WIRELESS OFDM SYSTEMS WITH MULTIPLE TRANSMIT AND RECEIVE ANTENNAS WITH BIT-INTERLEAVED CODED MODULATION

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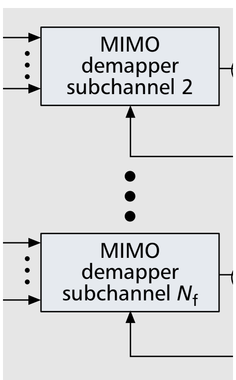

The capacity for multi-antenna dispersive radio channels is much higher than single receive and transmit antenna systems. The authors show that high data rates can be achieved at low power levels for systems where the number of transmit antennas is typically larger than the number of receive antennas.

ABSTRACT

It has recently been shown that the capacity for multi-antenna dispersive radio channels is considerably higher than single receive and transmit antenna systems. In this article we demonstrate that high data rates can be achieved at low power levels for systems where the number of transmit antennas is typically larger than the number of receive antennas. We use bit-interleaved coded modulation, iterative decoding, and OFDM system building blocks for a flexible class of space-time coding systems where it is easy to change convolutional code rate, constellation size, and the number of transmit and receive antennas for designing systems with a wide range of capabilities. The coding is typically done in the time, frequency, and space domains. The gain can be used for either high data rates and/or lower power levels. Applications can be found in future wireless LANs and/or B3G and 4G wireless cellular systems.

INTRODUCTION

Future wireless digital communication links demand higher data rates at lower power levels than most of today's systems [1]. A promising technology for achieving this goal is the use of multiple transmit and receive antennas with signaling that is coordinated between the transmit antennas. It has been shown that in a rich scattering environment, the channel capacity increases linearly with the number of transmit antennas [2–4]. The most powerful systems are achieved with effective channel estimation. Noncoherent systems without channel information have also been proposed, but realistic versions of such systems have a loss in performance.

In general, multiple antenna techniques can be classified into two classes. These are space-division multiplexing (SDM) and space time coding (STC) techniques. In SDM techniques, individual information streams are transmitted independently through each transmit antenna to increase system throughput. Typically, SDM receiver structures include the Bell Laboratories Layered Space Time (BLAST) architecture [2]. One constraint in conventional SDM techniques is that the number of receive antennas is at least the same as that of transmit antennas, which makes the mobile unit expensive and complicated in the downlink environment. On the other hand, STC techniques do not impose such receive antenna constraints. STC schemes improve link performance by means of transmit diversity.

It is well known that classical diversity improves the performance of a wireless link [1]. This diversity can, for example, be realized in the form of time or frequency diversity or space diversity in terms of multiple antennas at the receiver or transmitter only. More recently, with the advent of space-time coding systems, we have efficient schemes with both multiple transmit and receive antennas [2–7].

Channel coding is a way to achieve time diversity (often in combination with interleaving). Frequency diversity is obtained by the combination of so-called orthogonal frequency-division multiplexing (OFDM) modulation, channel coding, and interleaving over the multiple tones in the OFDM system. Such coded OFDM (COFDM) systems have many applications in high-data-rate wireless systems for digital audio and digital TV. Wideband systems can be implemented that are robust to frequency selective fadings; these systems require no adaptive equalizers [1].

High-data-rate systems often call for higher order modulation systems such as 16-quadrature amplitude modulation (QAM), 64-QAM, and so on [1]. To achieve efficient coded systems, we now need trellis coded modulation (TCM), or combined coding and modulation. It is well known that classical TCM designed for the Gaussian channel is not effective on Rayleigh fading channels [1]. This is due to the fact that the most important feature in the design for the Gaussian channel (minimum Euclidean distance) is different from that of the Rayleigh fading channel (diversity) [1]. There are, however, several ways to construct good TCM systems for fading channels. Among the most promising and flexible methods are so-called bit-interleaved coded modulation (BICM) systems [8, 9]. As the name suggests, an interleaver on the bit level is placed between a binary convolutional code and the multilevel modulator. The fading occurs on the symbol level, and diversity must be achieved on the symbol level. By using a conventional binary convolutional code with a large free distance and a bit interleaver, diversity on the symbol level is achieved for any modem constellation.

BICM systems can be decoded by means of a Viterbi decoder [1]. Higher performance is achieved by an iterative decoder (ID) [6]. By taking a demapper for the demodulating operation as an inner code and a maximum *a posteriori* (MAP) decoder for the convolutional decoder as an outer code, we have in fact a turbo decoder for serial concatenation [10, 11, 20]. The mapper is a rate 1 code that is used as an inner code in a pair with the bit interleaver in between in a conventional serial concatenation. It has been shown that BICM-ID outperforms the noniterative Viterbi algorithm in many cases. For wideband frequency selective channels, we can now put together multiple transmit and receive antennas, OFDM, and BICM-ID with a multi-input multi-output (MIMO) demapper into a flexible and powerful class of space-time coding systems [7]. This is the topic of this article. It turns out that these systems work well for any number of transmit and receive antennas, yielding a convenient arrangement for low terminal complexity.

