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Author(s)	Matsumoto, Tad; Ylitalo, Juha; Juntti, Makku
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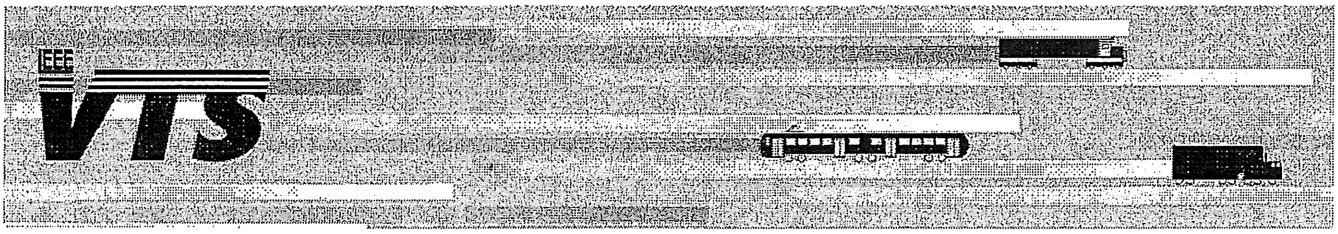

Overview and Recent Challenges of MIMO Systems

Tad Matsumoto, University of Oulu, Juha Ylitalo, Nokia Networks, and Markku Juntti, University of Oulu

The primary objective of this article is to provide an overview of techniques for multiple-input multiple-output (MIMO) wireless communication systems. Information theoretic background of the significant capacity enhancement supported by MIMO radio network configurations is first explained. Current activities towards the utilization of MIMO concepts in the third generation systems as well as recent challenges in signal processing for single carrier signaling-based MIMO communication systems are then introduced.

1. Introduction

It is natural to set the bit rate targets for post-third generation (3G) systems higher than 3G's maximum speed, with the aim of supporting *real-multimedia* communications. Given that the system bandwidth needed to realize broadband communication may not be fully available, the post-3G networks will have to have greater resistance to co-channel interference (CCI).

The recently raised interest towards multiple-input multiple-output (MIMO) systems has been largely triggered by the potential capacity increase promised by information theory. It has been well-known for a long time that using multiple receive antennae can improve communication link quality. Tremendous efforts are currently being made to exploit the spatial dimension of channels with the aim that the MIMO system concept can really be in place [1–3]. An enormous number of research papers have been published that introduce joint space/time (S/T-) signal processing algorithms for MIMO communications. References [4] and [5] survey the historical background of the technology, and summarize current trends in S/T-equalizer algorithm development.

There are two main mechanisms on which receive antenna-based capacity increase can rely on. One applies smart antenna (or beam-forming) techniques wherein CCI from other radio-frequency radiators other than the transmitter of interest can be suppressed. The other mechanism has been based on widely spaced receive antennae providing diversity against fading. Based on the same ideas, it became soon evident that rather similar advantages can also be obtained via multiple transmit antennae.

A goal of this article is to provide an overview of techniques for MIMO wireless communication systems. In Section 2, information theoretic background of the significant capacity enhancement supported by MIMO radio network configurations is introduced. Section 3 describes current activities towards the utilization of MIMO concepts in the third generation systems. Section 4 introduces recent challenges in signal processing for single carrier signaling-based MIMO communication systems.

2. Wireless MIMO Channel Capacity

We first review briefly the basic capacity considerations from information theory, and then present their application to MIMO systems. It is assumed that multiple antennas are used both at transmit and receive sides. In this set-up, statistically uncorrelated antenna elements with large distance are usually considered, and that is the case also in this section. In practice, the spatial channels often have some correlation which reduces the potential performance and capacity gains from the ideal ones predicted herein. The spatial channel modeling is under intensive study, and various channel models have been proposed and are under development. We do not go in detail to this issue, suffice it to say that the channel depends on the environment, and all the results depend on the true channel model.

