Implementable Wireless Access for B3G Networks — Part III: Complexity Reducing Transceiver Structures

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ABSTRACT

This article presents a comprehensive overview of some of the research conducted within Mobile VCE's Core Wireless Access Research Programme,[1] a key focus of which has naturally been on MIMO transceivers. The series of articles offers a coherent view of how the work was structured and comprises a compilation of material that has been presented in detail elsewhere (see references within the article). In this article MIMO channel measurements, analysis, and modeling, which were presented previously in the first article in this series of four, are utilized to develop compact and distributed antenna arrays. Parallel activities led to research into low-complexity MIMO single-user space-time coding techniques, as well as SISO and MIMO multi-user CDMA-based transceivers for B3G systems. As well as feeding into the industry's in-house research program, significant extensions of this work are now in hand, within Mobile VCE's own core activity, aiming toward securing major improvements in delivery efficiency in future wireless systems through cross-layer operation.

INTRODUCTION

The structure of this article reflects the objectives of the Movile VCE Wireless Access research program to identify and extend practicable B3G techniques that would result in implementable transceivers. In the first article, Part I, issues related to multiple-input multiple-output (MIMO) channel modeling and methods to exploit the MIMO nature of the communication system were reported. In Part II the focus was more on the exploitation of traditional and distributed MIMO transceivers and their performance characterization.

Following on from the first two articles, the performance and complexity reduction of various B3G code-division multiple access (CDMA)-based transceiver structures in a multi-user environment is the focus of this article. We introduce novel space-time trellis codes suitable for B3G systems. We introduce novel receiver strategies that drastically decrease the complexity in single-input single-output (SISO) multi-user systems. This analysis is complemented in a later section, which deals with multicarrier (MC)-CDMA schemes for B3G wireless systems. The CDMA-based multi-user analysis is then extended to generic MIMO systems; again, complexity reduction facilitating implementation has been a major concern. Finally, low-complexity iterative receivers for MIMO CDMA systems are presented.

DESIGN OF NOVEL SPACE-TIME TRELLIS CODES

INTRODUCTION

The use of multiple antennas (space diversity) is a well-known concept to combat the effect of multipath fading over wireless channels. This can be found in one form or another in present communication systems, and traditionally has formed part of the receiver side of the system (receive diversity). When applying this to present day small receiver systems, such as mobile handsets, several parameters must be considered, such as size, complexity, and signal correlation. However, this results in the limited use of multiple receiving antennas and motivates the need to move complexity to the base station: this is achieved by introducing several transmit antennas (transmit diversity). Additionally, error correcting codes can be employed, giving rise to the concept of space-time coding (STC). STC can be found in several forms, such as space-time block coding (STBC), space-time trellis coded modulation (STTCM), and layered space-time architecture (LST) [1–3].

The work reported in this article formed part of the Wireless Access area of the Core Research Program of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE, www.mobilevce.com, whose funding support, including that of EPSRC, is gratefully acknowledged. Fully detailed technical reports on this research are available to Industrial Member Companies of Mobile VCE.

[1] In addition to the Wireless Access research stream, two other research streams were established which undertook research in Software Based Systems and Networks & Services for future mobile systems. The work described herein comprised Mobile VCE's Core 2 program, undertaken in the period 20002004.

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As part of the work undertaken, the design, performance, and application of STTCM is considered as a means for achieving high-data-rate transmissions over wireless fading channels with no penalty in bandwidth efficiency. The design of STTCM jointly incorporates trellis-based channel coding, modulation, transmit diversity, and, optionally, receive diversity. The major contribution of the work is summarized in subsequent sections.