The design of efficient signaling schemes for wireless systems with multiple transmit and receive antennas is currently a very active area of research. Several different approaches to STC are described in the literature, based on both block and trellis codes [5, 12, 13]. One advantage with the systems described here is the combination of good performance and the flexibility of rate changes without complete redesign of the system. Furthermore, efficient systems employing more transmit antennas than receive antennas are feasible with this approach.

Future wireless systems such as upgrades of 802.11 LANs and fourth-generation (4G) cellular systems most likely will use MIMO technology [14]. Especially for next-generation wireless LAN systems, the new 802.11n task group has been formed to define an amendment to make standardized modifications to both the 802.11 physical layer (PHY) and medium access control (MAC) layer so that modes of operation can be enabled capable of much higher throughput, with a maximum throughput of at least 100 Mb/s. The architectures described in this article are good candidates for such applications. Further work is suggested on channel estimation algorithms, efficient low-complexity iterative decoding algorithms, and mappers for high-level QAM constellations.

It is the goal of this article to give a semi-tutorial type of presentation of the systems in [7], adding some new performance results as well as putting them in a technical perspective. We emphasize using well-known building blocks in system designs to achieve flexible and simple systems with good performance. The rest of the article is organized as follows. In the following section we review basic system parameters that should be considered in MIMO system design. Then we describe the proposed MIMO-OFDM system architecture. The simulation section reports performance results with various system configurations. Finally, the last section concludes this article.

SYSTEM DESIGN

In this section we describe the system design for MIMO-OFDM systems combined with BICM-ID. Generally speaking, the given system applications determine whether the SDM or STC schemes should be employed for multiple-antenna systems. Near the base station or access point, intercell interference is normally small. Also, it is desirable to maximize the transmission rate for users near the base station from the system capacity point of view. Therefore, it is natural to adopt the SDM technique when users are accessing the cellular system in the vicinity of the base station. This maximization of the user data rate is realized at the expense of link performance.

On the other hand, when users are at the cell boundary, the channel fluctuation becomes larger due to the increased intercell interference. In this case diversity techniques are preferred in order to average out intercell interference. Therefore, for users near the boundary of a cell, it is appealing to employ the STC schemes. Even in the case of a single-cell environment, the STC scheme is beneficial in terms of increasing the coverage area by maximizing link performance. It should be noted that when the line of sight (LOS) condition occurs, the performance of both SDM and STC techniques may deteriorate.

For the next-generation wireless access system, it is of interest to consider implementing a hybrid multiple-antenna system that can support both SDM and STC in the same transmit architecture. In such a system use of the SDM or STC schemes will be determined based on a user's conditions. There are several parameters affecting the selection mechanism for the operation mode. In order to fully utilize system capacity, an intelligent switch operation should be set up that takes those effects into account. A mobile user can, in principle, estimate several parameters such as the average signal-to-interference-plus-noise ratio (SINR), antenna correlations, and user mobility. Then the user determines whether the given condition is better suited to SDM or STC, and requests the selected operation mode to the base station. As a result, SDM may be applied for users who are near the base station with low mobility, whereas STC can be selected for users who are near the cell boundary or have low SINR values. In the "near the base station" scenario, normally SDM schemes are implemented using the BLAST architecture, and the design of the BLAST system has been extensively carried out in the literature; see [2, 15, 19] and references published later. Therefore, in this article we focus on the STC scheme as a means to maximize link performance in the cell boundary scenario. As we shall see later, the transmitter structure of the proposed scheme allows us to

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Among other things, the following four criteria are most important: diversity gain, coding gain, multiplexing gain, and receiver complexity. Depending on the given system environment, these design parameters may have different implications.

