SPACE-TIME/FREQUENCY CODING FOR MIMO-OFDM IN NEXT GENERATION BROADBAND WIRELESS SYSTEMS

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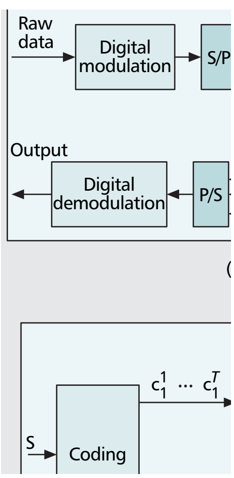

With the advent of 4G broadband wireless, the combination of MIMO wireless technology with OFDM has been recognized as one of the most promising techniques to support high data rate and high performance.

ABSTRACT

With the advent of next generation (4G) broadband wireless communications, the combination of multiple-input multiple-output (MIMO) wireless technology with orthogonal frequency division multiplexing (OFDM) has been recognized as one of the most promising techniques to support high data rate and high performance. In particular, coding over the space, time, and frequency domains provided by MIMO-OFDM will enable a much more reliable and robust transmission over the harsh wireless environment. In this article we provide an overview of space-time (ST) coding, space-frequency (SF) coding, and space-time-frequency (STF) coding for MIMO-OFDM systems. Performance results show that STF coding can achieve the maximum diversity gain in an end-to-end MIMO-OFDM system over broadband wireless channels. Furthermore, for orthogonal frequency division multiple access (OFDMA), we propose a multiuser SF coding scheme that can achieve the maximum diversity for each user while minimizing the interference introduced from all the other users.

INTRODUCTION

Swifter, higher, stronger — the Olympic motto is also being pursued for the upcoming 4G broadband wireless communication systems. Motivated by the huge demands for fast and reliable communications over wireless channels, future broadband communication systems should provide *swifter* data processing (low-complexity), *higher* data rate, and *stronger* (robust) performance. In practice, however, the broadband channel is a typically non-line-of-sight channel and includes many impairments such as time-selective and frequency-selective fading. To address these challenges, one promising solution is to combine two powerful technologies, namely, multiple-input multiple-output (MIMO) antennas and orthogonal frequency division multiplexing (OFDM) modulation [1].

MIMO systems have been recently under active consideration because of their potential for achieving higher data rate and providing more reliable reception performance compared with traditional single-antenna systems for wireless communications [2, 3]. A space-time (ST) code is a bandwidth-efficient method that can improve the reliability of data transmission in MIMO systems [4]. It encodes a data stream across different transmit antennas and time slots, so that multiple redundant copies of the data stream can be transmitted through independent fading channels. By doing so, more reliable detection can be obtained at the receiver. As an example of MIMO applications, the IEEE 802.11n standard is still being discussed, but one prototype can offer up to 250 Mb/s. This is more than five times the (theoretical maximum) speed of the existing IEEE 802.11g hardware.

OFDM is based on the principle of frequency division multiplexing (FDM), but is utilized as a digital modulation scheme via DFT. The data stream that is to be transmitted is split into several parallel streams, typically dozens to thousands. By doing so, the wideband frequency-selective channel is divided into a number of parallel narrowband subchannels, and each of the low-rate data streams is transmitted over one subchannel. The major advantage of OFDM is its ability to cope with severe channel conditions,

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for example, multipath fading and narrowband interference, without complicated equalization filters. OFDM is also now being used in ADSL and VDSL broadband access via telephone network copper wires, the terrestrial digital television systems (DVB-T), and some wireless local area networks (LAN) and metropolitan area networks (MAN) applications, including IEEE 802.11a/g (and the European alternative HIPERLAN/2) and WiMAX. MIMO can also be used in conjunction with OFDM, and is part of the IEEE 802.16 standard, and will also be part of the IEEE 802.11n high-throughput standard.

The air-link architecture of MIMO-OFDM has also been suggested for the future 4G wireless systems. MIMO-OFDM systems provide many freedoms in space, time, and frequency. Hence, ST coding, space-frequency (SF) coding, and space-time-frequency (STF) coding can be applied in order to exploit the maximum diversity from MIMO channels. In [1], the concept of SF coding in MIMO-OFDM systems and a few SF coding approaches were reviewed. In this article we attempt to provide an overview of ST coding, SF coding, and STF coding for MIMO-OFDM wireless systems, in particular focusing on recent work on high rate and full diversity ST/SF/STF code design.

The remainder of this article is organized as follows. We first give a brief introduction of MIMO technology and OFDM modulation. We then focus on a general coded MIMO-OFDM system and give two basic definitions, namely, the code rate and diversity gain. An overview of ST coding, SF coding, and STF coding employed in MIMO-OFDM systems is given. We will extend the discussion to orthogonal frequency division multiple access (OFDMA) and, in particular, we propose a new design of multiuser SF coding. Finally, we draw our conclusion.

MIMO-OFDM

MIMO

MIMO wireless communication refers to the transmissions over wireless links formed by multiple antennas equipped at both the transmitter and receiver. The key advantages of employing multiple antennas lie in the more reliable performance obtained through *diversity* and the achievable higher data rate through *spatial multiplexing* [2]. These concepts are briefly discussed below.

Diversity — The signal transmission over broadband wireless channels always suffers from attenuation due to the detrimental effect of multipath fading, and this can severely degrade the reception performance. In MIMO systems, the same information can be transmitted from multiple transmit antennas and received at multiple receive antennas simultaneously. Since the fading for each link between a pair of transmit and receive antennas can usually be considered to be independent, the probability that the information is detected accurately is increased. Apart from the spatial diversity, other forms of diversity are commonly available, namely, temporal diversity and frequency diversity, if the replicas of the faded signals are received in the form of redundancy in the temporal and frequency domains, respectively. The simplest way of achieving diversity in MIMO systems is through repetition coding that sends the same information symbol at different time slots from different transmit antennas. A more bandwidth efficient coding scheme is ST coding [4], where a block of information symbols are transmitted in a different order from each antenna.

Spatial Multiplexing — It is widely recognized that the capacity of a MIMO system is much higher than a single-antenna system. For a rich scattering environment, in a MIMO system with M_t transmit antennas and M_r receive antennas, the capacity will grow proportionally with $\min(M_t, M_r)$. MIMO systems provide more spatial freedoms or spatial multiplexing, so that different information can be transmitted simultaneously over multiple antennas, thereby boosting the system throughput. Spatial multiplexing needs a dedicated detection algorithm at the receiver to sort out different transmitted signals from their mixed one. V-BLAST is an example of such an algorithm and it can be realized in an efficient way with a series of ordering and successive cancellation [5].