FAST SEARCH TECHNIQUES FOR STTCM OVER RAYLEIGH FADING CHANNELS

A fast search technique was developed to obtain novel space-time trellis codes that are constructed for up to six transmit antennas, modulation of up to 32-quadrature amplitude modulation (QAM), and trellis coding with up to 64 states. The codes for slow fading channels are obtained according to the *rank and determinant* criteria [1], when the diversity order of the system (i.e., the product of the rank and the number of receiving antennas) is less than 4. Alternatively, the codes are obtained by satisfying the *rank and trace* criteria. These novel techniques reduce the overall code search by up to twice the factorial of the number of transmit antennas under consideration. In turn, this enables the search for STTCM for 4-phase shift keying (PSK)codes; with 4, 8, 16, 32, and 64 states for up to 6 transmit antennas in an allowable timeframe [4]. Also, STTCM are obtained for 8-PSK, 16-QAM, and 32-QAM for up to 4 transmit antennas [5]. The performance of these new codes is evaluated by means of Monte Carlo simulation giving the result as a function of signal-to-noise ratio (SNR) against frame error rate (FER). Results showed improvements with increasing number of transmit antennas and transitional states of the STTCM.

ERROR ANALYSIS OF STTCM: CONCATENATION REQUIREMENT

The characteristics and error analysis of STTCM were studied. This enabled a better understanding of concatenating space-time trellis codes (STTCs) with other channel coding schemes [6]. Analyses of STTCM concatenated with outer channel codes, such as convolutional codes and Bose-Chaudhuri-Hocquenghem (BCH) codes, were performed, and the optimal combination of inner and outer codes was investigated. The performance results were further enhanced by use of a random interleaver and a recursive STTC as the inner code. The results demonstrate gains of up to 4 dB for a 4-PSK, 2-antenna, 4-state code at an FER of 10^{-2} (frame length 130 4-PSK symbols), but this comes at the expense of reduced spectral efficiency.

PUNCTURED STTCM FOR SPECTRALLY EFFICIENT TRANSMISSIONS

The concatenations considered achieve considerable gains, but these are produced at the expense of reduced spectral efficiency. This reduction, in turn, is compensated by constructing punctured STTCM. A search is performed over the appropriate puncturing pattern, which provides the best design criteria parameters. The puncturing reduces the overall rank of the matrix, and thereby leads to reduced performance over MIMO channels. However, concatenation with outer codes compensates for this loss. Results are obtained for punctured STTCM for a 2-antenna case with 4, 8, 16 and 32 states. For a punctured STTCM with rate 5/4 and concatenated with a half-rate convolutional encoder, the results show a loss of 1 dB at FER of 10^{-2} (frame length 130 4-PSK symbols) compared to a non-punctured 4-PSK, two-antenna, four-state STTCM concatenated scenario. A gain of 1.5 dB is maintained in comparison to a non-concatenated non-punctured four-state scenario.

STTCM FOR VIRTUAL ANTENNA ARRAYS

The obtained STTCs are applied to a virtual antenna array (VAA) scheme introduced in Part II of this series of articles, which involves a mutually cooperating group of mobile users. With codes obtained for up to six transmit antennas, ST trellis ccoded VAA schemes with, say, two transmit and four relaying terminals can be realized. Results show substantial coding advantages over a non-coded VAA scheme. For instance, a scheme with three transmitters and two cooperating mobiles employing STTCM of eight states can achieve a 10 dB gain at a FER of 10^{-2} (frame length 130 4-PSK symbols) over a non-coded scheme.

The performance of these new codes is evaluated by means of Monte Carlo simulation giving the result as a function of signal-to-noise ratio against frame error rate. Results showed improvements with increasing number of transmit antennas and transitional states of the STTCM.

LOW-COMPLEXITY SISO CDMA MULTI-USER RECEIVERS

INTRODUCTION

Many multi-user detectors (MUDs) for CDMA systems have been the subject of intense investigation over the years. The majority of such receivers can be classified into four main categories. The first category includes linear filter-based receivers, the most common examples of which are the matched filter (MF), decorrelator (DECOR), and minimum mean square error (MMSE) detectors. The second category is the cancellation type, for example, the successive and parallel cancellation receivers, SIC and PIC, respectively. Tree-search-based MUDs, such as the optimum maximum likelihood (ML), Viterbi algorithm (VA), and MT algorithm, among many others constitute the third category. Finally, there also exists the hybrid category of receivers, which includes the MMSE-PIC, DECOR-SIC, and DECOR-PIC. While the MF receiver is the simplest of all, it is also considered the optimum receiver when the received signal is composed of orthogonal spreading codes with modulated symbols. Orthogonality of the spreading codes is often difficult, if not impossible, to preserve due to the presence of common channel impairments such as multipath, Doppler dispersion, and asynchronous transmission. This leads to the undesirable creation of multiple access interference (MAI). While in the case of the MF receiver no attempt is made to remove the MAI effect (i.e., MAI is treated as additive noise), the rest of the above mentioned MUDs each use a unique strategy to try to elimi-

