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Description	

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Turbo Transceivers for MIMO Wireless Communications and Their Performance Verification via Multi-Dimensional Channel Sounding

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SUMMARY 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. Recently, this approach has made a drastic change in creating signal detection techniques and algorithms such as equalization of inter-symbol interference (ISI) experienced by broadband single carrier signaling over mobile radio channels. A goal of this paper is to provide readers with broad views and knowledge of the Turbo concept-based Multiple-Input Multiple-Output (MIMO) signal transmission techniques. How the techniques have been developed in various applications and how they perform in real-field environments are introduced.

key words: *multiple-input multiple-output (MIMO), turbo transceivers, multi-dimensional channel sounding, SC/MMSE, turbo concept*

1. Introduction

It has long been believed that the computational complexity needed for the equalization of inter-symbol interference (ISI) in broadband single carrier signaling is prohibitive, *the belief of which this paper shall overturn.* The recent advance in signal processing techniques has created a new flexible and robust iterative (Turbo) signal detection framework based on soft cancellation and minimum mean squared error (MMSE) filtering [1], [2], which is referred to as SC/MMSE in this paper. This paper is started by introducing the historical background of signal detection techniques in frequency selective MIMO channels. The bottleneck of techniques available before the advent [3] of the turbo equalization concept is briefly explained. This paper then ranges its focus with the SC/MMSE techniques as a general signal processing structure, and applies the technique to the equalization of single-input single-output (SISO) channels suffering from severe ISI.

A primary goal of this paper is to provide readers with large enough but not too detailed understanding of how the SC/MMSE framework can *overturn the conventional belief* that has long negated the thoughts of using single carrier signaling for broadband mobile communications. However, this paper does not use any mathematical tools or expressions because it aims to attain as large a constituent of the concept as possible, for which the authors do believe such detailed mathematics is unnecessary. In fact, the extension to not only the cases of multiple-input multiple-output (MIMO) is straightforward from the SISO case, but also so is to various applications; The extension *shall* invoke various inferences and ideas of the applications. After the introductory part to SC/MMSE, this paper then introduces a couple of derivative related techniques that are better suited in specific situations than the original one, like in the presence of spatial correlation as well as in multilevel bit interleaved trellis coded modulation (ML-BICM).

Now, looking back at the footprints/evolutions of mobile communications systems, it is quite obvious that standardization activities towards the development of new mobile communications systems have long been dominated by big communication system operators. Especially in Japan, because of its hierarchal structure of the industry, research and development activities have mostly been lead by the big operators, from planning stage to prototyping for in-lab testing to the final in-field testing phases. Performance evaluations through in-field testing have in many cases been conducted by them, because only they can allocate huge size of budgetary and human resources to the testing through costly prototyping; Even though standardization bodies are participated by many partners, showing the in-field test results has always been really the powerful means in convincing the partners. However, if this scenario continues its being in the future, only organizations having enough budget and human resources always dominate the process, and for small research organizations including universities can not make any *substantial contributions*, even though they may have very smart and outstanding concepts.

Recent advances in channel sounding techniques [4] make it possible to analyze the channels in realistic conditions. The sequence of channel impulse response (CIR) from each of the multiple antenna elements at the transmitter side-to-each of the multiple antenna elements at the receiver side can be recorded at a very high sampling frequency [8]. This technique is sometimes referred to as "real-time multi-dimensional channel sounding." We can identify how channels have behaved in the spatial and temporal domains by analyzing the recorded data.

The subspace-based super-resolution techniques [5], [6] have long been used for multi-dimensional channel analyses. However, iterative Maximum Likelihood (ML) methods, e.g. based on the SAGE algorithm [7] are most intensively researched because of their flexibility in terms of the applicable data model and array geometry. The major outcomes of the multi-dimensional channel analysis are the

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prediction of direction-of-departure (DoD) and direction-of-arrival (DoA), both in azimuth and elevation domains, and time-of-arrival (ToA) of the component signals [8].

A side product of real-time multi-dimensional channel sounding is that the recorded channel impulse response (CIR) data can be used for realistic off-line simulations for signal transmission techniques. Since the data represents the real propagation scenario, in-field performances can be accurately evaluated by running simulations for signal processing algorithms of interest using the measurement data. This technique provides us with far more realistic performance estimates than model-based simulations. Especially, realizing that future broadband wireless communication systems are most likely to use the spatial and temporal signal processing techniques, and that two dimensional bi-directional channel modeling is still under way, evaluating performances using measured two dimensional (space and time) data is very important from the practical implementation viewpoint. Furthermore, the performance curves can be correlated with the multi-dimensional channel analysis results, by which the performance tendency can be well understood in reflection to the real propagation phenomena.

By using the multi-dimensional channel sounding field measurement data, we can not only predict in-field performances of the techniques of interest, but also compare them with other candidate technologies using the same data, and finally make reasonable assessments with accurate explanations. Furthermore, if the measurement coverage is large enough, we can predict spectrum efficiencies (= bps per Hz per squared meter) achieved by the candidate technologies in real fields. Of course, results of the measurement data-based simulation still only represents performance figures at the measurement areas, and therefore it does not eliminate the needs for costly prototyping. However, at least it can reduce the necessity of prototyping, by which small organizations can make *substantial contributions* when creating new system concepts.

This paper is organized as follows: Sect. 2 first describes the historical background of the MIMO techniques, and explains how SC/MMSE MIMO Turbo equalization works. Section 3 describes the recent advances and state-of-the-art of the multi-dimensional bi-directional channel sounding techniques for broadband wireless communications. Section 3 also presents results of simulations for the SC/MMSE MIMO Turbo equalizer using field measurement data collected in Ilmenau, Germany. Section 4 describes a couple of techniques related to the SC/MMSE MIMO turbo equalization, where modifications are made to the original algorithm. Results of measurement data-based simulations are also shown. Section 5 concludes this contribution.