Diversity-Multiplexing Tradeoff — Earlier research on MIMO systems has focused either on extracting the maximal diversity gain or the maximal spatial multiplexing gain of a channel. This has led to either a diversity-oriented or multiplexing-oriented design approach. For example, ST coding is regarded as a diversity-oriented scheme and V-BLAST is a multiplexing-oriented scheme. However, maximizing one type of the gain may not necessarily maximize the other. Later, in [6] it is found that both types of gains can be simultaneously obtained for a given MIMO channel, but there is a fundamental trade-off between how much of each type of gain any coding scheme can extract. Group detection was shown to play a key role in designing schemes that achieve optimal diversity-multiplexing trade-off [7, 8]. First, all transmit antennas are partitioned into G groups, and data is encoded over these G blocks, each of which fades independently. Within the gth ($g = 1, \cdots, G$) group, the signals to be sent are associated with a data rate R_g. Then, at the receiver group detection should be used and two approaches were proposed, namely, group zero forcing (GZF) and group successive interference cancellation (GSIC) [8]. In the first approach, a ZF decorrelator is used to separate the various groups of data and then maximum likelihood (ML) detection is applied to detect each group of data. In the GSIC approach, each group is detected using ML after canceling the interference of the already detected groups in previous stages. In [9] a framework for constructing optimal coding/decoding schemes, which was referred to as LAttice Space-Time (LAST) coding/decoding, was also proposed for achieving the optimal diversity-multiplexing trade-off. More recently, systematic constructions of space-time codes achieving the diversity-multiplexing trade-off for any number of antennas have been shown in [10].

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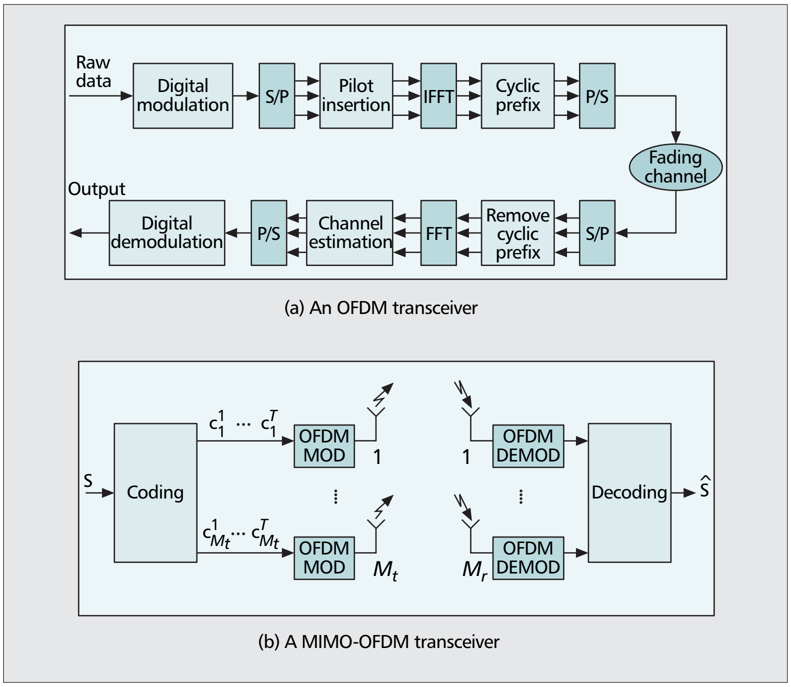


(a) An OFDM transceiver

(b) A MIMO-OFDM transceiver

Figure 1. *A simplified block diagram of MIMO-OFDM system, where* $\mathbf{S} = [s_1, s_2, \cdots, s_{Ns}]$ *denotes a block of Ns data symbols.*

OFDM

OFDM is essentially a discrete implementation of multicarrier modulation, which divides the transmitted bitstream into many different substreams and sends them over many different subchannels. Typically, the subchannels are orthogonal and the number of subchannels are chosen such that each subchannel has a bandwidth much less than the coherence bandwidth of the channel. Thus, intersymbol interference (ISI) on each subchannel is very small. For this reason, OFDM is widely used in many high data rate wireless systems.

Figure 1a shows a simplified block diagram of an N-tone OFDM system. First, the incoming bits are mapped to data symbols according to some modulation scheme such as QPSK or QAM. Then the serial data stream is converted into a number of parallel blocks, and each of them has length-N. Then, each block of symbols (including pilot symbols, which are used for channel estimation or synchronization) will be forwarded to the IFFT and transformed into an OFDM signal. After that, the OFDM signal will be appended with a cyclic prefix by copying the last N_{cp} samples to the top of the current OFDM block. By choosing the length of the cyclic prefix larger than the maximum path delay of the channel, ISI can be eliminated [11]. Afterward, the OFDM blocks will be converted to serial signals and sent out. At the receiver, assuming a perfect timing and carrier frequency synchronization, the received signals will be first converted to parallel signals and then the cyclic prefix will be removed. After going through the DFT block, the data symbols are detected with the estimated channel information. After demodulation, the transmitted bit stream is recovered.

In broadband time-varying multipath fading channels, OFDM has some of its own challenging issues, such as peak-to-average-power ratio (PAPR) and carrier frequency offset (CFO). However, much more unique merits of OFDM make it widely used in wireless applications and standards. The merits can be generally summarized as follows [11]:

- OFDM is easy to implement in the digital domain thanks to the use of DFT.
- OFDM is bandwidth efficient, since the parallel subcarriers are overlapping but orthogonal to each other without causing interference.
- OFDM is robust to multipath fading thanks to the use of a cyclic prefix.
- OFDM is insusceptible to most forms of impulse noise thanks to the parallel transmission.
- OFDM provides a high flexibility in resource allocation since it splits the broadband channel into a number of parallel subchannels. Thus, various resources (data rate and power) can be dynamically allocated to different subchannels.

MIMO-OFDM System Model

Future broadband wireless systems should provide high data rate and high performance over very challenging channels that may be time-selective and frequency-selective. The combination of MIMO and OFDM has the potential of meeting this stringent requirement since MIMO can boost the capacity and the diversity and OFDM can mitigate the detrimental effects due to multipath fading.

A general MIMO-OFDM system is shown in Fig. 1b, where M_t transmit antennas, M_r receive antennas, and N-tone OFDM are used. First, the incoming bit stream is mapped into a number of data symbols via some modulation type such as QAM. Then a block of N_s data symbols $\mathbf{S} = [s_1, s_2, \cdots, s_{Ns}]$ are encoded into a codeword matrix $\mathbf{C}$ of size $NT \times M_t$, which will then be sent through M_t antennas in T OFDM blocks, each block consisting of N subchannels. Specifically, $\mathbf{c}_j^1, \mathbf{c}_j^2, \cdots, \mathbf{c}_j^T$ will be transmitted from the jth transmit antenna in OFDM blocks $1, 2, \cdots, T$, respectively, where $\mathbf{c}_j^n$ denotes a vector of length-N, for all $j = 1, 2, \cdots, M_t$ and $n = 1, 2, \cdots, T$. The codeword matrix $\mathbf{C}$ can be expressed as

$$\mathbf{C} = \begin{pmatrix} \mathbf{c}_1^1 & \cdots & \mathbf{c}_{M_t}^1 \\ \vdots & \ddots & \vdots \\ \mathbf{c}_1^T & \cdots & \mathbf{c}_{M_t}^T \end{pmatrix}. \tag{1}$$

After appending the cyclic prefix on each OFDM block, $\mathbf{c}_j^n$ will be transmitted from the jth transmit antenna in the nth OFDM block.