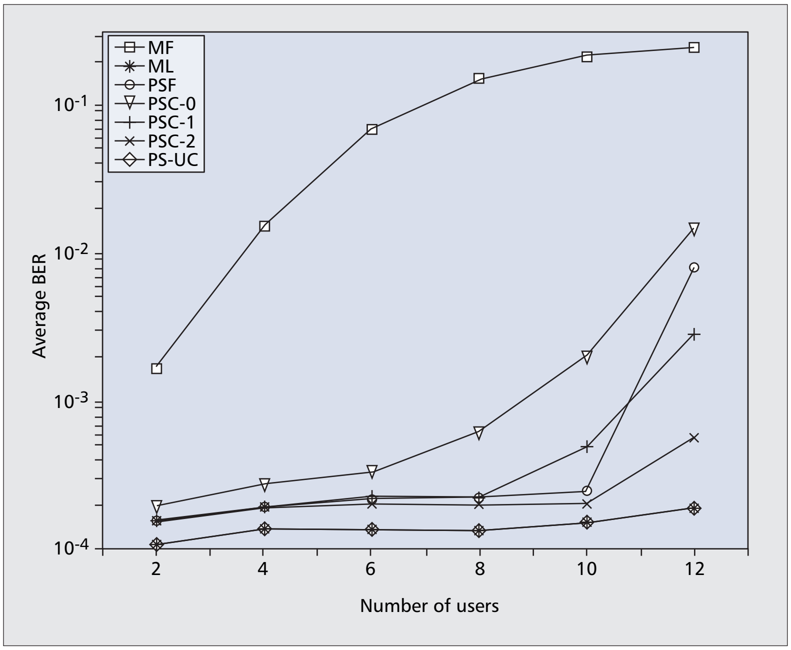


Figure 1. *BER performance vs. number of users at* $E_b/N_0 = 8$ *dB, number of outer iterations =4.*

nate most/some of the MAI; therefore, they have better bit error rate (BER) performance than the MF receiver. The DECOR receiver requires an estimate of the cross-correlation matrix of the received data signal to eliminate the MAI, but suffers from noise enhancement associated with the zero-forcing criterion it uses. The MMSE receiver, on the other hand, requires knowledge of the cross-correlation matrix of the data as well as that of the noise to eliminate the MAI, and hence has a better performance than the DECOR at low SNR values. In cancellation and hybrid MUDs, the MAI is estimated and subtracted from the wanted signal in an iterative fashion. The performance of these detectors depends on the reliability of their initial estimates and the order in which users are cancelled; they are especially efficient when there is a significant imbalance in the powers of the received users. In tree-search-based MUDs the received signal is decoded by comparing it to a set of possible transmitted bit combinations (in the MLMUD all possible combinations are tested) and choosing the closest match as the most likely transmitted combination. In general, all suboptimum receivers require considerably less computational complexity than the optimum MLMUD, but this is at the expense of some BER performance degradation that becomes more pronounced in proportion to the percentage load. A good introduction to these families of receivers can be found in [6] along with a brief review of the advantages and disadvantages of these receivers.