2. Turbo Equalization with Soft Cancellation and MMSE Filtering

2.1 Historical Background of MIMO Techniques

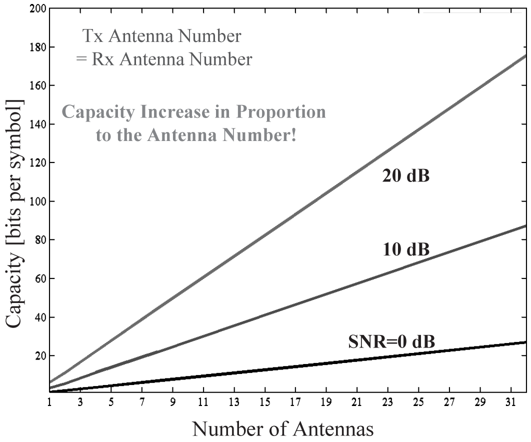


Fig. 1 Per/Hz capacity versus number of antennas of MIMO systems [50].

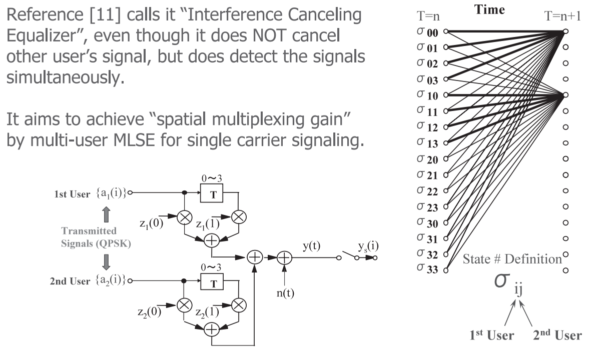
“MIMO” is not a terminology to express specific technique, but it is a terminology to express concept, spanning over a couple of scientific areas that have long been researched quite independently. The technological areas that are closely related to MIMO are information theory, signal processing, communication system aspects, and propagation and electric-magnetic field theory. The MIMO merit can be exploited in the four ways: spatial multiplexing, diversity, interference suppression, and beam gain. Therefore, MIMO system design policy depends on which of the MIMO gains is aimed at. Alternatively, combining those gains is also possible, and the methodology towards such hybrid systems is a key issue; It is largely depending on the scenarios of services and target market areas, e.g., macro-area coverage and/or short range hotspot coverage.

Figure 1 shows [50] the per-Hertz *ergodic* capacity (=capacity averaged over all possible realizations of the MIMO fading channel, derived assuming the *ergodicity* of the channel random variables [9]) of a MIMO system versus the number of the antennas, where the numbers of the antenna elements at the transmitter and receiver sides are assumed to be the same, with the received average signal-to-noise power ratio as a parameter. The key message from Fig. 1 is that the *ergodic* capacity of MIMO channels as a whole increases in proportion to the number of the antennas used. A crucial assumption in this case is that all antennas are spatially uncorrelated. This capacity increase was first indicated by G.J. Foschini and M.J. Gans’ paper in 1998 [9], and the layered spatial multiplexing signal transmission concept by G.J. Foschini in 1996 [10], which is even earlier than his 1998 capacity analysis paper.

However, it should be emphasized that the spatial multiplexing idea was introduced by Japanese researchers even before 1996, which was in 1994 [11]. The authors of [11] were the researchers of NTT DoCoMo, and the major target of their proposed spatial multiplexing technique was a single-carrier time division multiple access (TDMA) system. At that time, the majority of the research activities were directed towards 3rd-generation system development, for which significant research efforts were made to create code division multiple access (CDMA) technologies. Amid the strong trend of research activities towards CDMA, especially in their company, NTT DoCoMo, their revolutionary research for spatial multiplexing seems to have been ignored.

The authors of their 1994 paper called the technique "interference canceling equalizer" (ICE), even though it does not cancel the interference but does detect simultaneously with the desired signal. They developed an ICE prototype system for in-lab and in-field testing, of which air interface was compatible with the Japanese personal digital cellular system (PDC). The results of the field measurements were presented in their paper in 1999 [12]. They also proposed a spatial multiplexing system concept, "path division multiple access (PDMA)," which is *indeed the origin* of the space division multiple access (SDMA) concept. Nowadays, the terminology SDMA is widely accepted but PDMA is not. This is because of the two factors that the PDMA concept was published in an article written in Japanese, and that, again, TDMA research was a minority amid the strong driving force towards CDMA, which the music has to be faced of by the CDMA-driving force.

Figure 2 shows a block diagram of the ICE system where there are 2-transmit antennas and each radio link has two propagation paths. As shown in Fig. 2, the ICE system uses a super-trellis diagram that expresses all the possible transition of the states defined by the modulation alphabets stored in the channel memories. The sequence search takes place along with the trellis diagram, for which usually the Viterbi algorithm [13] is used. The ICE system can be classified as a maximum likelihood sequence estimator (MLSE), and it can achieve the optimal detection performance. The size of the trellis diagram increases exponentially with the number of the transmit antennas (or equivalently the number of the simultaneous users) and the channel memory lengths. This imposes a limit of its practicality; Even in a single-user scenario, if the user aims to transmit 10 Mega-symbol per second (Msps) of binary phase-shift keying (BPSK) signal in the presence of 10 micro-second of delay spread, the equalizer coverage has to be a 100-symbol duration, for which Viterbi detector requires a trellis diagram having 2^{100} states.


Reference [11] calls it "Interference Canceling Equalizer", even though it does NOT cancel other user's signal, but does detect the signals simultaneously.

It aims to achieve "spatial multiplexing gain" by multi-user MLSE for single carrier signaling.

Fig. 2 A block diagram of ICE.

Because of the exponentially increasing complexity, the equalization for single carrier signaling has long been considered intractable. Since then, the research for severe ISI equalization seems to have been bogged down, and the majority of the research activities have been directed towards the creation of the technological bases that use either spread-spectrum [14] or orthogonal signaling [15] concepts. Such a fad of trying to make light of the single carrier approach has lasted at least until the advent of Turbo signal detection concept.

2.2 Soft Cancellation and MMSE Filtering Equalization Technique

Now, let's consider a single carrier single-input single-output system shown in Fig. 3. At the transmitter, the input sequence is encoded by the channel encoder used, interleaved, and then mapped onto a constellation point of the modulation format used. For the simplicity of explanation, we assume BPSK in this article. The transmitted signal suffers from severe fading frequency selectivity due to the multipath propagation, resulting in severe ISI imposed upon the received signal. The equalizer aims to eliminate the ISI and detect the BPSK symbols corresponding to the coded bits. The equalizer output is de-interleaved and input to the decoder of the channel code used.