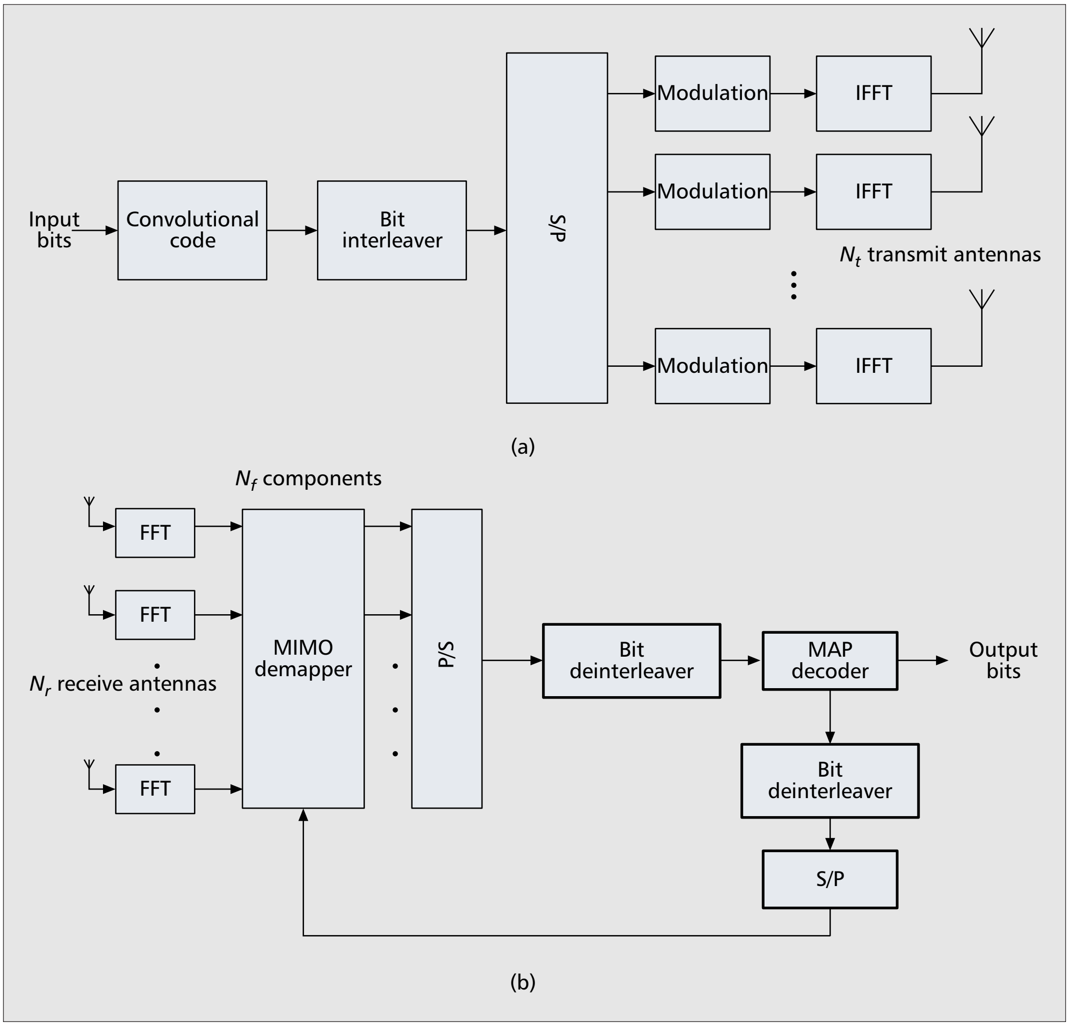


Figure 1. *MIMO-OFDM with BICM-ID structure (a) transmitter (b) receiver.*

employ both SDM and STC in the same architecture. In this hybrid system design the adaptation potential of the proposed scheme is quite attractive. For example, when user transmission is in SDM mode, and the monitored SINR falls below certain threshold values, the operation mode can be switched to STC. Thus, the operation switch between STC or SDM in the proposed scheme can be carried out seamlessly by sharing the same transmitter structure. Design of such switch mechanisms for hybrid systems was also illustrated in [16]. It should be noted, however, that a system with STC alone is completely viable, which motivates the results presented here.

Now we review some basic parameters for the MIMO system design. Consider an N_f subcarrier MIMO-OFDM system with N_t transmit antennas and N_r receive antennas. When designing space time coding schemes that employ multiple antennas, several issues should be carefully looked into. Among other things, the following four criteria are most important: diversity gain, coding gain, multiplexing gain, and receiver complexity. Depending on the given system environment, these design parameters may have different implications. Here we discuss them for wideband frequency-selective channels.

Diversity Gain

Most STC schemes proposed in the literature were originally developed for flat fading channels. For such channels, optimizing the diversity order is important in designing STC systems. Extra diversity gain introduced by STC exhibits drastic improvement in the bit error rate (BER) performance in flat fading channels, as the flat fading channel lacks frequency diversity. Therefore, achieving the full diversity order is the most critical point in STC design for flat fading channels. In contrast, for frequency-selective channels where frequency diversity is available, full diversity becomes less important, as the performance improvement due to the additional diversity gain from STC becomes smaller. Therefore, a better strategy may be to relax the full diversity condition and complement the diversity loss by other factors such as higher coding gain or multiplexing gain.