After passing through the MIMO channels, the received signals will be first sent to the reverse OFDM block (cyclic prefix removal and DFT) and then sent to the decoder. If the channel state information (CSI) is available at the receiver, the optimal ML detection can be performed.

Code Rate

Since in Eq. 1 the total number of N_s information symbols are sent over NT channels where N channels are used in T times, we can get the code rate of the above coded MIMO-OFDM system as

$$\mathcal{R} \triangleq \frac{N_s}{NT}, \text{ symbols per channel use (pcu).}$$

In the following examples, we discuss the code rate for some of the most common communication systems.

Example 1: Single-Antenna System — For conventional single-carrier single-antenna uncoded signals, we have $N_s = N = T = 1$ and its rate is only 1 symbol pcu. We will omit the unit of rate "symbol(s) pcu" in the following discussion. For uncoded OFDM systems with a single-antenna, we have $N_s = N$ and $T = 1$. The transmitted codeword matrix **C** in Eq. 1 will be a vector of length N. Its rate is still 1.

Example 2: BLAST [5] — In this system, where independent information symbols are sent through multiple antennas simultaneously, $N_s = M_t$ and $N = T = 1$. The transmitted codeword matrix **C** in Eq. 1 will reduce to a row vector of N_s information symbols. Hence, the code rate is M_t. The difference between BLAST and OFDM is that the signals are sent from multiple antennas simultaneously for BLAST and from multiple separate subchannels simultaneously for OFDM. Thus, the received signals are superimposed on each other from all transmit antennas in BLAST but are separated on different subchannels in OFDM.

Example 3: ST Coding — For a general ST-coded MIMO system, $N = 1$ which results in the rate being

$$\mathcal{R} = \frac{N_s}{T}.$$

The transmitted codeword matrix **C** in Eq. 1 will be equal to a matrix of size $T \times M_t$, which denotes the signals will be sent from M_t antennas in T symbol intervals. For example, the classical ST code for two transmit antennas [4] has the form

$$\begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix} \quad (2)$$

where s_1 and s_2 denote the two independent data symbols and the superscript * represents the complex conjugate operation. In this coding scheme, s_1 and s_2 are transmitted from the first and second antennas, respectively. Then, at the next time slot, symbol $-s_2^*$ is transmitted from the first antenna and symbol s_1^* is transmitted from the second antenna. Obviously, the code rate is 1 because the two symbols are sent through two symbol intervals.

Diversity Gain

Using some diversity technique, faded replicas of the same information symbols can be provided to the receiver in a form of redundancy in various domains (time, space, and frequency). Since the probability that all the signal replicas fade simultaneously is extremely small, the reception performance will be enhanced significantly. The reception performance of a communication system is usually evaluated by the average bit error rate (BER) or symbol error rate (SER) versus the signal-to-noise ratio (SNR). In the high SNR region, the average error probability P_e over a fading channel usually behaves as

$$P_e \sim (G_c \cdot SNR)^{-G_d}, \quad (3)$$

where G_c is referred to as the *coding gain* and G_d is called the *diversity gain* of the system. To further highlight the difference between the coding gain and the diversity gain, the P_e is plotted in terms of SNR (in dB) in Fig. 2. It can be seen that the diversity gain can be interpreted as the slope of the curve, whereas the coding gain corresponds to the horizontal shift of the curve. Moreover, the diversity gain dominates the error rate performance in the high SNR region. In the following, we present two examples of the diversity gain.

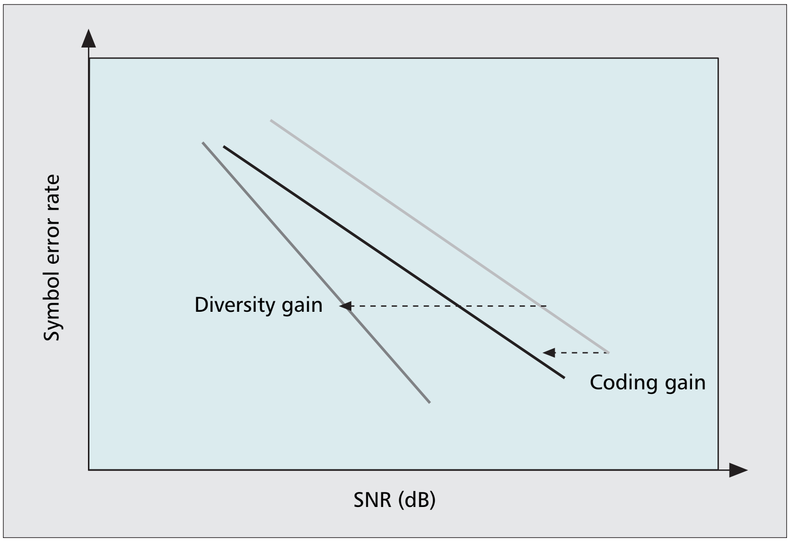


Figure 2. *Diversity gain and coding gain.*

Example 1: Flat MIMO Channels — One attractive merit of MIMO systems is the increased antenna diversity which can alleviate the detrimental effect of fading. In a MIMO system with M_t transmit antennas and M_r receive antennas, if the channels for any pair of transmit-receive antennas are independent and experience flat fading, the maximum or full diversity gain is M_tM_r. A common way of achieving the full diversity is through ST coding, which is discussed in the next section.

Example 2: Frequency-Selective MIMO Channels — In MIMO systems where any transmit-receive link is subject to multipath fading independently and the channel impulse response is characterized by L resolvable paths, the full diversity gain is M_tM_rL [12, 13]. In frequency-selective MIMO channels, OFDM is usually applied to eliminate the ISI. To achieve full diversity, coding is used across OFDM subchannels, OFDM blocks, and transmit antennas. Hence, we have SF coding and STF coding.

The strategy which consists of coding across antennas and OFDM subchannels is called SF coding. A straightforward way of realizing SF coding for two transmit antennas is to directly spread the Alamouti code over two subchannels in one OFDM block.

