on the one hand that spatial multiplexing outperforms single-stream transmission only above a certain average SNR. On the other hand, we observe that a cross-polarized configuration outperforms an equally polarized configuration. In the right plot, the throughput was maximized over the number of spatial streams for every channel realization, resembling a feedback selection scheme. More details on measurements comparing different vertical and horizontal setups for 2x2 as well as for 4x4 transmissions are described by Lerch and Rupp.[8]

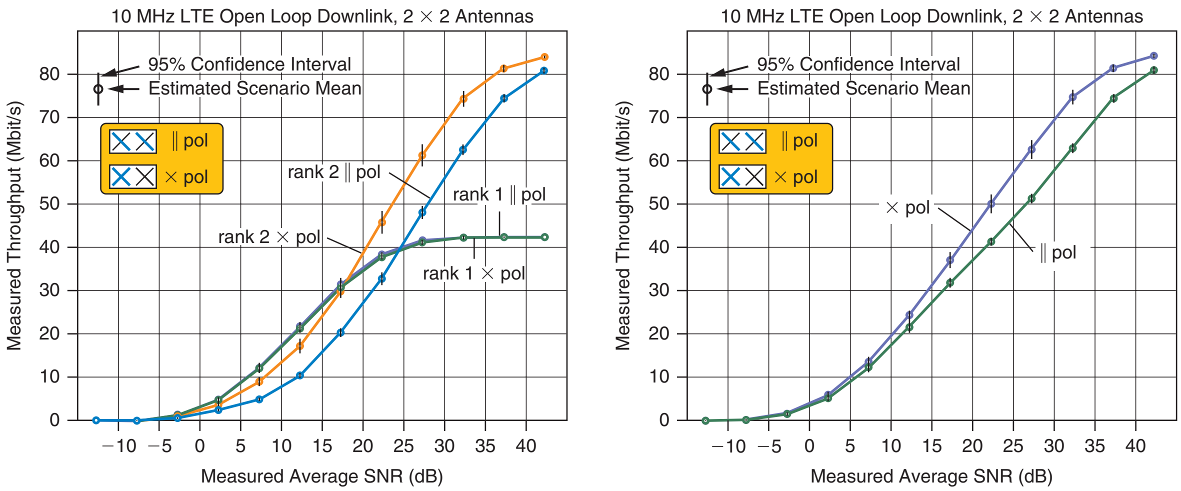

Figure 3: Comparison of cross-polarized and equally polarized transmit antennas in terms of LTE throughput (Source: Vienna University of Technology, 2014)

A Comparison of Different Scenarios

While the previous results were obtained in a certain scenario given by the location of the transmitter and the receiver, we were further interested in a comparison of different scenarios. Therefore the measurement was repeated placing a transmitter at a different location and keeping the receiver location. In the previous scenario there was no line-of-sight path between the transmitter and the receiver. We considered a second scenario with a significant line-of-sight path. These two scenarios will be referred to as Non-Light-of-Sight (NLOS) and Line-of-Sight (LOS).

The left plot of Figure 4 shows the results considering two transmit antennas. While the cross-polarized antennas perform similarly in both scenarios, an even worse performance is obtained when considering equally polarized antennas in the LOS scenario, although only in the higher SNR regions where data is transmitted over two spatial streams. At lower SNRs, where only a single data stream is transmitted, the performance is quite independent of the scenario and the transmit antenna configuration used. Finally, the right plot of Figure 4 shows a comparison of both scenarios considering four transmit antennas. The results are similar to those for two antennas. While in the lower SNR regions the difference is negligible; at higher SNRs, where data is transmitted over multiple spatial streams, the performance in the NLOS scenario is better than in the LOS scenario.

"While in the lower SNR regions the difference is negligible; at higher SNRs, where data is transmitted over multiple spatial streams, the performance in the NLOS scenario is better than in the LOS scenario."

Interference Alignment Measurements

Interference alignment (IA)[2] is an example of a system setup that utilizes all three transmitters simultaneously with feedback. IA measurements fully exploit all capabilities of the Vienna MIMO testbed.