Knowing that the channel can be modeled as a tapped delay line, the multi-path propagation is the process of taking convolution over the transmitted symbol sequence, which, in turn, can be interpreted in information theory-related terminology as being equivalent to the coding process of a convolutional code. Then, the transmission system shown in Fig. 3 can be seen as a serially concatenated coding system, of which the outer code is the channel code used and the inner code is the multipath channel itself. Now, given the interpretation above, we know that we can use the Turbo "decoding" techniques for serially concatenated codes [16] when "detecting" the signal suffering from ISI. This concept is referred to as "Turbo equalization." In Turbo equalization, soft-information that expresses the ratio of the probability of a bit being one versus being zero (in BPSK's case), referred to as likelihood ratio, is exchanged between the equalizer part and the decoder part. To produce the soft-information, both the equalizer and the decoder have to per-

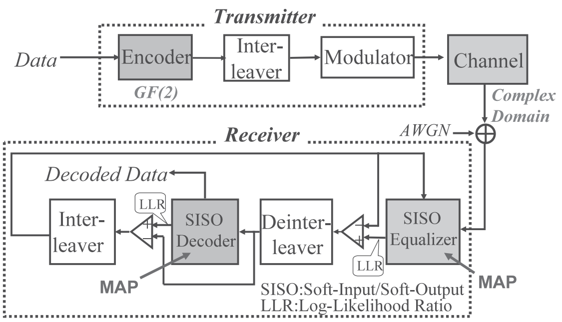


Fig. 3 Coded single carrier transmission system.

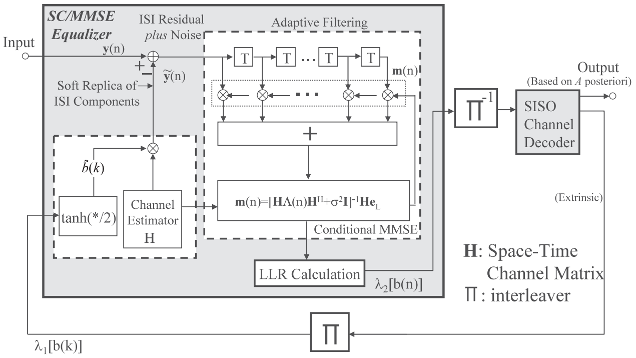


Fig. 4 Block diagram of single user SC-MMSE equalizer [51].

form a soft-input soft-output (SISO) algorithm, for which the "maximum *a* posteriori probability (MAP)" algorithm can be used [17]. Several reduced complexity versions of MAP are also known, but they all have to use the trellis diagram of the "code." As noted above, the multipath channel can be viewed as a convolutional code defined in the complex field; If the channel has a large memory size, the computational complexity for the MAP equalization increases exponentially, and is still prohibitive. Therefore, the MAP equalization part has to be replaced by a reduced-complexity soft-output equalizer.

Figure 4 shows a block diagram of the SC/MMSE Turbo Equalizer for a single-user single-carrier system. The SC/MMSE equalizer replaces the MAP equalization part by soft-cancellation and minimum mean squared error (MMSE) filtering. Like in the MAP-based Turbo equalizer, the equalization part of SC/MMSE has to calculate the likelihood ratio, but it does not use the trellis diagram of the channel. The SC/MMSE equalizer first calculates the "soft symbols" by using the soft-information fed back from the SISO decoder. The SC/MMSE signal processing is performed symbol-by-symbol basis, and by using the soft symbols neighboring the symbol to be detected, it produces an "estimate of ISI." The ISI estimate is then subtracted from the received signal vector. This process is referred to as "soft cancellation."

The residual ISI that remains at the output of the soft canceller is further suppressed by the MMSE filter, the criterion of which is such that the mean squared error between the filter output and the desired signal point of the symbol is minimized, *conditioned upon* the soft symbol fed back from the SISO decoder. In this sense, the *erdordicity* does not hold of the soft canceller output sequence, and therefore, the *conditional* MMSE filtering is not the standard MMSE filtering: The term "mean" (stood for by the second "M" in "MMSE") does *not* indicate "time averaging."

At the early stages of the iterations, the soft canceller output still has a lot of ISI components. Especially, for the first iteration, there is no soft feedback available, and the soft symbols are all zero over the frame considered. Therefore, the MMSE filter works simply as a linear equalizer, for which, only for the first iteration, the MMSE filtering is *not* *conditioned* upon any feedback, and therefore the taps can be calculated by using an adaptive algorithm such as the recursive least square (RLS) algorithm. The likelihood ratio for each symbol 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 likelihood values symbol-by-symbol, and then feed them back to the equalizer part for the next iteration.

Now, let's think about the asymptotic behavior of the SC/MMSE equalizer. If the channel code used is powerful enough, the soft symbols calculated by using the soft feedback approach +1 or −1 (Again, recall that this article assumes BPSK only), as more iterations are performed. With the accurate soft symbols, the ISI estimates are also accurate, by which the soft cancellation becomes perfect. With the perfect ISI cancellation by the soft canceller, what are fed to the MMSE filter is the *only desired signal components* spread over the ISI length due to the multipaths. Combining of those *desired components* according to the MMSE criterion results in the equalizer performance being equivalent to that of the matched filter matched to the multipath channel. Therefore, the SC/MMSE performance is asymptotically equivalent to that of the maximum ratio combining (MRC) path diversity.

The asymptotic performance of the SC/MMSE equalizer, described above, can *not always* be achieved, however, because in general the convergence of iterative techniques is largely affected by the strength of the channel code used, and especially in the case of Turbo equalizers, the convergence is also affected by the shape of the channel impulse response. The convergence of SC/MMSE can be analyzed more in detail by using the extrinsic information transfer (EXIT) Chart analysis [18].

2.3 Complexity Consideration

As described above, the *conditional* MMSE filtering for the residual interference suppression is on symbol-by-symbol basis, which means that the matrix inversion needed to calculate the filter taps has to be done every symbol-timing. This requires a cubic complexity order of the size of the covariance matrix of the equivalent channel matrix representing spatial and temporal structure of the channel. This complexity is much lower than that of the MAP-based Turbo equalizer, which is of an exponential order, but may still be too heavy for practical implementations. Several approximations have been made on the algorithm since the advent of SC/MMSE.