SPACE-TIME/FREQUENCY CODING FOR MIMO-OFDM SYSTEMS

SPACE-TIME CODED OFDM

ST coding is a powerful scheme that combines coding with transmit diversity to achieve high diversity performance in wireless systems. Such a coding scheme can in general be classified into two major classes: ST trellis codes and ST block codes. In an ST trellis coding scheme, an information stream is encoded via M_t convolutional encoders (or via one convolutional encoder with M_t outputs) to obtain M_t streams of symbols that are transmitted from M_t antennas simultaneously. A special case of ST trellis coding is delay diversity (DD). For DD, the first antenna transmits the information stream as $\{s_n, s_{n+1}, \cdots\}$, whereas the second antenna transmits the stream delayed by D symbol intervals as $\{s_{n-D}, s_{n-D+1}, \cdots\}$. One problem of ST trellis coding is that the decoding complexity increases exponentially as a function of the diversity level and transmission rate [3]. Orthogonal ST block code (OSTBC) design, which was first proposed by Alamouti in 1998 [4], can address this problem. This OSTBC design is now referred to as the Alamouti code. Specifically, the information symbols are transmitted in a different order from two transmit antennas with some modification (conjugate and sign) and the code design can be shown as in Eq. 2. The Alamouti code can provide the full diversity of 2 for two transmit antennas with a rate of 1. Due to the orthogonality of the code matrix, the Alamouti code has a fast ML decoding property which allows a simple single-symbol ML detection. The Alamouti ST block code has been later generalized to the case of more than two transmit antennas using the theory of orthogonal designs [14]. Unfortunately, OSTBC cannot in general provide any coding gain nor achieve a rate larger than 3/4 for more than two transmit antennas. For further details about ST code design, interested readers are referred to [3, 10, 15] and references therein.

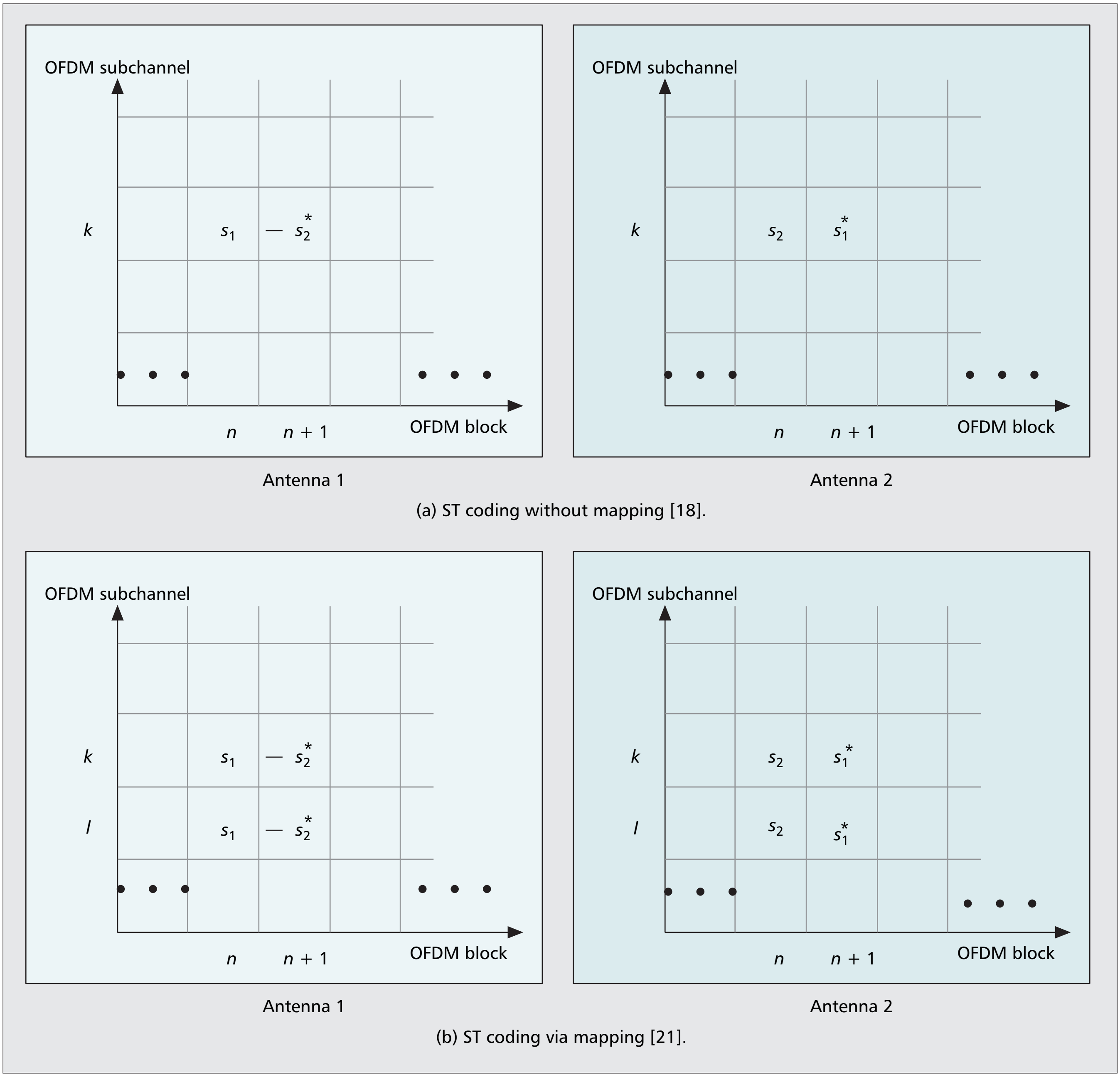
For broadband wireless systems, the MIMO channels experience frequency-selective fading, which complicates the design of ST codes because of ISI. To address this issue, OFDM can be combined with MIMO systems, and this is referred to as MIMO-OFDM [16]. The first ST coded OFDM system was proposed in [17], where ST trellis codes were used. The coded symbols are interleaved across OFDM subchannels and a large decoding complexity is incurred. Later, OSTBC was directly applied to MIMO-OFDM on each subcarrier [18]. For example, the ST coding for a MIMO-OFDM with two transmit antennas is illustrated in Fig. 3a. Two information symbols s_1 and $-s_2^*$ are sent through subchannel k of antenna 1 in OFDM blocks n and $n + 1$, respectively. Meanwhile, s_2 and s_1^* are sent through subchannel k of antenna 2 in OFDM blocks n and $n + 1$, respectively. Although the above ST coded OFDM can exploit the space diversity, the potential multipath diversity offered by frequency-selective fading channels is not exploited.

In order to obtain the additional multipath diversity in MIMO-OFDM systems, ST trellis coding was mainly considered in an OFDM framework where the incoming information symbols are trellis coded across both the OFDM subchannels and transmit antennas [13, 19, 20]. Recently, a general design of OSTBC was proposed for MIMO-OFDM systems to be able to achieve both multipath diversity and space diversity [21]. The coding structure is shown in Fig. 3b, where the ST codeword is copied on other subchannels. Although the rate is reduced because of the mapping, the simple single-symbol ML decoding is admitted due to the orthogonality of the code matrix. Moreover, the multipath diversity of 2 can be exploited by the repeat transmission on different subchannels.