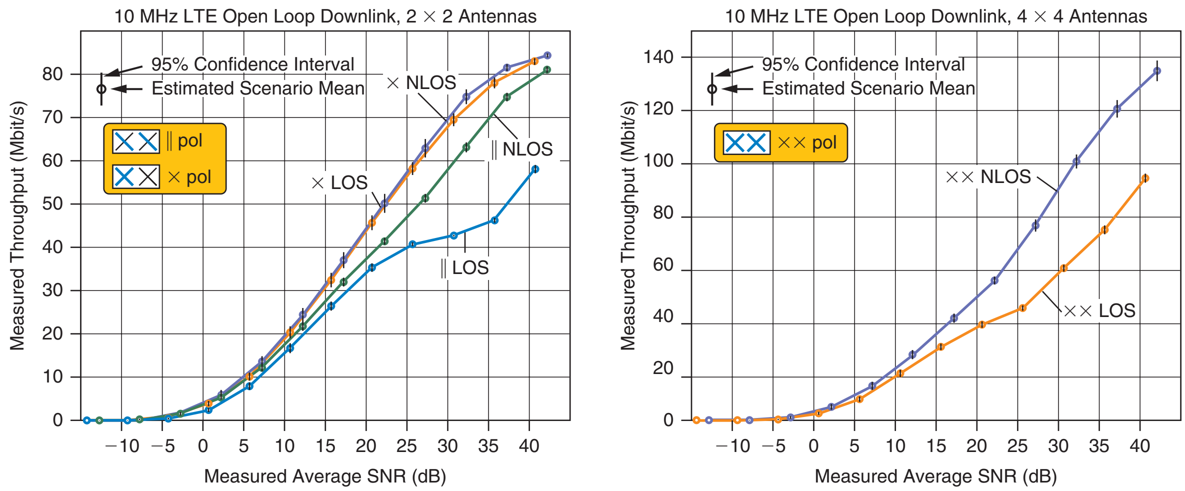

Figure 4: LTE throughput measurement results comparing LOS and NLOS scenarios for two and four transmit antennas.
(Source: Vienna University of Technology, 2014)

"All three users experience heavy interference from the other base stations approximately as strong as the desired downlink signal."

"In the ideal case, half of the capacity of the interference-free case with four data streams can be achieved, which is more than what is obtained by using resource sharing."

The Concept of Interference Alignment

Consider the cellular scenario shown in Figure 5 where three mobile users at the cell edges wish to communicate with a different base station. All three users experience heavy interference from the other base stations approximately as strong as the desired downlink signal. An emerging MIMO technique to cope with such a scenario is called *interference alignment.* Based on the knowledge of the channels between every user and every base station, a joint calculation of precoding matrices, V_i i = 1, 2, and 3 and receive filters, U_i i = 1, 2, and 3, is performed, by which half of the degrees of freedom of the MIMO channels are utilized for data transmission while the other half are exploited to align the interferences at the receiver. By applying the receive filters, interferences are eliminated and only the data signal of interest is retained. Thus, instead of transmitting the maximum number of four data streams over a 4x4 MIMO channel, only two data streams are transmitted. In the ideal case, half of the

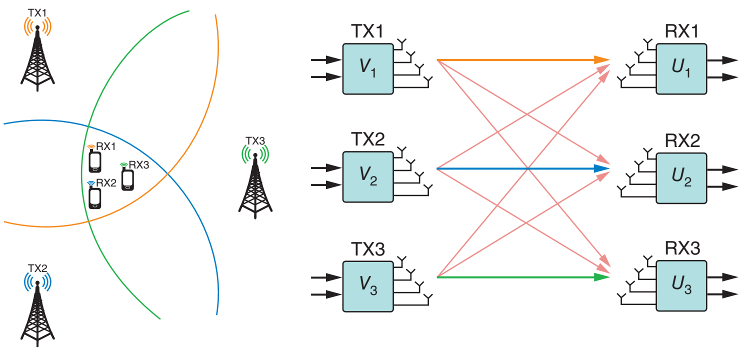

Figure 5: Interference alignment scenario and setup
(Source: Vienna University of Technology, 2014)

capacity of the interference-free case with four data streams can be achieved, which is more than what is obtained by using resource sharing. (Orthogonal multiple access schemes like time division multiple access can only offer a third of the capacity for each of the three users).

Measurements

Measurements with the Vienna MIMO testbed were carried out to show the feasibility of IA in a real-world scenario and to provide a basis for further investigations on the impact of different kinds of practical issues on the performance of IA. In order to evaluate IA on our testbed, we implemented the ideas below:

- While all three base stations are needed in order to transmit at the same time, one receiver that can act as any of the three receivers is indeed sufficient. The other two receivers can be virtual receivers and the respective channels can either be generated randomly or can be results of past channel measurements.
- Every mobile user has to estimate the channels to all transmitters. Therefore, not only must the training symbols from different antennas of each base station be orthogonal among themselves, but the training symbols of all different base stations must also be orthogonal. In the case of three base stations, each having four antennas, the channels from twelve transmit antennas have to be estimated simultaneously. Thus, standard compliant LTE, whose pilot structure only supports up to four transmit antennas, is not applicable, and therefore we implemented our own transmission scheme described below.
- Each transmit frame consists of a pilot preamble followed by the data payload. The pilot preamble is constructed to estimate the channels to all transmit antennas simultaneously and the data payload is designed to estimate the mutual information of the transmission. The precoders applied to the data payload are based on the channel estimates obtained from the respectively previous transmission. In order to keep the time between the channel measurement and the application of the respective precoders short (less than 20 ms), we took only a single subcarrier into account.