For example, assuming a frequency-selective Rayleigh fading channel with K equal power taps, it can be shown that the diversity order D for MIMO-OFDM systems is equal to

$$D = \min(L, KN_t) \cdot N_r,$$

where L denotes the effective code length of the code [7]. Here L is related to the symbol level Hamming distance for the given code.

The above diversity order equation leads to many interesting interpretations. First, for a flat fading case ($K = 1$), the diversity order equation reduces to the well-known full diversity case $N_t \cdot N_r$ with a practical choice of N_t. Thus, compared to the single-antenna case, the MIMO system shows an N_t fold increase in diversity order. However, as the channel becomes more dispersive (higher K), the effect of multiple transmit antennas on diversity order becomes smaller. At a certain point, KN_t gets larger than L; then eventually the diversity order for highly dispersive channels becomes $L \cdot N_r$, which is independent of the number of transmit antennas. This means that when the channel already contains enough diversity, the diversity gain due to multiple transmit antennas is saturated. The independent fading case is certainly an extreme one, and practical wideband channels lie between the flat fading and independently fading case. This suggests that too many transmit antennas are certainly not needed for highly dispersive channels in terms of diversity order. However, as will be shown later, diversity order is not the only gain a MIMO system can achieve.

Coding Gain

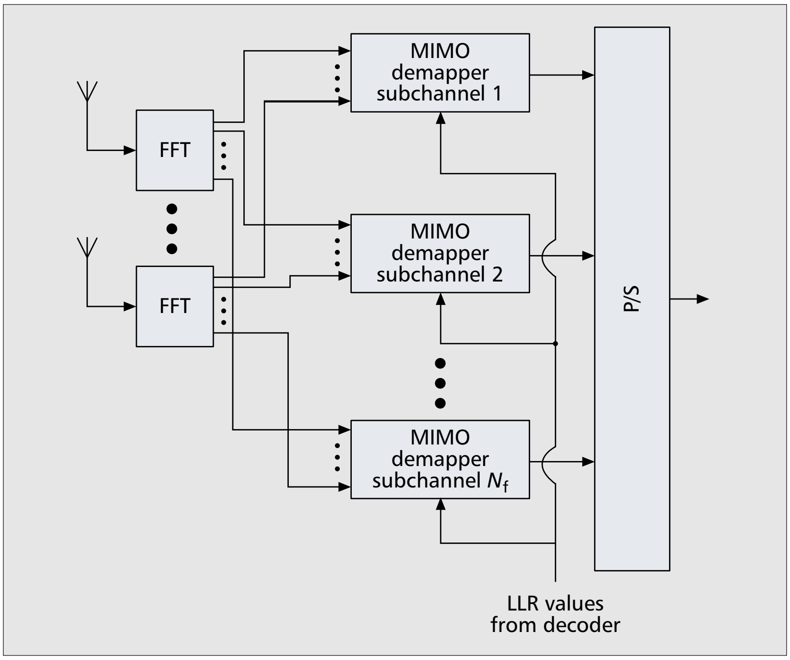
For similar reasons as those described above, the coding gain optimization for flat fading channels has been treated with lower priority. As the channel becomes frequency-selective, however, coding gain plays a more important role in overall performance, since optimization of diversity gain becomes less critical. The coding gain optimization for MIMO-OFDM systems currently remains an ongoing research topic. A basic rule of thumb is to employ a standard maximum free Hamming distance convolutional code as an outer code to exploit the maximum coding gain.

Multiplexing Gain

Multiplexing gain, or code rate, is determined by the ratio of the number of transmitted symbols to the transmission time slot. A scheme is said to have a spatial multiplexing gain r and a diversity gain D if the rate of the scheme scales like r log SNR and the average error probability decays like $1/\mathrm{SNR}^D$. The optimal trade-off between multiplexing gain and diversity gain has been studied in [17].

For the proposed MIMO-OFDM scheme, coded sequences from the individual transmit antennas are transmitted independently. Therefore, the spatial multiplexing gain for the MIMO-OFDM scheme is equal to the number of transmit antennas N_t. For comparison, the well-known Alamouti scheme [18] transmits two symbols in two consecutive time slots. Thus, the multiplexing gain is 1, which is sometimes called full rate. Naturally, when the multiplexing gain is greater than 1, an advanced receiver such as an iterative decoder is beneficial to process the received signal, as there are more symbols to decode than equations. However, as shown later, when the number of receive antennas is at least the same as that of transmit antennas, the overall receiver structure becomes simpler.

Another advantage of multiplexing gain higher than 1 is reduced constellation size. To get the same spectral efficiency, the proposed



■ **Figure 2.** *MIMO demapper block.*

MIMO-BICM can use a lower modulation level, which in turn results in a performance gain in receiver signal processing.