SPACE-FREQUENCY CODED OFDM

This strategy, which consists of coding across antennas and OFDM subchannels, is called *SF coding* [22]. A straightforward way of realizing SF coding for two transmit antennas is to directly spread the Alamouti code over two subchannels in one OFDM block. Figure 4a shows the example of SF coding for two transmit antennas. The two symbols s_1 and $-s_2^*$ are sent from subchannels k and l of the same OFDM block n at antenna 1, respectively, where k and l denote the indices of two separated subchannels. Meanwhile, s_2 and s_1^* are sent from subchannels k and l of the same OFDM block n at antenna 2, respectively. However, this simple SF coding approach can only achieve space diversity gain, whereas the maximum diversity gain in frequency-selective MIMO channels is M_tM_rL, shown earlier. In [12] the full diversity SF code design criteria were derived. To exploit the full diversity in MIMO multipath fading channels, an SF code design approach was proposed by multiplying the input information stream with a part of the DFT matrix [23]. The resulting SF codes can achieve full diversity at the expense of a large bandwidth efficiency loss. The symbol rate is not more than $1/(M_tL)$. In [24] a systematic design of full diversity SF block codes (SFBC) was proposed. By repeating each row of the ST codes matrix on L different subchannels of the same OFDM block, the SF codes provide higher data rates than the approach described in [23]. However, they cannot achieve a rate larger than $1/L$. The detailed SF coding structure via mapping for two transmit antennas is shown in Fig. 4b.

The design of full diversity SFBC with rate-1 was recently proposed in MIMO-OFDM systems for any number of transmit antennas and arbitrary power delay profiles [25]. To obtain the rate-1, the information symbol vector $\mathbf{S}$ is first coded via an algebraic rotation matrix $\mathbf{\Theta}$. The resulting coded vector $\mathbf{X} = \mathbf{\Theta S}$ is then split and spread over different antennas and OFDM subchannels. For example, a rate-1 SF coding for two transmit antennas is shown in Fig. 5a. The coded symbols $x_1, \cdots, x_4$ are obtained from the information symbols $s_1, \cdots, s_4$ via a 4×4 rotation matrix and placed in a diagonal manner such that they are orthogonal for two transmit antennas. Obviously, this code achieves the rate of 1. The rotation matrix $\mathbf{\Theta}$ is carefully designed such that signal space diversity can be produced



■ **Figure 3.** *ST coding in a MIMO-OFDM system with 2 transmit antennas.*

by rotating the signal constellation [26]. Finally, a multipath diversity gain of 2 can be obtained.

Recently, a systematic design of high rate SFBC was proposed to achieve the rate-M_t and the full diversity in MIMO-OFDM systems for any number of transmit antennas [27]. However, because a zero-padding matrix has to be used when N is not an integer multiple of M_tL, the symbol transmission rate M_t cannot always be guaranteed. To address this issue, a universal design of SFBC, as a special case of STF coding, was then proposed in [34] that can always achieve the rate-M_t and the full diversity for any number of transmit antennas and any arbitrary channel power delay profiles. It is constructed by applying the layering concept, which was used in the design of threaded algebraic space-time (TAST) code [15], with algebraic component codes, where each component code is assigned to a "thread" and interleaved over space and frequency. An example of the rate-2 SF code for two transmit antennas is shown in Fig. 5b. The first layer of the coded symbols $x_1, \cdots, x_4$ are interleaved over two antennas and four subchannels. The second layer of symbols $y_1, \cdots, y_4$ are then placed in a complementary manner such that all the subchannels are occupied. Obviously, the rate of this code is 2. By applying a phase rotation ϕ on each symbol of the second layer, the two layers of coded symbols can be sent as if they were "transparent" with each other. The aforementioned high-rate SFBC mostly relies on joint detection and thus increases the decoding complexity. This decoding burden can be alleviated by an approximate ML decoding, known as sphere decoding [28].