Figure 5 summarizes the history of the SC/MMSE complexity reduction. With the common covariance inversion technique [19], the complexity can be reduced to a square order of the channel covariance matrix. A frequency domain version of SC/MMSE has been presented most recently [20], [49] with which signal processing is performed block-wise (=length of the frame), and it requires only a logarithmic order of the frame size of complexity per iteration. This complexity requirement is almost the same as that of orthogonal frequency division multiplexing (OFDM). The OFDM performance is known to be quite sensitive to the synchronization error, and OFDM imposes a heavy burden on to the amplifier because of its high peak-to-average power ratio (PAPR). With single carrier signaling, the frame duration is very short compared to the fading variation, for which the phase offset due to synchronization error can be seen as a part of the channel. Furthermore, C-class amplifiers can be used for single carrier signal transmission, which enhances the life length of battery of mobile handsets. Given such a low complexity requirement, the authors do believe that now there is no reason for not using single carrier signaling for future broadband mobile communications.

2.4 Extension to MIMO Scenarios

This subsection extends the single-user single-carrier SC/MMSE turbo equalization algorithm to MIMO cases [21], [22], [50]. Figure 6 shows [50] a block diagram of a MIMO system with SC/MMSE MIMO Turbo equalization for a multi-user single-carrier system. MIMO refers in this case to a situation where multiple signals are transmitted simultaneously using the same time- and the same frequency-slots. Some groups of the signals may be transmitted by some single users, each using multiple antennas, and some transmitted by multiple independent users, each using single antenna. In the former case, each single user's data is divided into different chains that perform encoding and interleaving separately. However, the symbol detection algorithm shown in this section can be extended easily to the case where the transmit antennas are grouped into several sub-groups, in which coding and interleaving take place over the multiple antennas [23], [24].

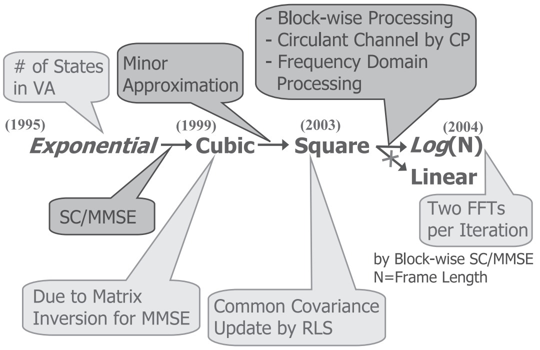


Fig. 5 History of SC/MMSE complexity reduction.

Despite the possible scenarios of the radio network configuration described above, it is assumed later on that each antenna transmits signal of a single "user" for simplicity. Now, the system has multiple "users," each having a single transmit antenna, and the receiver is equipped with multiple antennas. The receiver is comprised of the SC/MMSE multi-user detector and SISO decoders for each user. The SC/MMSE multi-user detector consists of soft interference cancellers for the multiple users, each followed by the MMSE filter. How the SC/MMSE MIMO Turbo equalizer works is basically the same as that for the single-user's case, but the only difference is that it aims to soft-cancel both the ISI and co-channel interference (CCI) due to other users. The estimates of ISI and CCI can be calculated by using the soft information fed back from each user's SISO decoder, and the knowledge about the channel matrix H. To estimate the channel matrix H, the frames transmitted by each user are headed by their own unique word sequences, and the receiver has the knowledge about the waveforms of the sequence. The accuracy of the channel estimation can further be enhanced by using the channel re-estimation technique, of which details are described in [25]. More details about the signal processing for the SC/MMSE MIMO Turbo detector is found in [26].

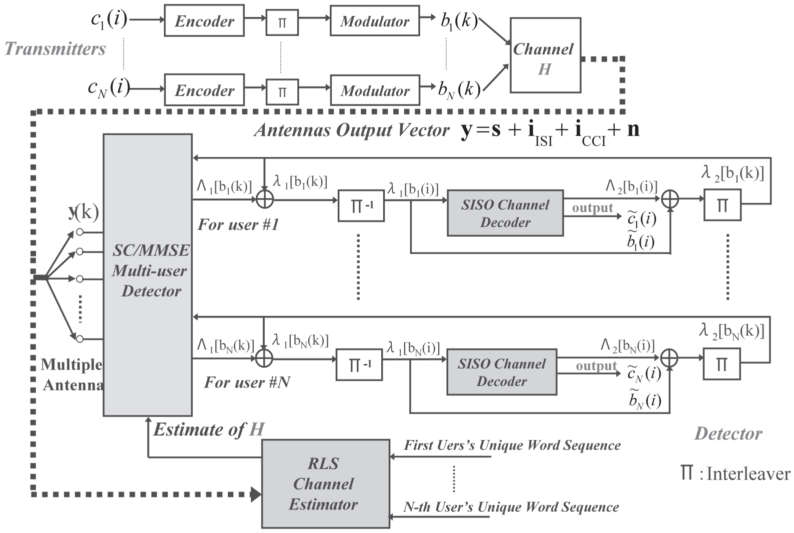


Fig. 6 Block diagram for SC/MMSE MIMO turbo equalization [50].

3. MIMO Channel Sounding and Performance Evaluation

Performances of MIMO transmission systems largely depend on the joint spatial-temporal multipath structure at the both the transmitter (Tx) and receiver (Rx) sides of the radio link. For example, in a rich scattering environment the MIMO channel matrix normally contains enough degrees-of-freedom to achieve the theoretical capacity as shown in Fig. 1. In this case, transmission schemes that are optimized only for spatial multiplexing are the best choice when achieving the highest throughput is aimed at. However, those algorithms will completely break down if the effective rank of the channel matrix decreases or even collapses to one as it occurs, e.g., when the propagation scenario changes from scattering-rich to line-of-sight (LOS) environments. More robust link performance may be achieved by optimizing and adaptively controlling the iterative signal processing schemes at the both transmitter and receiver sides according to the observed channel conditions.

Hence, evaluating performance of a wideband MIMO link by means of simulations requires much more detailed knowledge about and model exactness of the channel's multipath structure than conventional systems having single antenna at either transmitter or receiver, or the both. However, wave reflection, scattering, and diffraction as well as interaction of antennas and propagating waves in real propagation environments are too complex for electromagnetic simulation techniques such as ray tracing and ray launching to model and replicate the scenario for simulations. Furthermore, because significant simplifications have to be made when creating alternative statistical models [27], all those models have to be verified, calibrated, and parameterized through propagation measurements.