2.1 Capacity of Gaussian Channels

The information theoretic capacity [6], [7] refers to the maximum rate at which it is possible to communicate reliably, i.e., with decoding error probability approaching zero when the codeword length is approaching infinity. Finding the capacity of a memory-less channel reduces to selecting the input codewords (signals) so that the mutual information between channel input and output is maximized. In the additive white Gaussian noise (AWGN) channel, the achievable capacity in bits per channel use is

$$C = \log(1+\gamma),$$

where γ is the signal-to-noise ratio (SNR) per symbol. The capacity is achieved by so called Gaussian codebook, i.e., by coding the information messages to random(-like) signals with Gaussian distribution.

2.2 Capacity of Fixed MIMO Channels

The capacity of MIMO channels subject to AWGN can be easily derived as an extension of the well-known capacity of parallel Gaussian channels. The capacity of K parallel, independent AWGN sub-channels is the sum of the capacities of each of the sub-channels, i.e.,

$$C = \sum_{k=1}^{K} \log\left(1+\gamma_k\right),$$

where γ_k is the SNR per symbol on the kth sub-channel. A practical well-known example of the parallel channel concept is multicarrier or orthogonal frequency-division multiplexing (OFDM) communications, where each subcarrier is considered as an independent sub-channel. The capacity is again achieved by Gaussian signals. Since the noise power spectral density values on each sub-channel are in general different, maximum capacity is achieved by allocating different powers for different sub-channels. This needs to be done according to the celebrated water-filling principle, where most power is allocated to those sub-channels on which the noise level is the lowest. The water-filling naturally requires that the transmitter has the channel state information available. In other words, the transmitter needs to know the channel gain and noise power spectral density on each sub-channel. The channel state information can be based either on feedback information or in time-division duplex systems to the channel estimation of the receiver.

The MIMO channel capacity is a special case of the parallel channel capacity [8], [9]. The output vector of a MIMO channel is the channel input vector multiplied from the left by the channel gain matrix **H**. By applying the singular value decomposition to the channel matrix **H**, equivalent independent parallel sub-channels can be formed. In that way, the MIMO channel capacity with channel state information at the transmitter becomes

$$C = \log\left[\det\left(\mathbf{I}_{N_R} + \frac{\gamma}{N_T}\mathbf{HQH}^{H}\right)\right]$$

where $\mathbf{I}_n$ is an n-by-n identity matrix, $\mathbf{Q}$ is power allocation matrix, N_T and N_R denote the number of transmit and receive antennae, respectively. The capacity is achieved with Gaussian signaling and spatial water-filling. The latter means that the transmit power is directed towards the eigenvectors of $\mathbf{H}^H\mathbf{H}$ proportionally to the singular values of matrix $\mathbf{H}$ or equivalently to the eigenvalues of $\mathbf{H}^H\mathbf{H}$; $()^H$ denotes complex conjugate transpose.

2.3 Capacity of Fading MIMO Channels

Fading in radio channels complicates the capacity analysis in many respects. If the coding and interleaving frame is long enough so that the fading can be modeled as an *ergodic* random process, the fading AWGN channel capacity is the expected value of the capacity in fixed AWGN channels averaged of the distribution of the channel gain, i.e.,

$$C = \mathrm{E}_{H}\left\{\log\left[\det\left(\mathbf{I}_{N_R} + \frac{\gamma}{N_T}\mathbf{HH}^{H}\right)\right]\right\}$$

The above expression is illustrated in Fig. 1 when the number of transmit and receive antennae is equal. The capacity can be observed to increase linearly with respect to the number of antenna elements. This phenomenal capacity increase is the great motivator for the interest towards MIMO techniques.

If the fading process is *non-ergodic* over the interleaving frame, the conventional Shannon capacity is usually zero. For such cases, the probability of outage needs to be considered. For more details on MIMO capacity in fading, see [1], and capacity in fading channels [9] and references therein.

2.4 Practical Considerations

The great capacity increased promised by MIMO channel configuration is based on several over-simplified assumptions. The channel is assumed to be perfectly known in both the transmitter and receiver. This is never reality even in the receiver, and even harder to obtain in the transmitter. Furthermore, the singular value decomposition is sensitive to errors in channel estimates. By carefully designed closed-loop link adaptation techniques [10], these problems can, however, sometimes be overcome, and the optimal transmission can be approximated up to adequate accuracy. There has also been major interest towards open loop MIMO and transmit diversity techniques, which do not assume channel state information in the transmitter. In particular, space-time coding techniques [20] have been under intensive study recently. In the sequel, some of the most promising techniques are briefly reviewed.