IA requires all involved transmitters and receivers to be synchronous in terms of carrier frequency and time. On our testbed, rubidium frequency standards at every station combined with a GPS based trigger network provide the required synchronicity. In order to receive the signals from different transmitters perfectly synchronous at the receiver, the transmit signals are time shifted according to the delays between the respective transmitter and the receiver. For a more detailed discussion of IA measurements on the Vienna MIMO testbed, the reader is referred to Mayer et al.[9]

"IA requires all involved transmitters and receivers to be synchronous in terms of carrier frequency and time."

Results

The left plot of Figure 6 shows the mutual information results of a measurement for a fixed signal-to-interference ratio (SIR) of −3 dB, that is, the signals from all three base stations are received equally strongly at the receivers. In order to compare the performance of IA to a non-cooperative scheme, a full rank

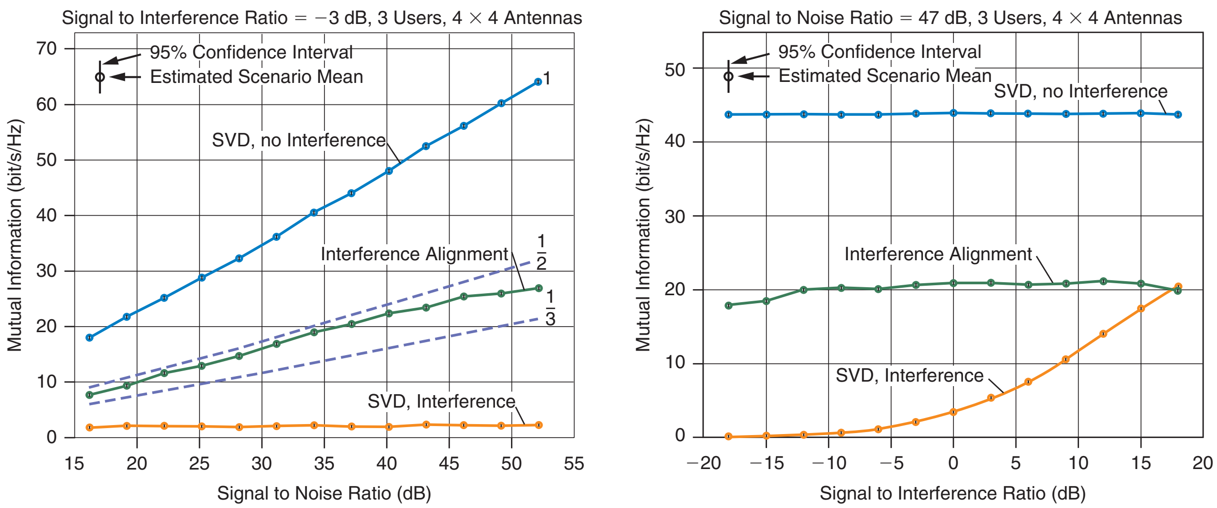

Figure 6: Performance of IA for a fixed SIR (left) and a fixed SNR (right).
(Source: Vienna University of Technology, 2014)

transmission based on the Singular Value Decomposition (SVD) of the channel utilizing all four available data streams was measured in the same scenario. In the case of interference, the performance of the SVD transmission (orange curve) is solely determined by the rather low SIR and therefore quite constant over the observed SNR region. IA (green curve) reaches, following the theory (dashed blue curve), almost half of the mutual information of the interference-free full rank case (blue continuous line). At high SNR, a saturation of mutual information is observed in the IA case. This is due to the fact that IA is very sensitive to channel estimation errors as mentioned by Garcia-Naya et al.[10] The precoders are always computed from the channel estimate of the previous transmission, and since our feedback is only finitely fast, the channels have time to change between transmissions. Thus, despite the high SNR, there will always be residual interference power due to imperfect alignment that limits mutual information, as long as the channel is not perfectly static.

"IA reaches, almost half of the mutual information of the interference-free full rank case IA is very sensitive to channel estimation errors…"

The results for a fixed signal-to-noise ratio of 47 dB are shown on the right plot of Figure 6. With increasing SIR (decreasing interference) the performance of the non-cooperative full rank transmission increases and outperforms IA at a certain level of SIR. Above this level, a mobile user should rather be scheduled for a different transmission scheme than IA.

"With increasing SIR (decreasing interference) the performance of the non-cooperative full rank transmission increases and outperforms IA…"

Conclusion

The article describes a testbed methodology that combines the rapid development speed of software with the precise measurements results including physical wireless channels.