Recent advances in MIMO channel sounding [4], [28] have shown that these sounding devices are suitable for resolving such a complex multipath structure of MIMO channels. A MIMO channel sounder also delivers an experimental platform for realistic, in-field performance evaluation of MIMO communication systems. The advantages of the measurement data-based off-line simulation approach in comparison to the field measurement using system prototype are higher flexibility, lower costs, and higher capability for analyzing the behavior of the tested transceiver algorithms. In fact, joint measurement data-based simulation and channel analysis makes it possible to back-trace the observed transceiver's behavior, and by correlating the obtained performance tendency with the actual propagation phenomena, we can delve into how the algorithm has behaved in real fields. In contrast to this approach, field-test using a prototype system under investigation always results in performance curves that are jumbled up with many factors related to the temporal and spatial channel structure. This is because it is only specified for the system under investigation and it usually has no channel analyzing capabilities.

3.1 Real-Time MIMO Sounding

MIMO channel sounder is a measuring device, which allows observing the time-varying CIR matrix in its relevant multiple dimensions, which may be temporal and spatial domains in nature. We need a broadband excitation signal to "sound" the channel in the frequency range of interest and antenna arrays at the both sides of the link, which excite and sense, respectively, the wave-field in a properly defined spatial aperture. Both excitation and sensing, of which results are recorded in a mass-storage device, must be repetitive with a period short enough to preserve the temporal variation statistics according to fast fading variation. Moreover, the data recording must be continuous along the measurement route to be able to reproduce slow channel parameter variations. The process that satisfies those measurement requirements is called *real-time* MIMO channel sounding.

A sounder system may consist of a mobile transmitter (Tx) and a fixed receiver (Rx) that play the roles of the mobile station (MS) and the base station (BS), respectively. Obviously, this setting applies to the typical uplink scenarios of cellular and/or wireless local area network (WLAN) systems. However, since the channel is reciprocal, the results of the channel analysis using the channel sounding measurement data can be understood as representing both up- and down-links. The receiver may also be moving if we consider a peer-to-peer communication between two mobile platforms.

The choice of the antenna array architecture depends on the objectives of the measurement and usage of the data. The flexibility of the sounder system is attributed to the switched mode antenna access, which allows the use of antenna arrays with a wide range number of elements [4], [28]. Very specific design requirements for the antenna arrays arise if we have in mind high-resolution of estimates related to the ray-optical multipath model such as DoA and DoD. The achievable resolution performance in terms of the Cramér-Rao Lower Bound (CRLB) directly relates to the array design and calibration quality [30].

3.2 Measurement Data-Based Simulation

The huge memory size of a real-time channel sounder system allows recording of channel data in real time-varying in-field environments. Proper choice of the measurement setup and careful planning of measurement campaign allows emulation of certain link and network scenarios off-line; Only if the measurement scenario is defined properly, the recorded CIR data can be used for realistic link- and system level simulations. The recorded data can be used for performance comparison of even completely different transceiver architectures with exact reproducibility. It has been shown in [31] that the latest version of the sounder system has a capability of recording large enough amount of data, with which it is even possible to simulate cross-layer operations where slow variations of parameters are involved in. The cross layer issues may include adaptive bit loading, adaptive modulation, and incremental coding strategies at the transmitter, which are implicitly controlled by specific ARQ schemes.

The antenna array design and its element arrangement are of crucial importance when considering certain system and application scenarios. BS array has to meet the requirement for the deployment scenario of the infrastructure. MS array location must take into account human factors of the handset use, which should include not only stationary user terminals but also high mobility user platforms such as cars, aircrafts, and/or trains. For ad-hoc and multi-hop networking, the situation changes completely since there is no dedicated BS. Instead, on the both sides of the link are mobile terminals. Even more advanced network specific scenarios such as multiple users including known and unknown interference, cooperative down-links from multiple BS or AP, multi-hop networking and relaying, etc. have to be emulated by the measurement setup. As a whole, investigations upon measurement data based simulations and evaluations may be concluded with some system level assessments.

The MS antenna array design has to take into account the morphology of the terminal. Small and dedicated arrays may well suit for the requirement. However, a large-size array, comprised of a high number of antenna elements, has to be used when high-resolution angle estimation is aimed at. In this case, a subset of the array can be used to emulate a certain MIMO transmission system configuration with a smaller number of antennas. Moreover, the method of taking a subset of such a large-size MIMO array provides the flexibility of locating antenna elements, when investigating the influences of the locations and distances of the elements.

Figure 7 presents a system model for MIMO signal transmission that can be used for simulations, in general. The bandwidth for channel observation and delay window of CIR are normally much wider than the required system specification. Therefore, the recorded channel matrix with its CIR elements $h_{\nu\mu}(l)$ has to be adapted according to the desired simulation parameters. This can include bandwidth, delay window and also the transmitter and receiver filters $g_T(t)$ and $g_R(t)$. Then, the data stream is processed at the waveform or symbol level by the fast convolution technique. Absorbing the Tx and Rx filters into CIR relaxes the simulation requirements, because the subtleties of symbol time recovery can be excluded when the respective implementation issues are beyond the scope of investigation. CIR updating in simulations can be done at symbol rate, or as low as at frame rate if block fading assumption is reasonable. It is easy to investigate the impact of different levels of channel knowledge at the receiver and the transmitter.

However, there is less flexibility in handling the antenna element influence. On one hand, the interaction of the directional, polarimetric response of the antennas and the spatial structure of the channel response can heavily influence the resulting link performance. On the other hand, the directions of the impinging waves are not known a priori in this modeling approach. Therefore, the individual antenna element characteristics of the measurement array have to be considered as being a part of the channel. More flexible antenna independent modeling would require explicit knowledge of the geometric parameters of the wave propagation as discussed in Sect. 3.3.

3.3 High-Resolution Channel Parameter Estimation

MIMO sounding is the key to multidimensional channel analysis. In general, the channel response can be observed only within a limited aperture volume which is somewhat related to the array size, frequency bandwidth and temporal observation window. This strictly limits the achievable parameter resolution and accuracy in terms of the structural parameters and calls for high-resolution parameter estimation methods.