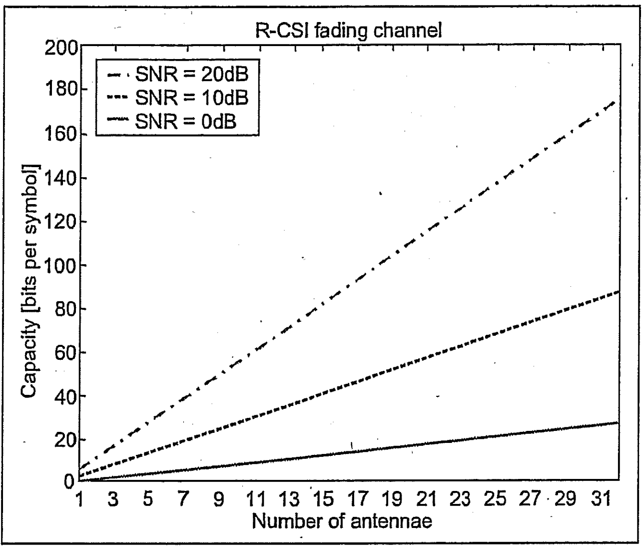

Figure 1 Capacity of fading MIMO channel vs. the number of antennae (N_T and N_R).

3 MIMO Techniques in 3G Networks

In this section we discuss the MIMO prospects mainly for 3GPP specification of the W-CDMA system. Except CDMA2000, there has not been much progress in developing MIMO schemes for other cellular standards such as EDGE and TD-SCDMA. However, it has been acknowledged in different considerations for 4G that MIMO may have an essential role in future wireless communication systems when striving towards throughput rates of 100 Mbit/s and beyond. First, some standard features of W-CDMA are described since they provide a good starting point for future MIMO system specification. Then the current harmonization work between 3GPP and 3GPP2 for MIMO channel modeling is discussed. As an example, we address briefly one MIMO scheme that has drawn attention in recent years, namely the so-called BLAST (PARC) concept.

3.1 Current Status

3GPP specification for W-CDMA inherently supports the MIMO transmitter structure because it includes different transmit diversity modes. For example, in the open loop Tx diversity mode called STTD (Space-Time Transmit Diversity) two different data streams for each user are transmitted from two separate antennae. Figure 2 illustrates the transmitter structure and the STTDti coding scheme, in which two consecutive symbols are transmitted from two transmit antennae using the same spreading code. The main benefits of the STTD coding are that only a single spreading code is needed, it preserves the orthogonality of the two data streams, and the decoding process is very simple in the terminal. The same transmitter structure allows in principle also the use of a de-multiplexer instead of the space-time encoder to produce two entirely different parallel data streams for doubling the data rate. Indeed, such code-reuse scheme originally known as BLAST (Bell Labs LAyered Space-Time Architecture) has been proposed already in the early phases of 3GPP specification [2].

Coding scheme of 2 consecutive symbols over 2 antennae:

Ant.	*[0, T]*	*[T, 2T]*
1	S_0	$-S_1^*$
2	S_1	S_0^*
	Symbol period n	Symbol period n+1

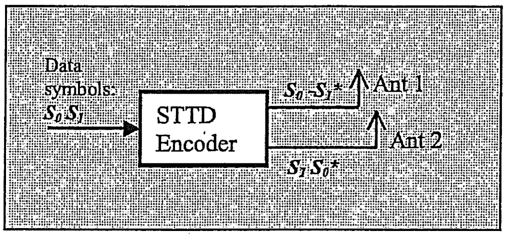

Figure 2 Principal block diagram of a transmitter employing open loop transmit diversity (STTD) in a W-CDMA system. Same symbol is transmitted from each antenna in consecutive symbol periods in a STTD coding manner enabling simple detection at the terminal.