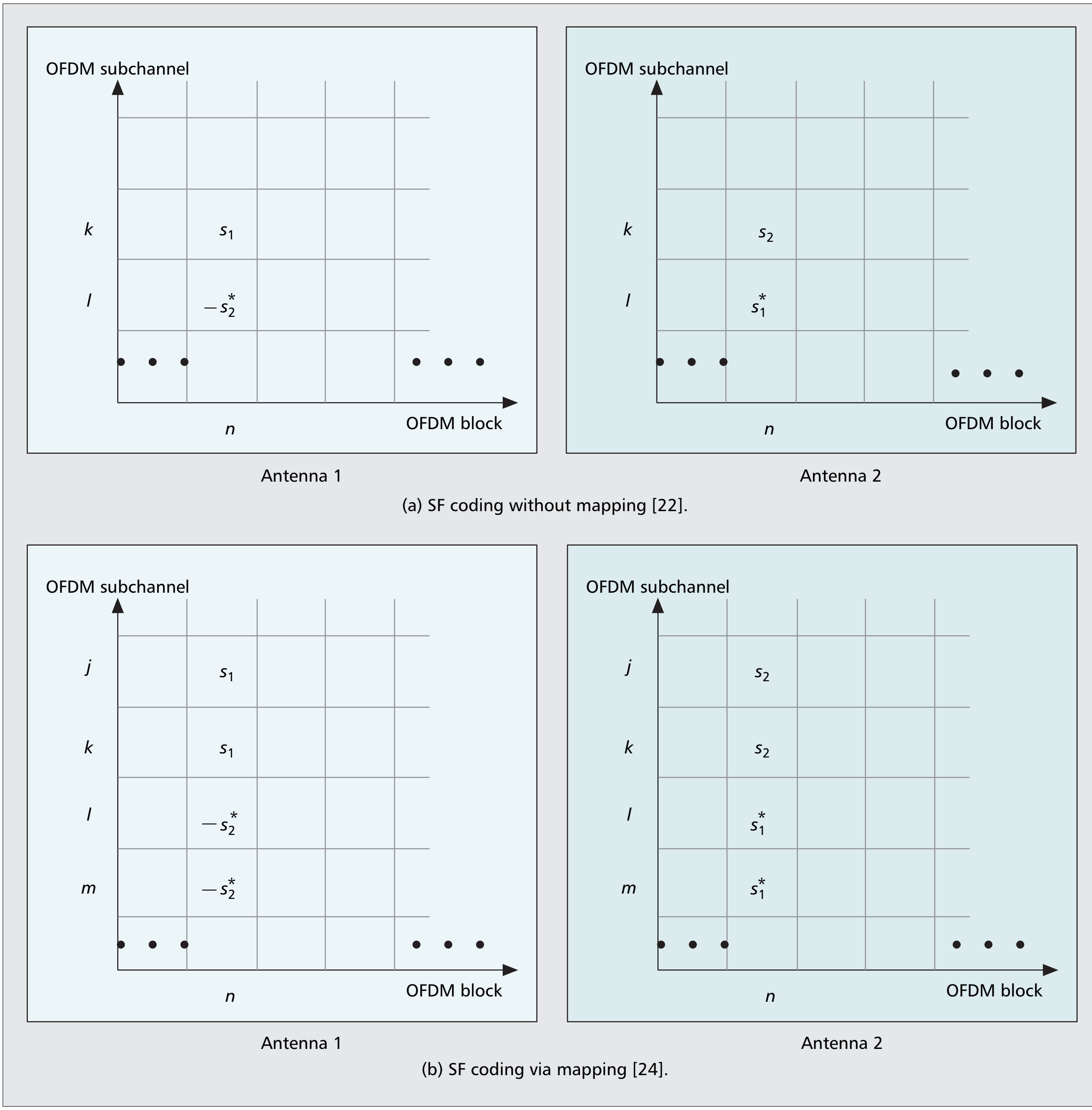


Figure 4. *SF coding in a MIMO-OFDM system with 2 transmit antennas.*

Space-Time-Frequency Coded OFDM

Most prior works on ST and SF code design have considered quasi-static fading channels in which the path gains remain fixed throughout the codeword. In practice, the channels are normally subject to block-fading, where the fading coefficients are constant over one fading block but are varied independently from block to block. It has been shown that the diversity gain in block-fading channels can be increased by coding across multiple fading blocks [29]. However, the coding approaches primarily focused on flat fading channels. On the other hand, STF codes have been proposed for exploiting multipath diversity in MIMO-OFDM systems over quasi-static channels [30–33]. The performance of STF codes in MIMO-OFDM systems was also recently studied for a variety of system configurations and channel conditions in [32]. It was shown that the maximum diversity is the product of time diversity, frequency diversity, and space diversity [33]. Recently, a systematic design of high-rate STF codes was proposed for MIMO frequency-selective block-fading channels in [34]. By spreading the algebraic coded symbols across different OFDM subchannels, transmit antennas, and fading blocks, the proposed STF codes can achieve a rate-M_t and a full diversity of $M_t M_r M_b L$, where M_b is the number of independent fading blocks in the codewords. Figure 6b shows an example of the rate-2 STF coding structure for two transmit

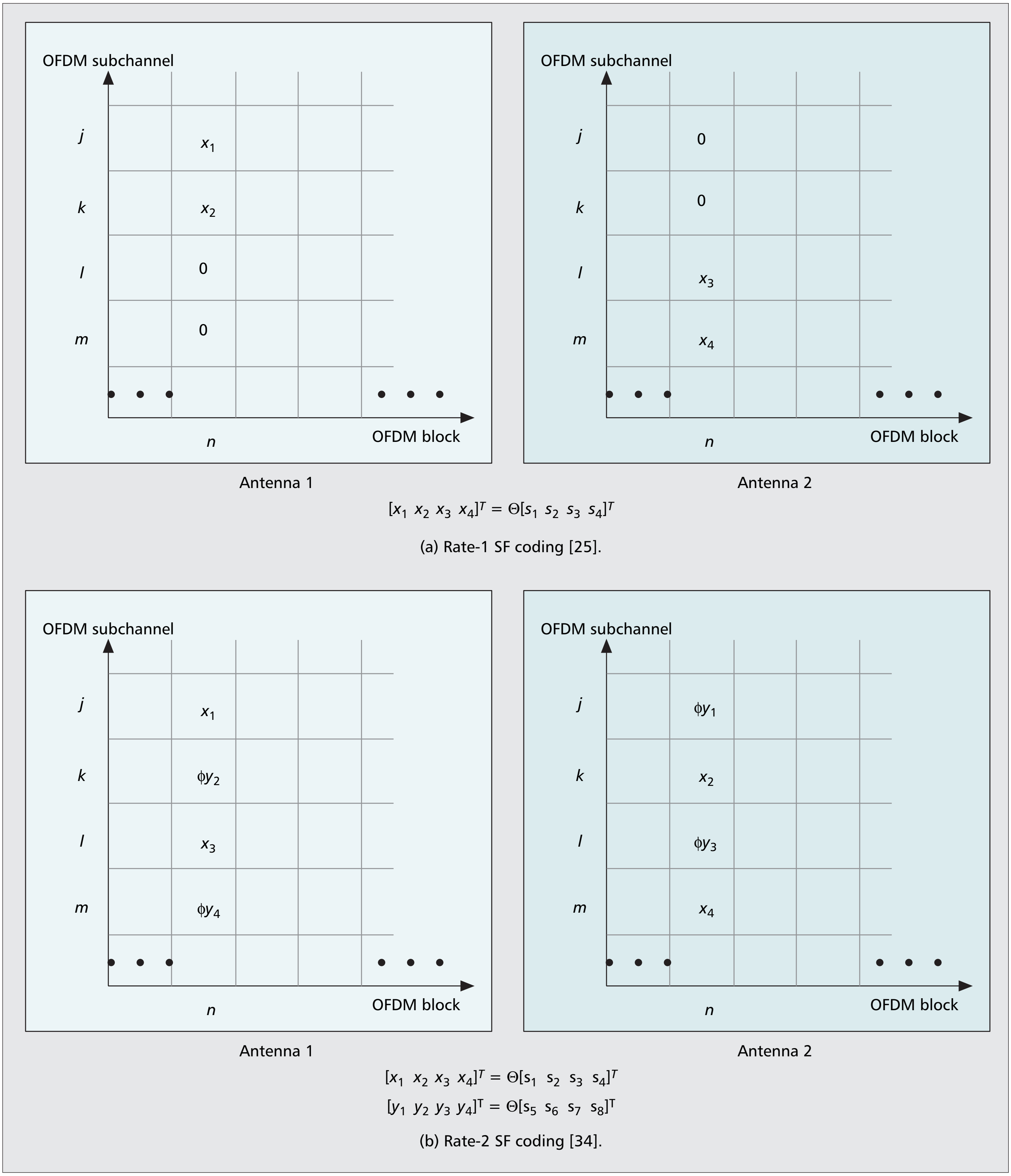


Figure 5. *High-rate SF coding for achieving spatial and multipath diversity in a MIMO-OFDM system with 2 transmit antennas.*

antennas. It can be seen that each layer of coded symbols are spread over space, time, and frequency dimensions. Another simple design of full-diversity STF codes can be obtained by repeating the rate-M_t full-diversity SF code M_b times along OFDM blocks, as shown in Fig. 6a for $M_b = 2$. Such a repetition STF coding approach can alleviate the large computational complexity of the ML decoding. As a special case of $M_b = 1$, the STF code is in fact a design of rate-M_t full diversity SF codes, as shown in Fig. 5b.