In contrast to the general STC case, SDM schemes attain higher multiplexing gain N_t, as the goal of SDM is to increase transmission rate at the expense of link performance. Normally SDM schemes require the number of receive antennas to be greater than or equal to that of transmit antennas.

Receiver Complexity

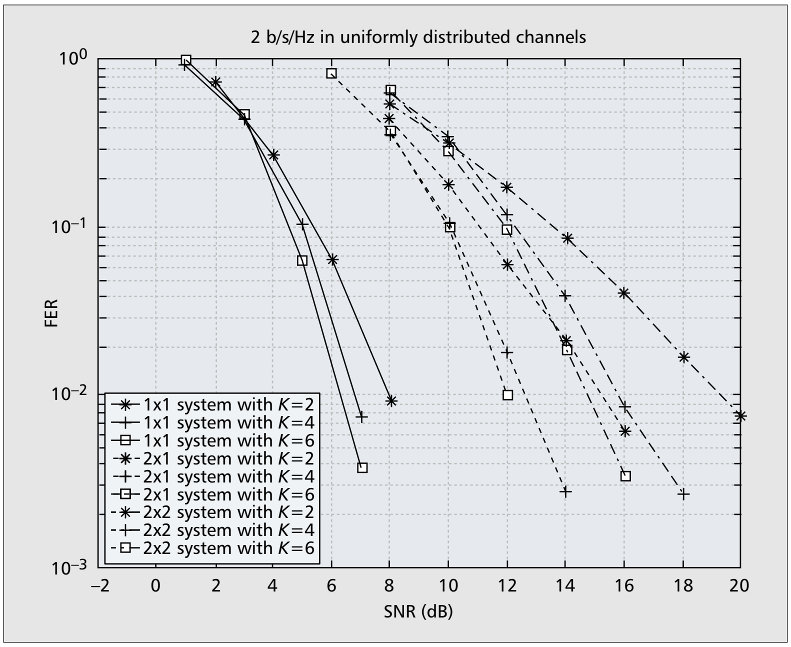
Designing a practical wireless system is often dictated by receiver complexity. One of the reasons the Alamouti scheme has become so popular in spite of somewhat reduced coding gain in comparison to other trellis-based STC schemes is its simple receiver structure. One unfortunate fact is that there exists no such simple STC scheme when the number of transmit antennas is greater than two. The trade-off between receiver complexity and system performance is one thing a designer should determine based on system requirements. The MIMO-OFDM with BICM-ID scheme proposed in this article is focused on maximizing overall performance without incurring too much complexity in the receiver.

Structure of MIMO-OFDM Combined with BICM-ID

In this section we describe the transmitter and receiver structure for multiple-antenna OFDM systems combined with BICM-ID [7]. Figure 1 shows the structures for the transmitter and receiver. For the wideband system, we apply an OFDM demodulator for each antenna, and the processing is done over N_f parallel narrowband flat fading subchannels. The convolutional coder uses a binary code with rate R_c. The modulation block converts $\log_2 M$ bits to one of M-ary sym-

Number of subcarriers (N_f)	128
Cyclic prefix symbol length	32
Channel	Rayleigh fading with K equal gain profile (K = 2, 4, 6)
Frame size (bits)	512

■ **Table 1.** *System configurations.*



■ **Figure 3.** *Performance comparison with MIMO-OFDM with 2 b/s/Hz.*

bols in the transmitted sequence. As for the structure shown in Fig. 1, it should be noted that the same transmitter structure can be employed for the BLAST scheme. Thus, it makes the proposed architecture attractive for the hybrid system design described in the previous section.

A key subsystem in the receiver is the MIMO demapper, which, based on the N_r antenna inputs, produces the MAP estimates of the transmitted bits for each subcarrier in the N_t transmitter streams corresponding to the N_t antennas in the transmitter. (See [7] for a detailed description of the MIMO demapper block.)

Figure 2 shows a detailed description of the MIMO demapper block. Let $d_{k,m}$ be the bit that is mapped at the kth subcarrier into the mth bit position (m = 1, 2, …N_t log$_2M$) of the constellation symbol. Also, denote χ_d^m, d = +1 or –1 as a set of all symbol vectors with a +1 or –1 value of bit $d_{k,m}$, respectively. Then the log likelihood ratios (LLR) are given by

$$L(d_{k,m}) = \ln \frac{\sum_{\mathbf{x}_k \in \chi_{+1}^m} p(\mathbf{x}_k, \mathbf{y}_k, \mathbf{H}_k)}{\sum_{\mathbf{x}_k \in \chi_{-1}^m} p(\mathbf{x}_k, \mathbf{y}_k, \mathbf{H}_k)}, \quad (1)$$

where $\mathbf{x}_k$, $\mathbf{y}_k$ and $\mathbf{H}_k$ denote the transmitted symbol vector of length N_t, received signal vector of length N_r, and the N_r by N_t MIMO channel response matrix, respectively, for the kth subcarrier. Here the total number of elements $\mathbf{x}_k$ to be searched for this optimal LLR computation is M^{N_t}.