Recently the 3GPP specification for Release 5 has further broaden the possibilities for MIMO type of transmission since it allows the deployment of a wide class of modulation and coding schemes (MCS). Thus the transmission data rate from the base station can be adjusted by adaptive MCS to the underlying radio channel status. The feedback of Channel Quality Indicator (CQI) from the terminal is an important feature of High-Speed Downlink Packet Access (HSDPA) in 3GPP. The HSDPA downlink channel can be shared by a number of users and it can take advantage of multiple transmit antennae. In the specification of HSDPA, the main goals have been to achieve higher data rates (up to 10 Mbit/s) in 5 MHz band and improve the spectral efficiency. Figure 3 shows the basic idea of HSDPA. When the radio channel to terminal 1 is in a good state the base station transmits data to it with the highest possible MCS for the particular channel condition. In the next moment, data is transmitted to terminal 2 with the proper MCS selection. It is obvious that system level issues like packet scheduling have a large impact to the overall network capacity. For example, the so-called round robin scheduler distributes capacity in a blind manner on a fair basis. On the other hand, the scheduler which serves on highest SIR basis allows significantly higher cell throughput but tends to give best service to those terminals that are close to the base station. Feedback of channel quality information can be further utilized in future MIMO systems for improved performance since transmission to partially known channel allows to employ water filling techniques. Similar techniques of link adaptation are also applied in the so-called High-Data Rate technique (HDR) for CDMA2000 evolution modes of 1xEV-DO and 1xEV-DV to achieve data rates of about 2-3 Mbits/s in 1.25 MHz band.

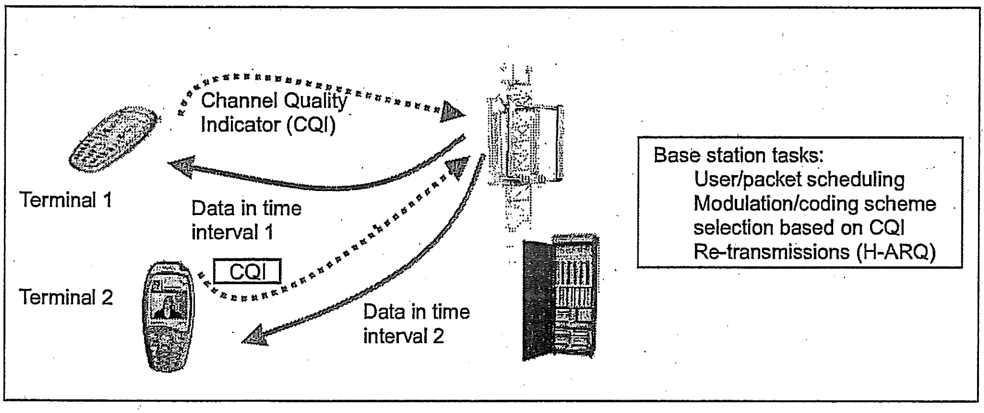

Figure 3 Principle of High-Speed Downlink Packet Access (HSDPA) employing channel state information from the terminals.

3.2 3GPP/W-CDMA Evolution Towards MIMO

The above mentioned characteristics of W-CDMA pave the road for a full adoption of the MIMO techniques as soon as multi-antenna terminals become feasible. MIMO was approved as a study item in 3GPP in 2001 but at the same time it was agreed that it will be specified in a later release than Rel. 5. Currently, as Rel. 5 is finalized, a combined ad-hoc group from 3GPP and 3GPP2 is defining the Spatial Channel Model (SCM) to be used as a common reference for evaluating different MIMO concepts [11]. The scope of the 3GPP-3GPP2 SCM AHG is to develop and specify parameters and methods associated with spatial channel modeling that are common to the needs of the 3GPP and 3GPP2 organizations (harmonization). The scope includes development of specifications for both the link level and system level evaluations. Important spatio-temporal radio channel parameters such as power delay profiles, number of propagation paths and azimuth power spectrum in different user environments are defined. In addition, different antenna configurations and reference cases are described for common system evaluation methodology. It has been agreed that link level evaluations are used only for calibration purposes of the simulators and the actual comparisons between different concept proposals are based on system level results. The final report of the SCM group for approval is expected to be ready by the end of March, 2003. However, the final conclusions will be drawn only in September, 2003. Therefore, it is evident that the specification of the MIMO concept for 3GPP release 6 will actually start only in the second half of 2003.