COMBINED FEC-MUD RECEIVER

Recent research in multi-user detection has shown that significant performance improvement can be gained from combining the multi-user detection process with the forward error correction (FEC) stage at the receiver. Giallorenzi and Wilson [7] have shown that the optimal decoding scheme for an asynchronous convolutionally coded CDMA system combines the trellis of both the asynchronous MUD and the convolutional code. This, however, resulted in a highly complex receiver with a minimum complexity of 2^{Uv}, where U is the number of users and v is the constraint length of the FEC code. Subsequent papers from various authors reported that it is possible to achieve single-user performance even for a highly loaded multi-user system. A theoretical analysis showed that a combination of FEC coding and random interleavers overcame the limitations of a multi-user receiver in a highly loaded system. Suboptimal turbo-based iterative combined FEC interference cancellation receivers were subsequently proposed. Such a receiver was shown to provide significantly better performance than the traditional non-iterative structure and nearly completely overcome the channel-associated problems of MAI and intersymbol interference (ISI).

Part of the work conducted was to design a low-complexity iterative MUD that has low complexity but can also provide system performance very similar to that achieved when using the optimal maximum likelihood based iterative receiver. The proposed receiver uses adaptive preselection in order to minimize complexity without degrading the system performance.

THE PRESELECTION ITERATIVE RECEIVER

The proposed receiver, inspired by Berrou's turbo principle, combines iterative detection with selective partial soft cancellation in order to minimize the MAI and improve the probability of correct detection. After initial estimates of the individual components of the received signal have been established by the matched filters (MFs), these estimates are passed on to the preselection control unit in the form of log likelihood ratios (LLRs).

Depending on the selected mode of the receiver and the magnitude of the received LLRs, the preselection control unit passes on to the cancellation stage soft estimates of the most likely symbols to be correctly detected. These soft estimates represent the symbols whose estimated LLRs have a magnitude larger than a specified threshold and are calculated using the relationship of the possible symbol values to their corresponding LLRs.

SELECTED RESULTS

This type of receiver can be operated in three modes. One mode hard limits the maximum number of symbols that can be detected by the sub-tree-search unit. This is referred to as preselection with fixed tree-search (PSF). The second mode is called preselection with capped tree-search (PSC) in which there is a limit on the maximum number of symbols that can be detected by the tree-search. Finally, there is the uncapped preselection mode (PS-UC) where there is no limit on the maximum number of symbols to be estimated by the tree-search unit. The main difference between these modes is that the instantaneous complexity of the PSF mode is fixed, while that of the other two modes, capped or uncapped, is variable.

MC-CDMA Schemes for Next-Generation Wireless Systems

Introduction

In the context of CDMA communication, there are two fundamental types of spread-spectrum schemes. The first scheme spreads the original data stream in the time (T) domain [8], while the second in the frequency (F) domain, resulting in the scheme known as F-domain spread MC-CDMA. As a further advance, in [8] an attractive amalgam of the above T-domain, F-domain, and even spatial (S)-domain spreading schemes mapping the signal to be transmitted to several transmit antennas has been developed. Explicitly, the original data stream is spread in the T-domain, the F-domain, as well as possibly the S-domain, for the sake of achieving the highest possible diversity order. Hence, each user may be assigned three spreading sequences for this operation, a T-domain, an F-domain, and an S-domain sequence. This system exhibits high flexibility, since variable spreading factors may be used in that particular domain, where the highest diversity order may be achieved. This measure also results in reduced MUD complexity, since when requiring a total spreading factor (SF) of 512, an SF of 8 is sufficient in each of the three domains.

Time- and Frequency-Domain Spreading Assisted MC DS-CDMA Using Interference Rejection Spreading Codes for Quasi-Synchronous Communications

The team at Southampton University also considered the employment of various novel families of spreading codes as the T-domain spreading code, which are known as generalized orthogonal codes [8]. These codes exhibit a so-called interference free window (IFW). Over the duration of the IFW both the cross-correlation and auto-correlation of the spreading codes is zero. The benefit of employing these specific codes as the T-domain code is that we are capable of achieving near-single-user performance without a T-domain MUD, since the MUI components arriving within this IFW do not contaminate the desired signal at all. Even if a T-domain MUD is invoked, its complexity is reduced, because only a small fraction of the total number of users has to be separated and detected by the MUD in the F-domain, just those, which belong to a given MUD group described the common T-domain code. By contrast, again, the set of users, who are differentiated with the aid of unique user-specific T-domain spreading codes, having an IFW do not interfere with each other, as a benefit of the IFW provided by the T-domain codes used. Another advantage of the proposed scheme is that we can significantly extend the width of the IFW in comparison to a single-carrier DS-CDMA system, because as a benefit of distributing the bits to several subcarriers, MC DS-CDMA has the potential to significantly reduce the chip rate, thereby extending the duration T_c of the chips. This also allows us to extend the width of the IFW, which renders the system more insensitive to timing imperfections, since larger timing errors can be accumulated without imposing interference.