The joint probability density in Eq. 1 is then related to

$$\exp\left(-\frac{1}{N_0} \left\| \mathbf{y}_k - \mathbf{H}_k \mathbf{x}_k \right\|^2 + \frac{1}{2} \sum_{m=1}^{N_t \log_2 M} d_{k,m} L(d_{k,m}) \right),$$

where N_0 denotes the noise variance. The second term in the exponent accounts for the so-called extrinsic LLR values from the previous iteration [10]. When computing the joint probability density function in the above LLR equation, the extrinsic information is provided from the MAP decoder for the convolutional code at the previous iteration. For the first pass through the iterative decoder, the initial extrinsic information values are set to zero. For the second pass and beyond, they are derived from the MAP decoder for the convolutional code. Then, by subtracting the input likelihood values from the output LLR values computed in Eq. 1, the extrinsic information is exchanged between the MIMO demapper and the MAP decoder to improve error rate performance [7]. This constitutes the conventional turbo principle for serial concatenation.

Simulation Results

In this section we present simulation results for the MIMO-OFDM with BICM-ID for wideband frequency-selective channels. As explained before, the performance of STC depends on the level of frequency selectivity (i.e., delay spread) for the given channel. To address this, we carry out several simulations for many channel configurations with different delay profiles.

The channel environments and OFDM system configurations assumed in the simulation

	2 b/s/Hz	3 b/s/Hz	4 b/s/Hz
N_t = 1	16-QAM R_c = 1/2 (133,171) code without iterative decoding	16-QAM R_c = 3/4 (133,171) code without iterative decoding	64-QAM R_c = 2/3 (133,171) code without iterative decoding
N_t = 2	QPSK R_c = 1/2 (23,35) code with iterative decoding	QPSK R_c = 3/4 (23,35) code with iterative decoding	8PSK R_c = 2/3 (23,35) code with iterative decoding

■ **Table 2.** *Modulation level, code rate, and polynomials (in octal form).*

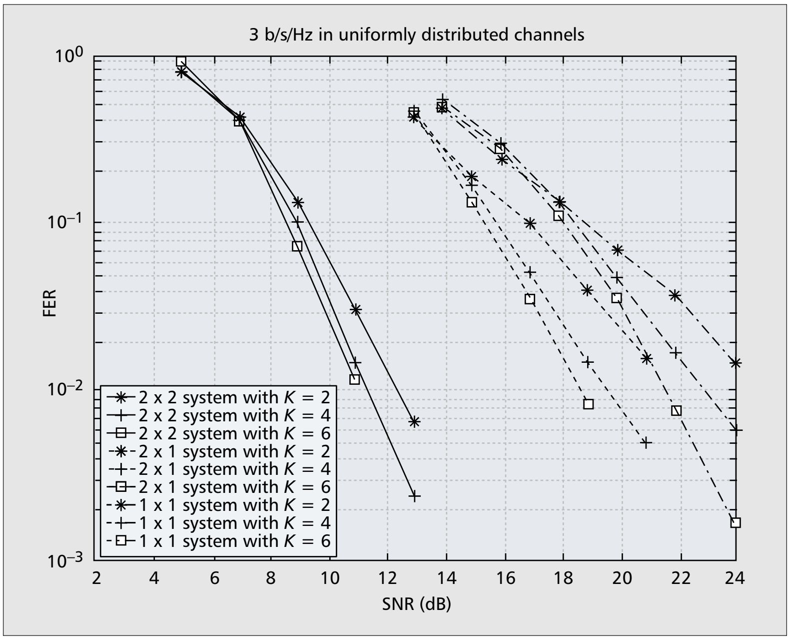
are summarized in Table 1. Uniformly distributed channel profiles with various numbers of equal gain taps are employed. (This may be used as a worst case type of scenario. Exponential decay profiles are used in the simulations in [7].) Each tap is assumed to be independently Rayleigh faded. Equal gain delay profile channels are adopted in order to illustrate the effect of the increased channel diversity order.

The system parameters employed in the simulations are shown in Table 2. The binary convolutional code polynomials are represented in octal notation. Punctured codes are used for R_c = 2/3 and 3/4, respectively [1, 7]. Gray mapping is assumed for the simulations. Here the case with one transmit antenna (N_t = 1) is given as a reference system. In this case no iterative decoding is applied for the single-antenna case. Instead, a 64-state convolutional code is used. Simulations indicate that the performance gain of codes with larger numbers of states is minimal since the degree of diversity is the dominant feature. For the N_t = 2 case, a 16-state convolutional code is employed with iterative decoding.