One example of the MIMO concept is the well-known BLAST that employs code re-use in transmission from multiple antennae. In BLAST the same spreading code is used for the parallel data streams. The basic idea is that transmitting parallel data streams without transmit diversity high data rates can be achieved while multiple receive antennae provide adequate diversity to combat fading. Simulation results suggest that depending on the number of transmit and receive antennas BLAST can offer spectral efficiency as high as 20-40 bits/s/Hz [2]. In addition, measurements have demonstrated that it is possible to increase cellular capacity in outdoor urban environment by a factor of four with 4x4 MIMO arrangement [21]. This result was obtained in good SNR conditions (approximately 20 dB) and is in good agreement with theory. A recent measurement campaign shows that in suburban outdoor environment a very high spectral efficiency of up to 38 bits/s/Hz could be reached in favorable radio channel conditions using 5 transmit and 7 receive antennae [22]. In general, the number of receive antennae must be equal or higher than the number of transmit antennae. In practise, it is realistic to assume that a 3G base station could employ 4-8 anten-

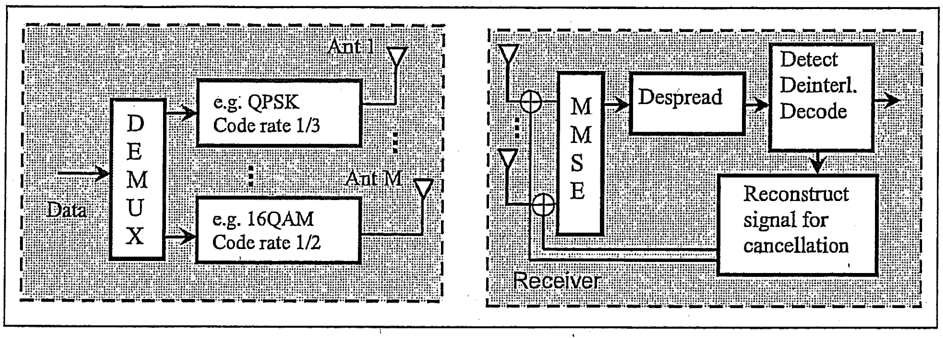

Figure 4 Principal block diagram of a PARC transmitter and receiver (multi-code option not illustrated). Different modulation and coding schemes (data rates) can be applied on antenna basis. An advanced receiver is required which applies on an iterative manner MMSE for antenna signal combining followed by interference cancellation of the detected signal.

nae and the terminal 2-4 antennae (in 3GPP 4x4 MIMO has been discussed). The drawback of exploiting parallel data streams is that the performance of the conventional Rake receiver is rather poor. Instead, advanced receiver structures are required due to the fact that the streams interfere with each other in practical radio channels with multi-path fading. Therefore, some degree of receive diversity must be allocated to interference suppression, which suggests that the number of receive antennae should be larger than the number of transmit antennae. An advanced version of BLAST is called PARC ("Per Antenna Rate Control"), which allows different data rates from different transmit antennae, see Fig. 4 [12]. This concept has also been discussed in 3GPP as a scheme which can take advantage of channel state information from the terminal. In PARC multi-code transmission can be used to further increase the data rate.

It remains to be seen in 3GPP specification whether the main focus will be in increased data rates (theoretically up to 20-40 Mbits/s) or in improved data coverage for medium data rates. Increased data coverage implies that the operation point of the W-CDMA is at low SNR range which favors for conventional diversity techniques. On the other hand, if high peak data rates with reduced covearage are desired, then the operation point is at relatively high SNR level and the use of MIMO techniques becomes feasible. Therefore, it is possible that some degree of reconfigurability between current W-CDMA diversity schemes and the MIMO approach is needed. This kind of flexibility allows effective combination of diversity and MIMO techniques to the radio resource management (RRM) algorithms, especially the packet scheduler. In any case, the MIMO concept which will be adopted to 3GPP Rel. 6 must be backward compatible to the diversity schemes of the earlier releases. In fact, the future MIMO terminals must co-exist with all the terminals from Rel.99 through Rel. 5.