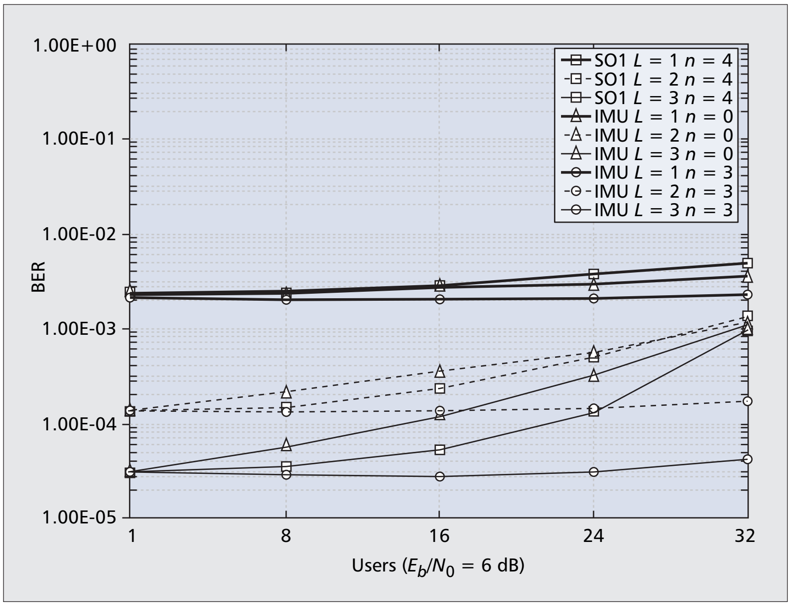
Number of users	Log$_2$(Number of operations)					
	ML	PSF	PSC-0	PSC-1	PSC-2	PS-UC
2	4	4	3.29	3.53	3.53	3.53
4	6	5	3.62	3.74	4.09	4.09
6	8	6	4.03	4.12	4.22	4.73
8	10	7	4.57	4.57	4.67	5.42
10	12	8	5.34	5.27	5.26	6.24
12	14	9	6.49	6.36	6.22	7.27

Table 1. *Complexity vs. number of users at* E_b/N_0 = *8 dB, number of outer iterations =4.*

Genetic Algorithm Assisted Multi-User Detection for Asynchronous Multicarrier CDMA

Numerous MUD schemes have been proposed in the literature. For example, the MMSE MUD and its numerous variants have been described in [8], along with various interference cancellation (IC) schemes. In [9] the ML MUD designed for MC-CDMA was considered. In this specific MUD the receiver constructs all the possible combinations of the transmitted signal and employs the estimated channel transfer function for generating all possible received signals in order to find the one that has the smallest Euclidean distance from the received signal. Hence, the ML-detection-based MUD designed for MC-CDMA is capable of achieving the optimum performance. However, it requires the calculation of $2K$ possible received signal combinations in conjunction with binary PSK (BPSK) modulation. In other words, the ML-detection-based MUD's complexity will increase exponentially with the number of users K. Hence, the complexity imposed will become excessive when the number of users K is high.