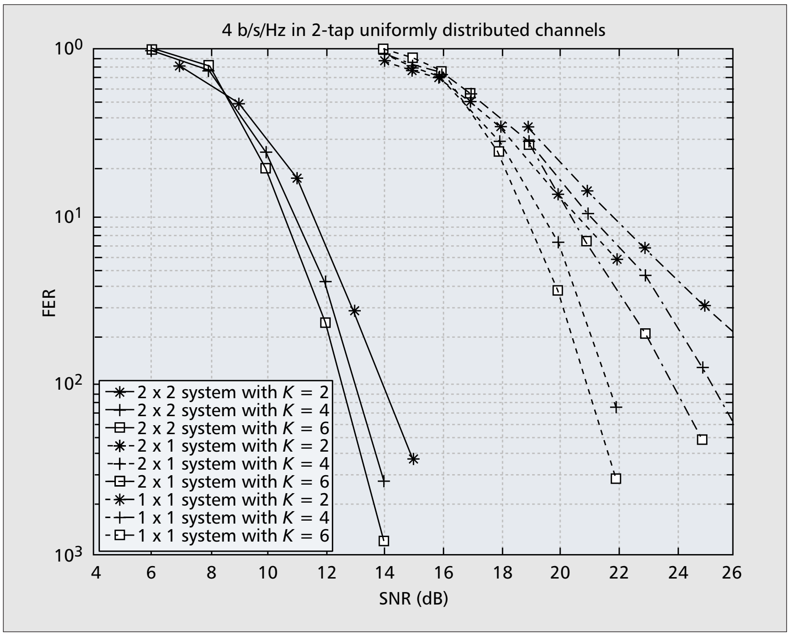
To make a fair comparison, both the single-antenna and MIMO cases are set to have the same spectral efficiency. Note that for the MIMO-OFDM case, the multiplexing gain is equal to N_t, as N_t coded sequences are independently transmitted through each transmit antenna in one time instance. Therefore, the constellation size required to get the same spectral efficiency as in the single-antenna case is smaller.

In the simulations we assume that the channel is quasi-static. If the channel is time varying, additional time diversity gain can be achieved. Throughout the simulations, for simplicity, one packet is assumed to consist of one OFDM symbol. A random interleaver is used in the simulations. The number of decoding iterations is set to four. However, we note from the simulations that after three iterations the error rate performance improvement is normally saturated.

Figures 3, 4, and 5 show simulation results comparing a single-antenna system and a MIMO-OFDM system with two transmit antennas. Here we compare them for the 2, 3, and 4 b/s/Hz cases for frequency-selective block Rayleigh fading channels with K equal power rays. In these figures the y axis represents the frame error rate (FER). Several interesting observations can be made in the plots. First, as analyzed earlier in the article, the performance improvement due to transmit diversity becomes smaller as the channel delay spread, which is proportional to K, increases. When the number of transmit and receive antennas is fixed, the slope increase in the FER plots is quickly saturated as K grows. For example, the performance difference between K = 4 and 6 is small compared to that between K = 2 and 4. Also, we note that the performance gain of the proposed MIMO-OFDM system grows as its spectral efficiency increases. This is attributed to the fact that the single-antenna system suffers from reduced Euclidean distance in higher constellation sizes. In contrast, the multiplexing gain N_t of the MIMO-OFDM system allows a smaller constellation size, resulting in good performance.



■ **Figure 4.** *Performance comparison with MIMO-OFDM with 3 b/s/Hz.*



■ **Figure 5.** *Performance comparison with MIMO-OFDM with 4 b/s/Hz.*

Figure 6 shows the simulation plot for four transmit antennas and different numbers of receive antennas with one and four iterations. In this case the frame size is set to 1024 bits. As the number of receive antennas increases, the performance gap between the first and fourth iterations gets smaller. This is due to the fact that the demapper operation in Eq. 1 solves N_R equations with N_t unknowns. When the number of receive antennas is smaller than that of transmit antennas, the computation of the demapper function becomes less reliable. Thus, the iterative decoding scheme is crucial for the $N_t > N_R$ case since a priori information computed at the decoder block in the previous iteration helps the demapper block improve the quality of the LLR values.