The most widely accepted data model for high-resolution channel parameter estimation is based on ray-optical understanding of the multipath propagation phenomena. Propagation paths are modeled by planar, narrowband wave-fronts. This is motivated by the idea of deterministic specular reflections at smooth surfaces. Figure 8 presents the resulted double directional structure of the multipath channel [32]. Given this model, the structural parameters of a suitably defined propagation path model are DoA at the receiver array, DoD at the transmitter array, ToA, Doppler shift, and complex polarimetric path weight matrix. A recently proposed extension of this model also contains dense stochastic multipath components which are a result of distributed diffuse scattering [33]. This contribution varies depending on the complexity of the propagation environment. It can be almost negligible in comparison to the specular part in macrocell line-of-site (LOS) scenarios and can even dominate in complicated propagation environments such as factory halls.

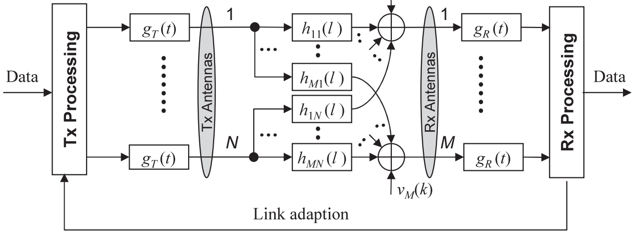


Fig. 7 System model for MIMO transmission.

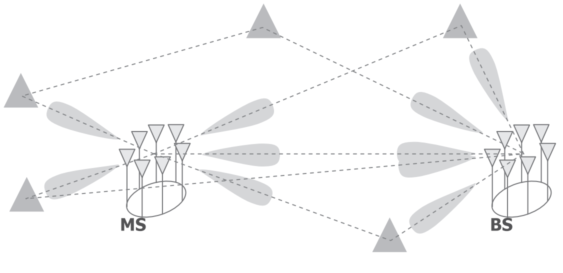
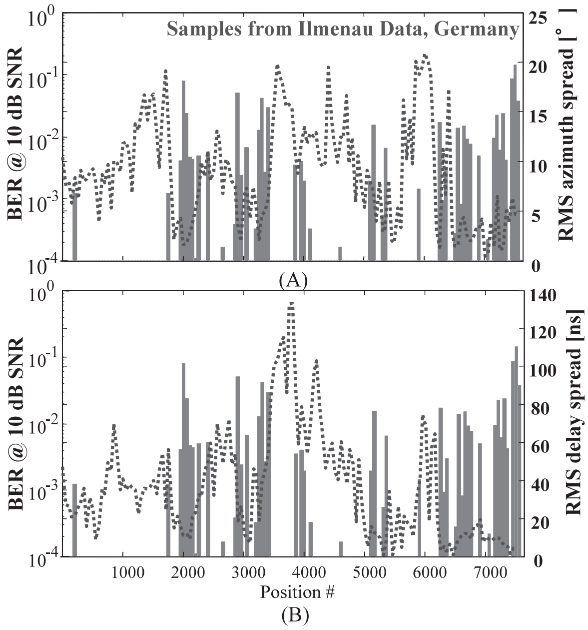


Fig. 8 Double directional DoD/DoA structure of a multipath channel.



- 5.2 GHz Carrier Frequency
- 3 x 3 MIMO
- Transmit Antenna Spacing : 1.0 λ
- Receive Antenna Spacing : 1.2 λ
–λ : Wave length

- 12 Mbps BPSK
- K=3 Half Rate Code
- Equalizer Coverage : 5T
- Block Random Interleaver
- Max Log Map
- 4 Iterations

Fig. 9 SC/MMSE BER performances versus (A) delay spread; (B) spatial spread [50].

Various high-resolution estimation algorithms have been proposed including the multidimensional Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) [5] and Unitary ESPRIT algorithms [6], [34] and iterative Maximum Likelihood (ML) methods. The latter are more flexible in terms of the applicable data model which also relaxes restrictions on the applicable array architecture. An ML parameter estimation framework for channel sounder application, called RIMAX, has been proposed in [29]. In essence, it is an iterative procedure which starts with a robust initialization algorithm. The algorithm uses parameter-wise expectation maximization and gradient based nonlinear Gauss-Newton/Levenberg-Marquardt least squares. The resulting estimates are the deterministic parameters of the specular propagation paths as well as the delay distribution of the diffuse scattered components. The estimator exhibits robust adaptive model order control and high resolution performance of closely spaced coherent propagation paths in all dimensions and provides reliability information of the estimated parameters based on the Fisher information matrix.

There are many advantages in application of model based, high-resolution parameter estimation methods. They are a prerequisite to accurately estimate angular distribution of multipath channel. Estimation of the structural parameters of the propagation channel is the key approach to understanding the propagation phenomena and its interaction to the performance of MIMO links. Therefore, a channel sounding experiment should eventually allow both simulation of a link between an application specific MIMO antenna setup and high resolution parameter estimation. Identification of the number of propagation paths (which somewhat corresponds to the number of degrees of freedom of the channel matrix), their characterization in terms of lifetime and tracking of the temporal parameter variation is important to define realistic channel models and also for adaptive control of the transmit parameters in a MIMO link. Precise directional parameter estimation at the receiver and the transmitter side allows to de-embed the influence of the measurement antennas from the recorded data and, consequently, do embed specific arrays responses throughout the simulation step. This can be seen as some mapping scheme from the measurement arrays to an application specific array which adds unprecedented flexibility to the simulation step.

3.4 Measurement Data-Based Simulation Results for SC/MMSE MIMO Turbo Detector

The purpose of this section is to estimate the in-field performance of the SC/MMSE MIMO Turbo equalizer for broadband single-carrier signaling, and to correlate the MIMO performance figures with channel characteristics such as DoA, ToA, and DoD. The methodologies for link-level simulations using channel sounding field measurement data described in Sect. 3.2 were used. Figures 9(A) and (B) show [50] for a 3-by-3 MIMO setup with the transmitter and receiver's antenna spacing being 1.0λ and 1.2λ, respectively, the time series of the bit error rate after 4 iterations, indicated by bars. The measurement took place in Ilmenau, a typical sub-urban area in Germany. The dotted lines in Figs. 9(A) and (B) indicate the RMS spatial and delay spreads, respectively, obtained by using the previous subsection. It is found that the larger the spreads in the spatial and temporal domains, the better the BER performance.