Therefore, genetic algorithms (GAs) were invoked [8, 10, 11] to reduce the complexity of the ML-detection-based MUD employed in MC-CDMA systems. The GA-based MUD was first proposed by Juntti *et al.* [10] for a synchronous DS-CDMA system communicating over an additive white Gaussian noise (AWGN) channel. Yen and Hanzo [11] further improved the performance of the GA-based MUD, demonstrating that its performance approaches the single-user performance bound at significantly lower computational complexity than that of Verdu's optimum MUD. Furthermore, the team at Southampton University also proposed GA assisted MUD schemes as a suboptimal MUD technique applicable to asynchronous MC-CDMA systems communicating over broadband frequency-selective fading channels. We assumed that each subcarrier obeys independent Rayleigh fading. The performance of this specific GA-



■ **Figure 2.** *BER performance comparison of SO1-MMSE and IMU-MMSE with 2-antennas 16-states STTC,* E_b/N_0 = *6dB,* spreading-factor = *32 and 2 receive antennas for different number of users and paths* L.

Detector	Multiplication/symbol
IMU-CS-MMSE	96,991,008
SO1-CS-MMSE	64,788,640
SO2-CS-MMSE	63,698,976
IMU-STMF-MMSE	183,617,824
SO1-STMF-MMSE	318,464
SO1-STMF-MMSE	286,912

■ **Table 2.** *Iterative MMSE detectors: computational complexity (*K = *16,* L = *3,* n = *3 in Fig. 4, CS = chip synchronous).*

assisted MUD was investigated as a function of the affordable detection complexity.

Coded Modulation Assisted Iterative Parallel Interference Cancellation Aided CDMA

Following the philosophy of iterative turbo detection [8, 12], in recent years iterative MUD has captured growing interest in the wireless communications community. In [13] an iterative decoding scheme designed for synchronous CDMA systems has been characterized. The algorithm proposed in [18] has a computational complexity proportional to the order of $O(2^{Kv})$, where K is the number of users supported, and v is the channel codec's memory length. These iterative MUDs, designed and characterized in [13], exhibit near single-user performance. However, its excessive complexity renders real-time implementations unrealistic, except when the number of users supported is low.

In [8] several sophisticated channel coded schemes were proposed for reducing the implementational complexity imposed. In this set of schemes interference cancellation (IC)-based iterative MUD exhibits the lowest complexity, rendering the complexity proportional to the order of $O(K \cdot 2^v)$.

In [14] an IC-based iterative MU was developed that exhibits acceptable implementational complexity. These schemes invoked a novel symbol probability-based iterative MUD-assisted receiver for employment in a trellis coded modulation (TCM) [20] and turbo trellis coded modulation (TTCM) [15] aided system. Symbol-based maximum *a posteriori* (MAP) algorithms [20] were employed for both the TCM and TTCM decoders, which are capable of feeding back the symbol probabilities to the soft symbol estimation and IC stages. More specifically, this algorithm relied on utilizing the probabilities of the channel-coded information symbols for symbol estimation, rather than employing the individual APP of the coded TCM/TTCM bits. A turbo MUD was analyzed in detail from a unified theoretical perspective in the excellent treatise of Boutros and Caire in 2002 under the assumption of using random spreading.

Iterative Receivers for MIMO CDMA Systems

Introduction

It is vital to make the best possible use of the limited radio spectrum in order to maximize the number of users and data rate available to each user. Recently, iterative processing has attracted vast attention due to its successful application in many areas of coding and signal processing, such as turbo coding and iterative detection for wideband CDMA (WCDMA) systems. Additionally, space-time coding techniques have been shown to provide significant improvement in spectral efficiency over fading wireless channels, by exploiting transmit and receive diversity. STTCs in particular have been extensively studied for the case of flat fading MIMO channels, and various code design criteria have been developed in order to achieve the highest possible antenna diversity and coding gain.

However, the presence of multiple antennas at the transmitter, along with multipath and multiple users, inevitably introduces not only ISI and MAI, but also intra-antenna interference (IAI) among the transmit antennas. Thus, the conventional matched-filter detector, which neglects the presence of the MAI and IAI, is not sufficient to cope with such a highly interfering scenario, and an enhanced detector is required to obtain significant improvement.