PERFORMANCE COMPARISON

Table 1 shows a comparison of some of the aforementioned ST coding, SF coding, and STF coding approaches for MIMO-OFDM systems in

One of the most promising multiple access techniques in future 4G wireless communication systems is OFDMA. The key advantages of OFDMA are its flexibility in resource allocation and robustness to frequency-selective fading.

terms of code rate, diversity gain, and decoding complexity. Typically, ST-coded OFDM has a simple implementation in providing a minimal decoding complexity, but it cannot achieve multipath diversity nor high rate. SF-coded OFDM, by mapping the symbols on other subchannels, can exploit the multipath diversity, but results in a reduction of the data rate. When combined with the signal space diversity technique via a constellation rotation [26], SF coding can achieve the maximum diversity and full rate over multipath fading channels, but the decoding complexity is increased and a joint ML decoding is needed. STF-coded OFDM tailored for block-fading channels can achieve full diversity in space, time, and frequency and full rate. However, and similar to SF coding, the decoding complexity is increased.

Figure 7 shows the SER performance of ST coding without mapping [18] (Fig. 3a), ST coding with mapping [21] (Fig. 3b), SF coding without mapping [22] (Fig. 4a), SF coding with mapping [24] (Fig. 4b), rate-1 SF coding [25] (Fig. 5a), rate-2 SF coding [34] (Fig. 5b), rate-1 STF coding [34] (Fig. 6a), and rate-2 STF coding (Fig. 6b), respectively. The simulated MIMO-OFDM system has two transmit antennas and two receive antennas. To keep the same bandwidth efficiency of 2 bits per second per hertz (bps/Hz), 16-QAM is used for the ST/SF coding with mapping, QPSK is used for the ST/SF coding without mapping and the rate-1 SF/STF coding, and BPSK is used for the rate-2 SF/STF coding, respectively. The OFDM has 64 subcarriers and a two-ray Rayleigh fading channel is considered. For ST coding approaches, the channels are assumed to be time-invariant during two consecutive OFDM blocks so that the simple ML decoding is admitted. For SF/STF coding approaches, the block-fading channel is considered and the channel coefficients are varied independently from one OFDM block to another.

It can be seen that the two STF coding approaches achieve a larger diversity gain than the other coding approaches. This diversity enhancement results from the fact that additional time diversity can be exploited by STF coding. Moreover, ST/SF coding without mapping has a smaller diversity gain than the ST/SF coding with mapping. This is because additional multipath diversity can be obtained by ST/SF coding with the mapping structure. Note that the rate-1 SF coding and the rate-2 SF coding can also achieve multipath diversity, and this can be corroborated by the observation that they have the same diversity gain as the ST/SF coding with mapping. However, compared to ST/SF coding with mapping, the rate-1 and rate-2 SF coding approaches have a larger coding gain which is due to the use of different modulation schemes.

Multiuser Space-Frequency Coding for OFDMA

OFDMA

One of the most promising multiple access techniques in future 4G wireless communication systems is OFDMA. It has attracted much attention, particularly in the emerging IEEE 802.16 WMAN standard. The key advantages of OFDMA are its flexibility in resource allocation and robustness to frequency-selective fading. In OFDMA, each user occupies its unique set of OFDM subchannels and the base station can allocate the subcarriers to users dynamically [35]. Since different users have different channel qualities, a subchannel that meets deep fade for one user may be favorable for others [36]. On the other hand, if a specific user requests a stringent quality of service (QoS), more resources (such as larger power, more subchannels, and higher modulation level) can be assigned to this user. Since the bandwidth of each subchannel is chosen to be sufficiently smaller than the coherent bandwidth of the channel, the destructive ISI induced by multipath fading can be mitigated.

OFDMA is essentially a form of FDMA in that users are separated in different frequency bands (subchannels). This certainly brings about the reduced data rate for each user when the number of users is increasingly large. MIMO is a straightforward way of achieving high bandwidth efficiency and can be applied in an OFDMA framework. Multiuser MIMO-OFDM systems benefit from the combined space and frequency domain freedom as well as multiuser diversity. To maximize spectrum efficiency while achieving a sufficiently large signal-to-interference ratio in MIMO-OFDM systems, the dynamic multiuser resource allocation can be done [35]. A critical element in all of the dynamic resource allocation schemes is the CSI knowledge available at the transmitter (CSIT).

Multiuser Space-Frequency Coding

Recently, the issue of increasing the information rate of multiuser MIMO-OFDM systems was considered without CSIT by Gärtner and Bölcskei [1, 37]. Their results show that joint code designs are necessary whenever multiple users transmit concurrently at high rates. Otherwise, employing the traditional single-user ST/SF codes for each of the users is optimal. It should be noted that the joint code design across transmit antennas has been widely used in point-to-point MIMO systems. However, in the multiple access case the individual users cannot coordinate their transmission. In [1, 37], for a specific case of 2-user multi-access channels (MAC), a simple design of multiuser SF codes was given by swapping and rotating one column of the Alamouti code matrix. The essence of the multiuser SF coding is to allow the users to choose their unique codebooks such that the error rate of the concurrent transmission is minimized. But this previous work is limited to a 2-user case and no explicit systematic code design was given.

More recently, in [38] we have shown that the achievable diversity gain of a multiuser MIMO-OFDM system is not larger than that of a single-user MIMO-OFDM system if each user is independently encoded. We have also found that multiuser interference can be minimized by applying a multiuser SF code. We then proposed a systematic design of multiuser SF codes for any number of users in MIMO frequency-selec-