4. Some New Results Related to MIMO and Considerations towards Future Work

Finally in this section, some recent results of research work conducted by the research group of one of the authors at Center for Wireless Communications, University of Oulu are briefly introduced. The techniques introduced in this section were evaluated through simulations using field measurement data. The measurement data was gathered in a courtyard of Ilmenau University of Technology, Ilmenau, Germany. Figure 10(A) shows a map of the measurement area, and Fig. 10(B) shows DoD at the transmitter side and DoA at the receiver side, obtained by using Unitary ESPRIT (see Sect. 3.3), versus the snapshot number. Because of the metal container between the transmitter and receiver positions, the measurement route can be classified into three categories: non-line-of-sight static (NLOS-STA), non-line-of-sight dynamic (NLOS-DYN), and line-of-sight dynamic (LOS-DYN).

4.1 BICM versus MLBICM

The SC/MMSE MIMO Turbo equalization technique can be extended to bit interleaved coded modulation (BICM) where higher order modulation such as quadrature amplitude modulation (QAM) can be utilized. In *standard* BICM, the coded bit sequence is interleaved, serial-to-parallel converted, and mapped onto a constellation point at the transmitter. The receiver performs the SC/MMSE equalization for the modulation format used, and outputs symbol-wise likelihood. The symbol-wise likelihood is converted into bitwise likelihood using the MAP algorithm, de-interleaved, and then fed into the SISO decoder of the channel code used [35].

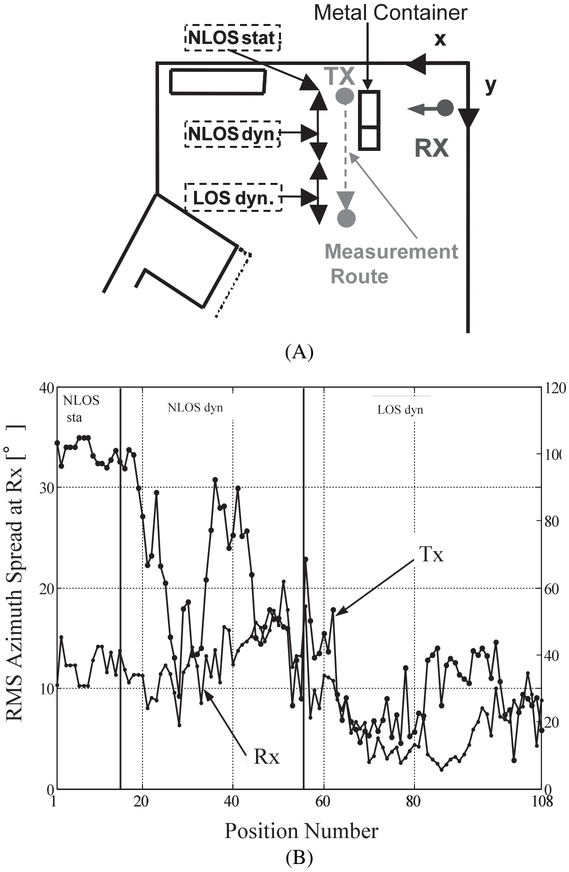


Fig. 10 (A) Map of the measurement area; (B) DoD at Tx and DoA at Rx versus snapshot number [37].

It is now obvious that with higher-order modulation format, the constellation points having lower signal-to-noise power ratios have smaller bit probabilities, and those having higher signal-to-noise power ratios have larger bit probabilities. The most crucial point of the standard BICM technique is that those bits belonging to different constellation layers are mixed by interleaving, resulting in the situation where the convergence of the equalizer is always dominated by the bits having smaller likelihood ratios.

If the bits belonging to the different layers having different signal-to-noise power ratios are *not* mixed, the convergence properties of the different layers are also independent with each other. This can be done by performing coding and interleaving layer-by-layer, and combine their corresponding signals by using linear mapping, resulting in the higher-order constellation points. This technique is referred to as multi-level BICM (ML-BICM) [36]. Since the mapping rule is linear, mapping and de-mapping pair can be seen as a part of the channel, and thereby the multiple layers' signals can be seen as "signals of MIMO users" simultaneously transmitting their signals. The detection of the signals transmitted at the different layers can be performed by using the SC/MMSE MIMO Turbo signal detection technique described in Sect. 2.4. In ML-BICM, the conversion from the symbol-wise likelihood to bit-wise is no longer needed because the whole signal processing is on the binary basis, layer-by-layer.

Simulations were conducted using the field measurement data collected in the measurement route shown in Fig. 10 [37]. A 2×2 MIMO scenario was assumed, and a roll-off factor 0.25 raised cosine response was equally shared by the transmitter and receiver. A 20 Msps 16QAM signal was transmitted using a 25 MHz band, resulting in 80 Mbps overall throughput. Each frame was comprised of 128 16QAM symbols. Figure 11 compared the frame error rate performance of the standard BICM and ML-BICM techniques under the NLOS-STAT, NLOS-DYN, and LOS-DYN environments. It is found that in the NLOS-STA condition, the standard BICM technique can achieve slightly better performance than ML-BICM. However, in NLOS-DYN and LOS-DYN conditions, ML-BICM can works much better than standard BICM. As a whole, the ML-BICM average performance, averaged over the measurement route, far outperforms that of standard BICM. This is because, as mentioned earlier, the convergence property is independent layer-by-layer with ML-BICM, but is dominated by the layers having the lowest signal-to-noise power

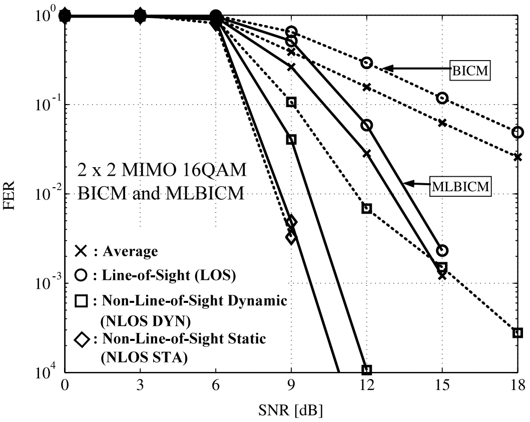


Fig. 11 Frame error rate performances of standard BICM and ML-BICM techniques under NLOS-STAT, NLOS-DYN, and LOS-DYN environments [37].