Parallel Interference Canceller

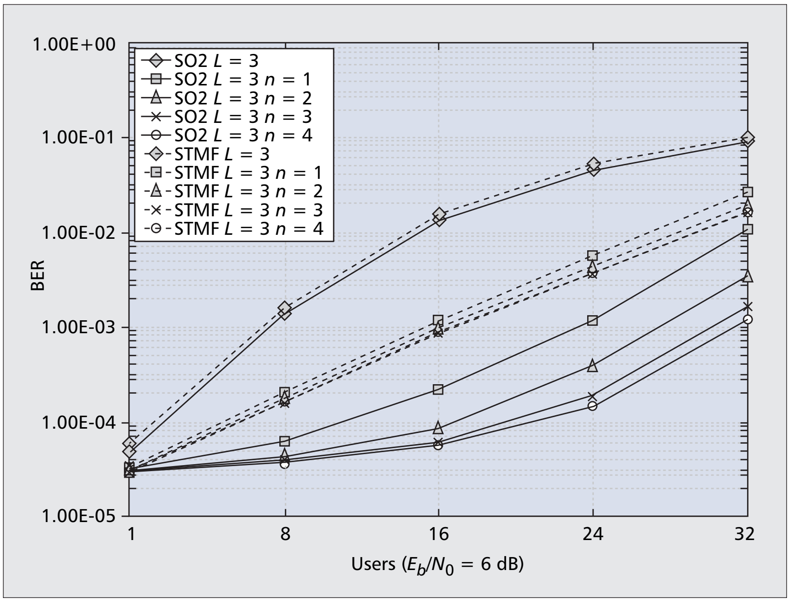
A very simple and efficient iterative receiver for WCDMA coded systems employs a parallel interference canceller (PIC) followed by a bank of space-time matched filters (STMFs). At each iteration, the *a posteriori* probabilities at the output of each user's decoder are used to calculate an estimated mean value of the transmitted symbols, and hence to regenerate the MAI on the desired user. The regenerated interference is cancelled from the received signal at the output of the PIC and fed into the STMF. The resulting receiver has a very good trade-off between performance and complexity, and it is able to approach the single-user performance on the error rate at any load (i.e., for any number of active users in the system) by effectively removing the MAI.

ITERATIVE MMSE MULTI-USER RECEIVERS FOR MIMO SYSTEMS

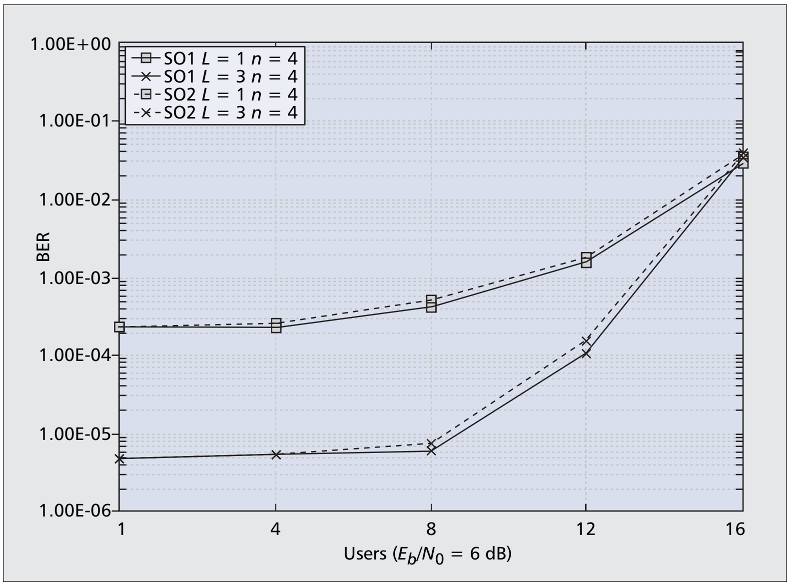
We have shown that the iterative receiver PIC performs very well for frequency-selective SIMO systems, where no transmit diversity is employed. In the case of STTC CDMA MIMO systems with frequency-selective subchannels, the presence of IAI further distorts the signal at the receiver, yielding performance degradation of the simple PIC detector with STMF. We have, therefore investigated iterative multi-user MMSE detectors for multipath CDMA systems and extended them to multiple antennas. An iterative multi-user MMSE detector is derived by directly equalizing the received signal at the chip level or, alternatively, filtering the sufficient statistics at the output of a space-time matched filter at the symbol level. This detector exploits the knowledge of signals detected at the previous iteration and enhances the overall performance of the receiver by a process of regeneration/cancellation of the MAI and IAI. At each iteration, the output of the decoders from the previous iteration is processed by a feedback filter, which is able to regenerate both MAI and IAI on the desired users' and transmit antennas' signal. It is shown that this iterative multi-user MMSE detector can effectively remove the interference even in highly loaded scenarios by reaching the single-user error rate lower bound after a sufficient number of stages, as shown in Fig. 2. Unfortunately, this is possible only at high computational cost. Therefore, two suboptimal MMSE detectors, with an acceptable trade-off between performance and computational complexity, are investigated, and we show that they still outperform the conventional noniterative multi-user MMSE receiver (Fig. 2).