One of the advantages in the proposed BICM based MIMO-OFDM system is its flexibility. Regardless of system configuration, such as number of transmit antenna and modulation level, the same system architecture can be used for the proposed system. Other STC schemes based on block codes are not easily extendable to systems other than the given antenna configurations. For example, the Alamouti scheme cannot be applied to anything other than a two-transmit-antenna system. Figure 7 compares the proposed MIMO-OFDM scheme and the Alamouti scheme [18] with the 2×2 ($N_t = N_r = 2$) case. For both schemes, the same 64-state convolutional code is employed to have the BICM structure. For the proposed scheme, no iterative decoding is applied so that a simple Viterbi decoder replaces the MAP decoder. As shown in the plot, the performance gain over the Alamouti scheme becomes larger as the spectral efficiency increases. It is expected that the performance gap becomes even larger when the iterative decoding is employed. Note that for the single-receive-antenna case, compared to the proposed scheme with iterative decoding, the Alamouti scheme may be a more attractive option due to its low complexity.

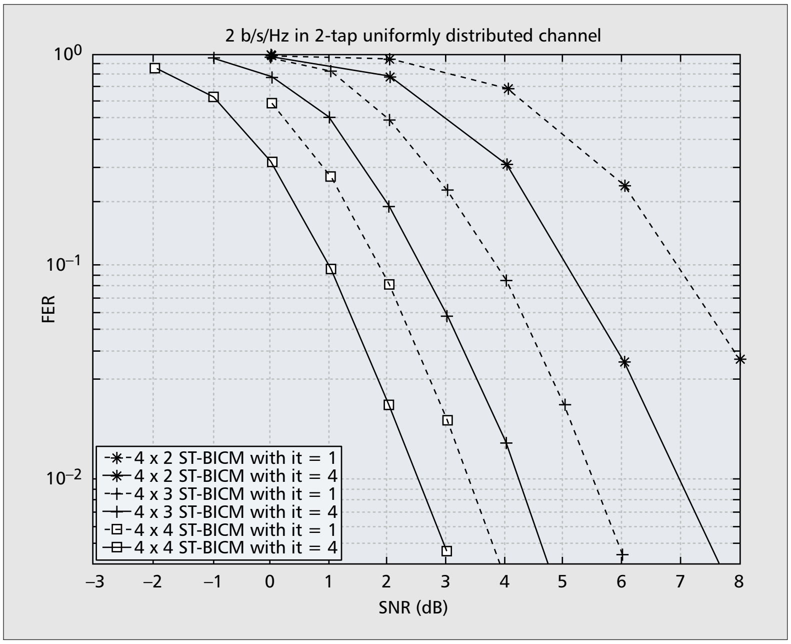


Figure 6. *Performance of* $N_t = 4$ *transmit antenna system.*

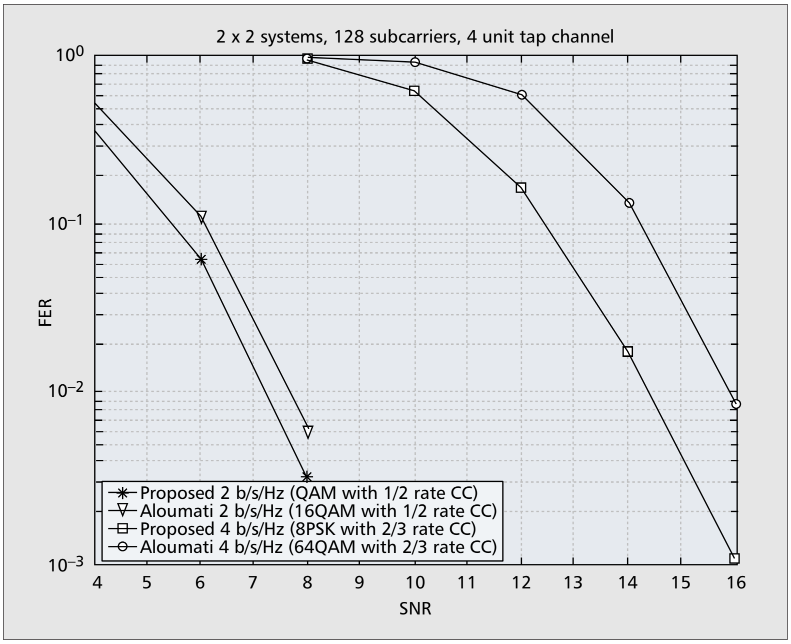


Figure 7. *Comparison of the proposed scheme with no iteration and the Alamouti code.*

Conclusions

By employing multiple transmit and receive antennas, significant improvements can be obtained on a wireless link over the case with a single transmit and receive antenna. In this article we demonstrate such gains for a flexible class of systems with OFDM and BICM with iterative decoding. Conventional building blocks are employed such as binary convolutional codes, interleavers, M-ary QAM modulators, and MAP decoders for serial concatenation. It is especially interesting to observe that this family of systems yields good performance for the practical case of a large number of transmit antennas and a small number of receive antennas. The power gains demonstrated earlier can also be transformed into gains in spectral efficiency by modifying the building blocks.

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Biographies

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