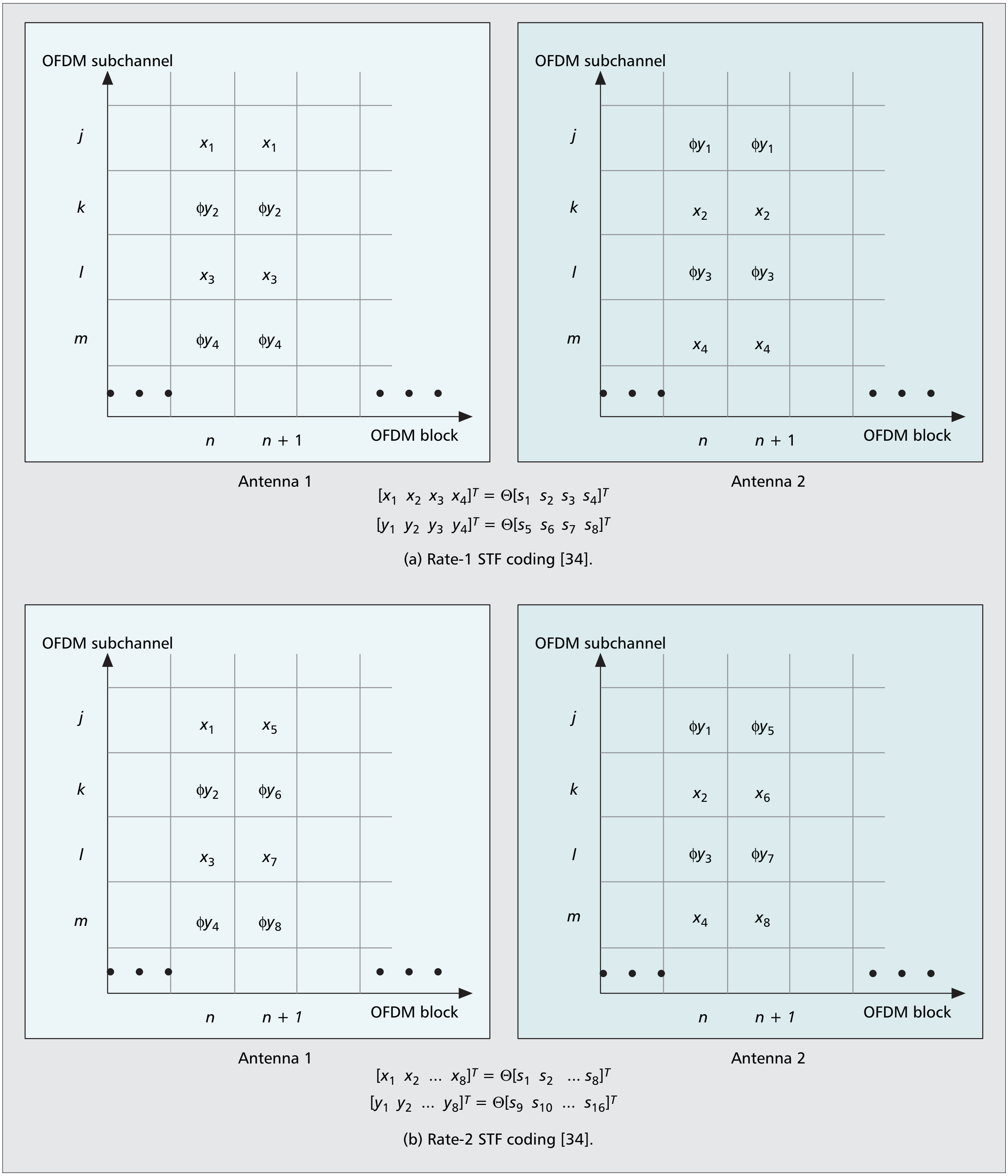


Figure 6. *High-rate STF coding for achieving spatial and multipath diversity in a MIMO-OFDM system with 2 transmit antennas.*

tive fading MAC. The proposed code for each user is structured as a constellation rotation followed by a unique phase rotation. The signal space diversity resulting from the constellation rotation can guarantee the full diversity for each user while the unique phase rotation for each user can ensure that multiuser interference is minimized. After employing a unique SF coding at each user, the coded symbols are allocated over all OFDM subcarriers, thereby increasing the data rate of each user. Assuming perfect CSI at the receivers and ML detection, it was shown that the proposed multiuser SF codes can achieve the diversity gain of M_tM_rL for every user and the minimal multiuser interference as well as a high data rate.

Conclusion

This article presented an overview of ST coding, SF coding and STF coding for 4G MIMO-OFDM broadband wireless systems. It was shown that orthogonal ST-coded OFDM has a simple implementation that can provide a minimal decoding complexity, but cannot achieve multipath diversity nor high rate. On the other hand, it was shown that SF-coded OFDM with signal space diversity technique can achieve the maximum diversity and full rate over multipath fading channels, at the expense of a high decoding complexity. For block-fading channels, we have demonstrated that STF-coded OFDM can achieve full rate along with full diversity in space, time, and frequency. However and similar to SF coding, a joint detection is needed in STF-coded OFDM, and this results in high decoding complexity. As one of the promising multiple access techniques in future 4G wireless communications, OFDMA has been shown to provide much flexibility in resource allocation and robustness to multipath fading. Unlike point-to-point MIMO-OFDM systems where the coding across transmit antennas is possible, coding across a group of uncoordinated users is generally impractical. In this article, we have shown that by applying signal space diversity and a unique phase rotation to each user, the proposed multiuser SF coding can guarantee the maximum diversity and high bandwidth efficiency as well as minimum multiuser interference.

Coding approach	Code rate	Diversity gain	Decoding
ST-OFDM [18]	1	$M_t M_r$	Single-symbol ML
ST-OFDM [21]	$1/L$	$M_t M_r L$	Single-symbol ML
SF-OFDM [24]	$1/L$	$M_t M_r L$	Sphere decoder [28]
SF-OFDM [25]	1	$M_t M_r L$	Sphere decoder
SF-OFDM [34]	M_t	$M_t M_r L$	Sphere decoder
STF-OFDM [34]	M_t	$M_t M_r M_b L$	Sphere decoder

Table 1. *Performance comparison among ST-/SF-/STF-coded OFDM.*

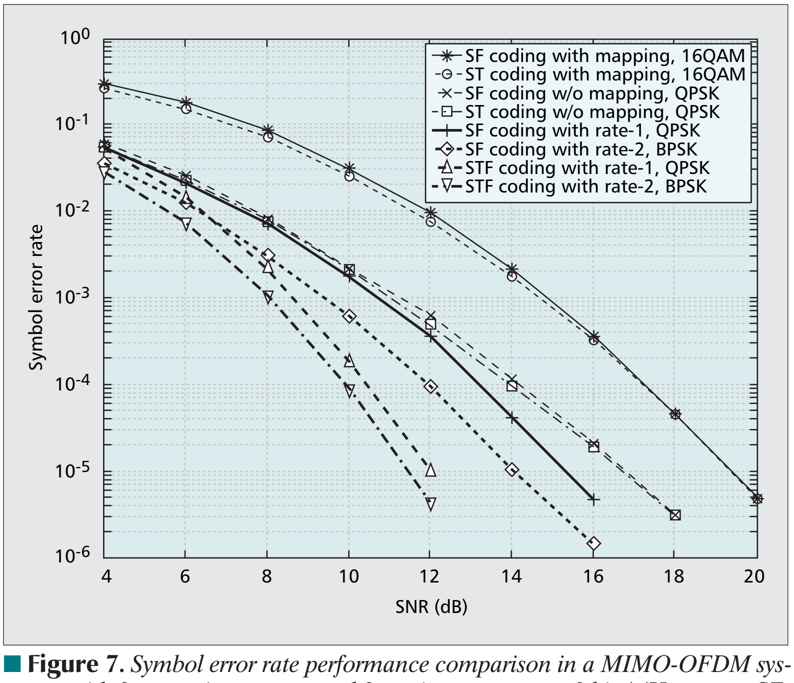


Figure 7. *Symbol error rate performance comparison in a MIMO-OFDM system with 2 transmit antennas and 2 receive antennas at 2 bits/s/Hz among SF coding with mapping [24], ST coding with mapping [21], SF coding without mapping [22], ST coding without mapping [18], rate-1 SF coding [25], rate-2 SF coding [34], rate-1 STF coding [34] and rate-2 STF coding [34].*

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