SUBOPTIMAL ITERATIVE MU MMSE RECEIVERS FOR MIMO SYSTEMS

These suboptimal solutions exploit the fact that, after a sufficient number of iterations, the overall MAI and IAI is mitigated at the input of the MMSE filter. Therefore, it is possible to equalize either the signal of the desired user jointly over all the transmit antennas (SO1-MMSE receiver), ignoring the MAI from the remaining users at each iteration, or simply apply single-user MMSE filters to each signal of the desired user coming from each single transmit antenna (SO2-MMSE receiver). The resulting suboptimal detectors show a consistent complexity reduction of up to three orders of magnitude from the iterative optimal multi-user MMSE solution (IMU-MMSE receiver). This is illustrated in the example in Table 2 after $n = 3$ iterations for a half loaded system over $n = 3$ multipaths in the channel. Figure 3 shows the improvement of SO2-MMSE over the simpler STMF-PIC receiver, and Fig. 4 shows a performance comparison of SO1-MMSE and SO2-MMSE receivers. It is clear that the best trade-off between performance and complexity is given by the SO2-STMF-MMSE solution, where the symbol level MMSE detection noticeably reduces the complexity of the receiver from that of the chip synchronous one. Moreover, the PIC with only STMF suffers from ISI, MAI, and IAI in a STTC MIMO system, whereas stronger detectors, such as iterative MMSE receivers, either optimal or suboptimal, can guarantee higher system capacity.



■ **Figure 3.** *BER performance of SO2-MMSE and STMF-PIC with 2-antenna 16-state STTC,* E_b/N_0 *= 6 dB,* spreading factor = *32, and 2 receive antennas for different numbers of users and iterations over three paths.*



■ **Figure 4.** *BER performance comparison of SO1-MMSE and SO2-MMSE with 4-antenna 4-state STTC,* E_b/N_0 *= 6 dB,* spreading factor = *16, and 2 receive antennas for different numbers of users over flat fading and 3 paths fading after 4 iterations.*

The research outcome clearly demonstrated that an extension from SISO to MIMO transceivers facilitates the high data rates required for media-centric applications and that such efficient implementations are feasible.

Concluding Remarks

This article, the third of four, has presented the technical activities within Mobile VCE's Wireless Access research area. Since the research was defined and driven by the leading companies in mobile communications, the research naturally focused on the provision of wireless access in future networks.

The research outcome clearly demonstrated that an extension from SISO to MIMO transceivers facilitates the high data rates required for media-centric applications and that such efficient implementations are feasible. Algorithmic beyond third generation (B3G) transceiver technologies have been suggested. To improve the B3G link capacity, various multiuser schemes have been analyzed with major focus on complexity reduction. The developed SISO and MIMO, iterative and noniterative CDMA-based detection schemes have been assessed in terms of their advantages and disadvantages, as well their range of potential application. It has been demonstrated that the achieved trade-off between performance and complexity reduction indeed facilitates B3G terminal designs.

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Biographies

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