4 Challenges Towards Single Carrier Signaling-Based MIMO Systems

It has long been believed that single carrier signaling is not suitable for broadband mobile communications. This is because the computational complexity of equalizers that can compensate for severe inter-symbol interference (ISI) caused by the multipath propagation scenario increases exponentially with the equalizer's coverage, which has been in many cases considered to be prohibitive.

The discovery of the Turbo codes has driven research on the creation of new signal detection concepts that are, in general, referred to as the Turbo approach [13]. Recently, a computationally efficient Turbo equalizer, soft-canceller followed by a minimum mean square error (SC/MMSE) filter, has been proposed for equalization of channels suffering from severe ISI. The SC/MMSE Turbo equalizer [14], [15] has overturned the belief of the equalizer complexity: it can achieve almost equivalent performance to that of the optimal detector based on the maximum likelihood sequence estimation (MLSE) technique, even though its computational complexity is only at a cubic order of the equalizer's coverage. References [16] and [17] further reduce the complexity to a square order of the equalizer's coverage without sacrificing its performance. The surprising results shown in References [13–17] have motivated the idea that the SC/MMSE concept be applied to the signal detection of single carrier broadband MIMO systems.

The low complexity of the SC/MMSE MIMO Turbo equalizer has triggered research on single carrier broadband MIMO systems, where all users use the same time-slots and the same frequency-slots without relying on orthogonal signaling or spread spectrum techniques. Obviously, the single

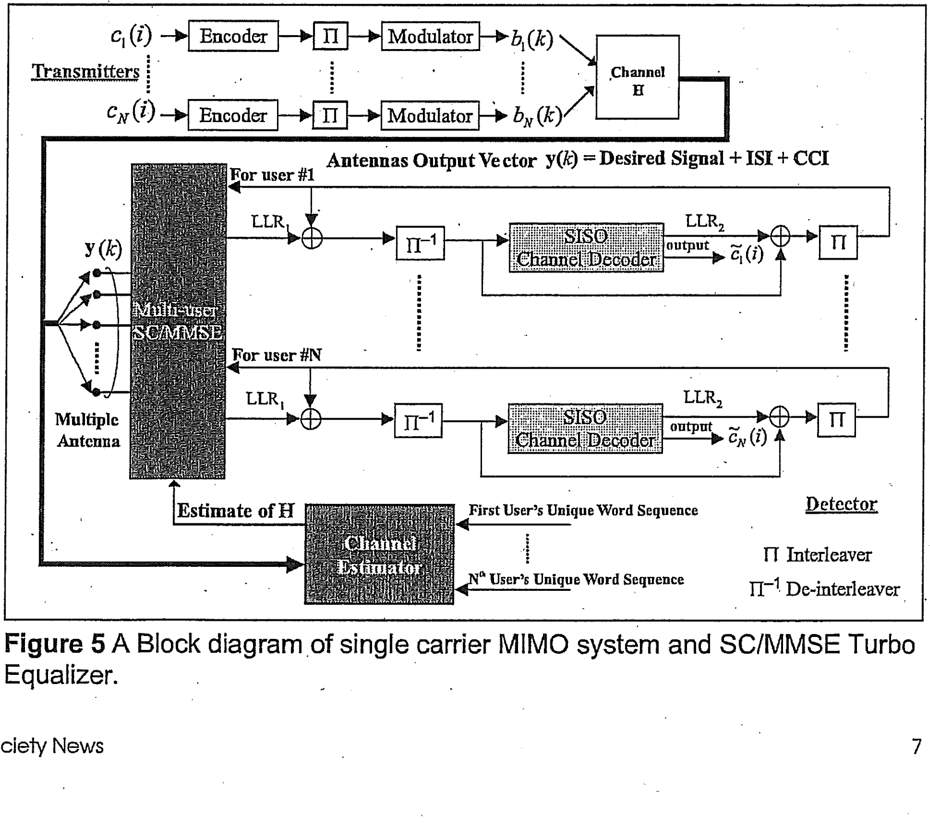

Figure 5 A Block diagram of single carrier MIMO system and SC/MMSE Turbo Equalizer.

carrier approach can fully exploit the path diversity improvement.