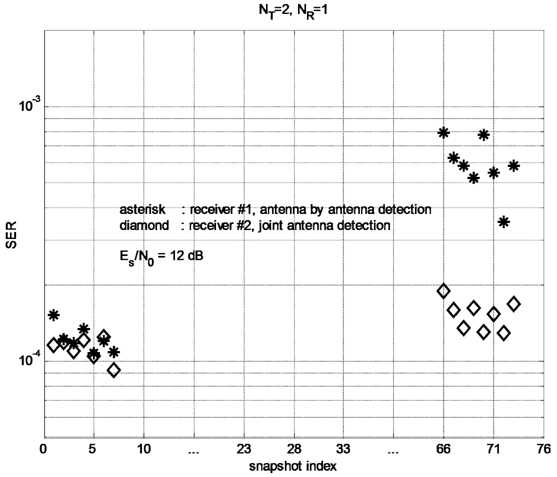


Fig. 12 In-filed performances of STTrC-SC/MMSE with antenna-by-antenna and joint optimization criteria [38].

ratio with standard BICM.

4.2 Antenna-by-Antenna Detection versus Joint Detection

The topic presented in this section is the impact of using different MMSE criterion on performances of Space-Time Trellis coded modulation in single carrier MIMO systems. Two criteria for MMSE filtering in SC/MMSE, one is antenna-by-antenna optimization, and the other joint over transmit-antennas optimization [23] and [24], are the possible choices. For the joint over transmit-antennas optimization, we need to jointly estimate the equivalent channel seen from the MMSE output, and optimize the *conditional* MMSE weights. A merit of the joint over transmit-antennas optimization technique is that it can reduce the performance sensitivity to the spatial correlation [38]. This is because the received composite signal comprised of the signals transmitted from the multiple antennas is treated as a single signal component, and the signals are separated by the Space-Time Trellis code's SISO decoder. On the contrary, the antenna-by-antenna optimization, signals transmitted from each of the multiple transmit antennas are detected independently, for which, for example, if the signals have the same incident angles, they can not be separated in the spatial domain.

Figure 12 shows, as an example, results of the measurement data-based simulations conducted to evaluate symbol error rate (SER) performances with the two different MMSE criteria. The measurement data collected in the courtyard shown in Fig. 10 was used. It is found that in the NLOS-DYN condition (Snapshot index # 1~7), performances of the both schemes are almost the same, but in LOS-DYN condition (Snapshot index # 66~73), the antenna-by-antenna optimization technique suffers from performance degradation, while the joint optimization does not.

4.3 Future Research Directions

SC/MMSE is a common signal processing platform that has a lot of applications. References [22] and [39] combine the SC/MMSE idea with covariance matrix estimation by using the soft feedback, by which unknown interference *not to be* detected can be suppressed while detecting the multiple users' signals. A similar technique can be found in [21] and [25] where the soft feedback is used to re-estimate the channel, by which the estimate's accuracy improves by the iterations. The frequency domain SC/MMSE algorithm described in Sect. 2.3 can also be use to analyze the equalizer's convergence property in terms of mutual information [40].

The use of the channel state information (CSI) at the transmitter in the context of the SC/MMSE Turbo equalization is another big research topic. References [41] and [42] propose the use of CSI to select, respectively, the antenna for transmission and modulation multiplicity. Up to the authors' knowledge, however, the adaptive bit and power loading techniques have not yet been intensively researched for single carrier signaling assuming iterative techniques. This is because for the iterative techniques, the convergence property is largely depending on the channel realization and the channel code used, which means that the optimal loading also depends on the convergence. This is an interesting research topic left for future study.

The optimal design of the channel code for SC/MMSE is of large scale interest. Combination of low density parity check codes (LDPC) and MIMO Turbo equalization is studied in [43]. The optimal design of LDPC based on the outage probability, which aims to minimize the information loss due to the extrinsic information exchange between the variable node and parity check node decoders, is presented in [44] where the EXIT chart analysis plays a crucial role. Recently, it has been shown that in frequency flat channels the space-time non-binary repeat accumulate codes can achieve the full spatial diversity order (= $N_T \times N_R$) in MIMO systems, where N_T is the transmit antenna number and N_R the receive antenna number [45]. Reference [46] extends this idea to frequency-selective channels, where by using the joint over-antenna optimization SC/MMSE the diversity order $N_T \times N_R \times L$ can be achieved where L is the number of the multipath components in the channel of each transmit-receive antenna pair.

Reference [47] applies the SC/MMSE algorithm to the signal detection of spatially layered spatial multiplexing systems like BLAST. Reference [48] aims to reduce the effects of the inter-channel interference (ICI) and inter-block interference (IBI) experienced by OFDM systems by using the SC/MMSE concept. There are a lot of applications of the SC/MMSE and its derivative algorithms.

5. Conclusions

In this paper we first touched upon the historical background of the MIMO techniques, and then introduced the Soft-cancellation with MMSE filtering (SC/MMSE) Turbo equalization technique. We briefly explained how it works in single-carrier single-user systems suffering from severe ISI. The SC/MMSE approach was then extended to MIMO, and recent advances in signal processing for its computational complexity reduction were introduced.

Our discussions in this paper then put more focus on the issues related to the recent advances in multi-dimensional channel sounding techniques, where we briefly explained how the channel sounder systems work. A strong emphasis has been placed on the fact that the use the common channel sounder's measurement data makes the fair comparison possible of performances of different signal transmission techniques, and thereby we can make adequate assessments on the technologies investigated. This approach does open the door for small organizations *not* having enough budgetary or human resources to play crucial roles when discussing the future generation systems.

After brief discussions about the measurement data-based simulation results on MIMO systems, this paper introduced some recent results on the related topics and future directions. In summary, the SC/MMSE technique is really a powerful technique, and has a lot of applications. The authors strongly encourage the readers to take the opportunities where they can make contributions to the further enhancements of this powerful, flexible, and practical technique, and test their performances using field measurement data.

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