The capability of our testbed to measure over a wide range of transmit power within the same scenario allows for deep insights into the performance of modern mobile communication systems. As an example, we demonstrated in terms of LTE throughput that the performance of MIMO techniques does not only depend on the signal-to-noise ratio. It also depends on the actual transmit antenna configuration and the scenario. Our measurement based evaluation of interference alignment provides viable information regarding its possible fields of application and the entailed constraints. The inherent precoder feedback delay and the extensive channel knowledge requirement narrow the field down to applications that comprise reliable feedback and coordination. Fully exploiting the capabilities of the Vienna MIMO Testbed, interference alignment was shown to be feasible, achieving results close to theory and outperforming orthogonal access schemes in case of intermediate to strong interference at fairly high SNR.

"…the performance of MIMO techniques does not only depend on the signal-to-noise ratio. It also depends on the actual transmit antenna configuration and the scenario."

References

[1] Caban, S., C. Mehlführer, M. Rupp, and M. Wrulich, *Evaluation of HSDPA and LTE: From Testbed Measurements to System Level Performance* (New York: John Wiley & Sons, 2012), p. 404.

[2] Cadambe, V. R. and S. A. Jafar, "Interference Alignment and Degrees of Freedom of the K-User Interference Channel," *IEEE Transactions on Information Theory,* vol. 54, no. 8, pp. 3425–3441, 2008.

[3] Mehlführer, C., J. Colom Ikuno, M. Simko, S. Schwarz, M. Wrulich, and M. Rupp, "The Vienna LTE Simulators - Enabling Reproducibility in Wireless Communications Research," *EURASIP Journal on Advances in Signal Processing*, vol. 2011, pp. 1–13, 2011.

[4] Schwarz, S., J. Colom Ikuno, M. Simko, M. Taranetz, Q. Wang, and M. Rupp, "Pushing the Limits of LTE: A Survey on Research Enhancing the Standard," *IEEE Access,* vol. 1, pp. 51–62, 2013.

[5] "The Vienna LTE simulators," Institute of telecommunications, Vienna University of Technology, [Online]. Available: www.nt.tuwien.ac.at/ltesimulator.

[6] Caban, S., A. Disslbacher-Fink, J. A. Garcia Naya, and M. Rupp, "Synchronization of Wireless Radio Testbed Measurements," in *IEEE International Instrumentation and Measurement Technology Conference,* Binjiang, 2011.

[7] Caban, S., J. A. Garcia Naya, and M. Rupp, "Measuring the Physical Layer Performance of Wireless Communication Systems," *IEEE Instrumentation & Measurement Magazine, v*ol. 14, pp. 8–17, 2011.

[8] Lerch, M. and M. Rupp, "Measurement-Based Evaluation of the LTE MIMO Downlink at Different Antenna Configurations," in *17th International ITG Workshop on Smart Antennas*, Stuttgart, 2013.

[9] Mayer, M., G. Artner, G. Hannak, M. Lerch, and M. Guillaud, "Measurement Based Evaluation of Interference Alignment on the Vienna MIMO Testbed," in *The Tenth International Symposium on Wireless Communication Systems*, Ilmenau, 2013.

[10] Garcia-Naya, J. A., L. Castedo, O. Gonzalez, I. Ramirez, and I. Santamaria, "Experimental evaluation of Interference Alignment under imperfect channel state information," in *9th European Signal Processing Conference (EUSIPCO),* Barcelona, Spain, 2011.

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Author Biographies

Martin Lerch studied electrical and communication engineering at the Vienna University of Technology where he received his master's degree in 2008. During this time and later, Martin developed several database, Web, and desktop applications before he returned to the Vienna University of Technology in 2011 to work on the Vienna MIMO testbed. Martin's work focuses on the development of new measurement methodologies for static and high mobility mobile communication scenarios. Contact him at mlerch@nt.tuwien.ac.at

Sebastian Caban works as a consultant for operational excellence next to being a postdoctoral researcher at the Vienna University of Technology. He holds a BSc, MSc, and PhD in Telecommunication Engineering as well as a BBA and MBA in business administration. His research focuses on developing measurement methodologies and building testbeds to quantify the *actual* performance of wireless communication systems. He can be contacted at scaban@nt.tuwien.ac.at

Martin Mayer is a research assistant at the Vienna University of Technology. He holds a BSc degree in Electrical Engineering and Information Technology and an MSc degree in Telecommunication Engineering, both received at the Vienna University of Technology in 2011 and 2013, respectively. For his master's degree,

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Markus Rupp holds the chair for signal processing in mobile communications at the Vienna University of Technology. His research is devoted to digital wireless communication systems with a focus on cellular communications but also addressing near field communications as well as traffic modelling. He can be contacted at mrupp@nt.tuwien.ac.at