Figure 5 shows a block diagram of the SC/MMSE MIMO Turbo Equalizer for single carrier signaling. The SC/MMSE MIMO Turbo detector performs joint channel estimation, multiple stream signal detection, and decoding of channel codes, all in an iterative manner. The SC/MMSE MIMO Turbo detector forms soft replicas of CCI from other users' signals and ISI on the desired signal to be detected using *a priori* Log-Likelihood Ratios (LLRs) output by each user's Soft-Input Soft-Output (SISO) channel decoder. The soft CCI and ISI replicas are subtracted from the received signal vector, of which process is refereed to as soft cancellation. MMSE filtering that follows the soft cancellation aims at suppressing the residual interference components remaining at the output of the soft canceller. *A posteriori* LLR value for each data stream is calculated from the MMSE filter output, and after de-interleaving, it is brought to each user's SISO decoder. The SISO decoders update the LLR values user-by-user, and then feed them back to the equalizer part, where soft estimates of CCI and ISI are formed using the updated LLR. The entire process is repeated. The more iterations, the better the performances.

Current advances in multi-dimensional channel sounding techniques [18] make it possible to evaluate performances of signal processing algorithms in realistic conditions. Channel impulse response (CIR) sequences from a transmitter to each of the multiple antenna elements can be recorded. Recorded real-time channel sounding measurement data can be used for realistic off-line simulations. Since the data represents a real propagation scenario, in-field performances can be accurately evaluated by running the measurement data through the signal processing algorithms of interest. This technique provides us with significantly more realistic performance estimates than model-based simulations [19].

Figures 6 (A) and (B) show for a 3-by-3 MIMO with the transmitter and receiver's antenna spacings being 1.0λ and 1.2λ, respectively, the time series of the bit errors after 4 iterations, indicated by grey bars. The measurement took place in Ilmenau, a typical sub-urban area in Germany. Through the measurement campaign, a series of the 3-by-3 MIMO channel's impulse response was recorded, and the set of data was used in off-line simulations to evaluate performance of the single carrier SC/MMSE MIMO Turbo Equalizer. The green curves in Fig. 6 (A) and (B) indicate the RMS spatial and delay spreads, respectively. It is found that the larger the spreads in the spatial and temporal domains, the better the BER performance.

5 Conclusions

In this article we have given an overview of MIMO wireless technologies that have been widely recognized as being able to achieve technological breakthrough towards future broadband mobile communications systems. The information theoretic background of the significant capacity enhancement supported by MIMO radio network configurations as well as current activities towards the utilization of MIMO concepts in the third generation systems were discussed. Recent challenges in signal processing for single carrier signaling-based MIMO communication systems was also introduced, where it has been shown that SC/MMSE MIMO Turbo Equalizers play a key role in simultaneously separating other users' signals and combining desired signal's multipath components.

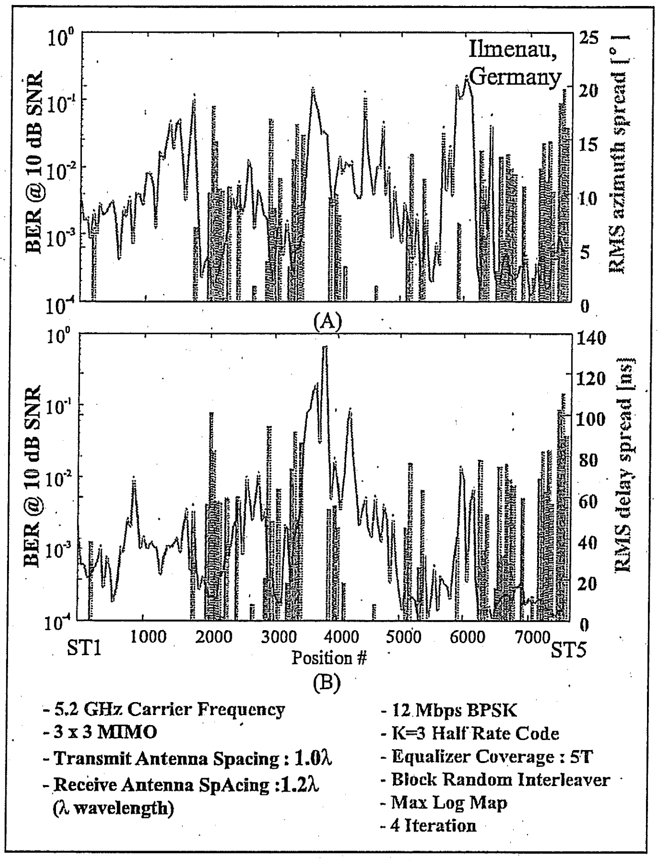

Figure 6 SC/MMSE BER Performances versus Delay and Spatial Spreads.

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Tadashi Matsumoto received his B.S., M.S., and Ph.D. degrees in electrical engineering from Keio University, Yokohama-shi, Japan, in 1978, 1980 and 1991, respectively. He joined Nippon Telegraph and Telephone Corporation (NTT) in April 1980, working first on research in signal transmission technologies, and he was involved in the development of a Japanese TDMA Digital Cellular Mobile Communications System (PDC), and more latterly in the research on Code Division Multiple Access (CDMA) mobile communication systems. From 1992 to 1994, he served as a part-time lecturer at Keio University. In April 1994, he transfered to NTT America, before returning to NTT DoCoMo in March 1996, as a head of radio signal processing laboratory until August of 2001. For his work on the organization of VTC2000-Spring in Tokyo, he received an outstanding service award from the IEEE VTS. In May 2002, he moved to the Oulu University, Finland, where he is a professor at the Center for the Wireless Communications. He is a member of the VTS Board of Governors.

Juha Ylitalo received his M.Sc.EE, Lic.Tech, and Dr. Tech degrees in electrical engineering at the University of Oulu, Oulu, Finland in 1981, 1985 and 1987, respectively. He has held various research positions at the University of Oulu and the Academy of Finland. He was a visiting scientist at the Mayo Clinic, Rochester, MN, USA in 1984-85, at Ruhr University of Bochum, Germany in 1991-92, and at the University of Trondheim, Norway in 1994-95. He joined Nokia in 1995. His research interests include synthetic aperture radar techniques, beamforming and diversity shemes, 2D radio channel modeling, and multi-antenna receiver algorithms for TDMA and CDMA mobile communication systems. In recent years he has been involved in performance evaluation of UMTS applying multiple antennas in transmission and reception (MIMO). Dr. Ylitalo is an author or co-author of more than 70 scientific articles or conference publications and he has several patents. He is a co-author in two recent books on UMTS.

Markku Juntti received his M.Sc. (Tech.) and Dr.Sc. (Tech.) degrees in Electrical Engineering from University of Oulu, Oulu, Finland in 1993 and 1997, respectively. During 1994–95 he was a Visiting Research Scientist at Rice University, Houston, Texas. In 1999–2000 he was with Nokia Networks, Radio Access Systems as a Senior Specialist of WCDMA Research and Solutions. Dr. Juntti has been a Professor of Telecommunications at University of Oulu since 2000, and is also Research Manager at Centre for Wireless Communications, University of Oulu. His research interests include communication theory and signal processing for wireless communication systems as well as their application in wireless communication system design. Dr. Juntti is an author of WCDMA for UMTS published by Wiley, and is an Associate Editor for IEEE Transactions on Vehicular Technology, as well as being a past secretary and chairman of the IEEE Communication Society Finland Chapter. He was Secretary of the Technical Program Committee of the 2001 IEEE International Conference on Communications (ICC'01), and Chairman of the Technical Program Committees of two Finnish conferences.