A Road to Future Broadband Wireless Access: MIMO-OFDM-Based Air Interface

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ABSTRACT

Orthogonal frequency-division multiplexing is a popular method for high-data-rate wireless transmission. OFDM may be combined with multiple antennas at both the access point and mobile terminal to increase diversity gain and/or enhance system capacity on a time-varying multipath fading channel, resulting in a multiple-input multiple-output OFDM system. In this article we give a brief technical overview of MIMO-OFDM system design. We focus on various research topics for the MIMO-OFDM-based air interface, including spatial channel modeling, MIMO-OFDM transceiver design, MIMO-OFDM channel estimation, space-time techniques for MIMO-OFDM, and error correction code. The corresponding link-level simulation results are encouraging, and show that MIMO-OFDM is a promising road to future broadband wireless access.

INTRODUCTION

The first-generation (1G) radio systems use analog communication techniques to transmit voice over radio, such as Advanced Mobile Phone Services (AMPS), the Nordic Mobile Telephone (NMT) system, and the Total Access Communication System (TACS), which were developed in the 1970s and 1980s. The 2G systems were built in the 1980s and 1990s, and featured the implementation of digital technology, such as Global System for Mobile Communications (GSM), Digital-AMPS (D-AMPS), code-division multiple access (CDMA), and personal digital cellular (PDC); among them GSM is the most successful and widely used 2G system. 3G mobile technologies provide users with high-data-rate mobile access, which developed rapidly in the 1990s and is still developing today. The three major radio air interface standards for 3G are wideband CDMA (WCDMA), time-division synchronous CDMA (TD-SCDMA), and cdma2000. The transmitted data rate of 3G is up to 144 kb/s for high-mobility traffic, 384 kb/s for low-mobility traffic, and 2 Mb/s in good conditions. However, there are two limitations with 3G. One is the difficult extension to very high data rates such as 100 Mb/s with CDMA due to excessive interference between services. The other is the difficulty of providing a full range of multirate services, all with different quality of service (QoS) and performance requirements, due to the restrictions imposed on the core network by the air interference standard. Therefore, the future mobile communication system with features of high-data-rate transmission and open network architecture, called 4G, is desired to satisfy the increasing demand for broadband wireless access. Hence, 4G refers to a collection of technologies and standards that will find their way into a range of new ubiquitous computing and communication systems. The key objectives of 4G are to provide reliable transmission with high peak data rates ranging from 100 Mb/s for high-mobility applications to 1 Gb/s for low-mobility applications, high spectrum efficiency up to 10 b/s/Hz, and ubiquitous services that can accommodate various radio accesses.

To take international technology leadership and reserve competitiveness in the growing mobile communication market, Alcatel Research and Innovation Center has been carrying out research and innovation toward 4G for a long time. Their research topics cover MIMO and OFDM related technologies including turbo product code, channel modeling, channel estimation, adaptive modulation and coding (AMC), hybrid automatic repeat request (H-ARQ), dynamic resource allocation (DRA), and so on. They have also participated in a program sponsored by the Chinese government, Future Technologies for Universal Radio Environment (FuTURE), since 2001.

This article focuses on 4G air interface technologies, especially MIMO-OFDM-based air interface to provide reliable communications with high data rates and bandwidth efficiency.

OFDM AND MIMO

OFDM

OFDM has become a popular technique for transmission of signals over wireless channels. It converts a frequency-selective channel into a parallel collection of frequency flat subchannels, which makes the receiver simpler. The time

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domain waveforms of the subcarriers are orthogonal, yet the signal spectra corresponding to the different subcarriers overlap in frequency. Hence, the available bandwidth is used very efficiently. Using adaptive bit loading techniques based on the estimated dynamic properties of the channel, the OFDM transmitter can adapt its signaling to match channel conditions, and approach the ideal water pouring capacity of a frequency-selective channel.

Advantages of OFDM systems are:
- High spectral efficiency
- Simple implementation by fast Fourier transform (FFT)
- Low receiver complexity
- Suitability for high-data-rate transmission over a multipath fading channel
- High flexibility in terms of link adaptation
- Low-complexity multiple access schemes such as orthogonal frequency-division multiple access (OFDMA)

Disadvantages of OFDM systems are:
- Higher peak-to-average power ratio (PAPR) compared to single-carrier modulation
- Sensitivity to time and frequency synchronization errors

OFDM has been adopted in several wireless standards such as digital audio broadcasting (DAB), terrestrial digital video broadcasting (DVB-T), the IEEE 802.11a wireless local area network (WLAN) standard, and IEEE 802.16a. Undoubtedly, OFDM could be a potential air interface candidate for future-generation mobile wireless systems.

MIMO

Multiple antennas can be used at the transmitter and receiver, now widely termed a MIMO system. A MIMO system takes advantage of the spatial diversity obtained by spatially separated antennas in a dense multipath scattering environment. MIMO systems may be implemented in a number of different ways to obtain either a diversity gain to combat signal fading or to obtain a capacity gain. Generally, there are three categories of MIMO techniques. The first one aims to improve the power efficiency by maximizing spatial diversity. Such techniques include delay diversity, space-time block codes (STBC) [1], and space-time trellis codes (STTC) [2]. The second type uses a layered approach to increase capacity [3]. One popular example of such a system is the vertical-Bell Laboratories layered space-time (V-BLAST) architecture, where independent data signals are transmitted over antennas to increase the data rate, but full spatial diversity is usually not achieved. The third type exploits knowledge of the channel at the transmitter. It decomposes the channel matrix using singular value decomposition (SVD) and uses these decomposed unitary matrices as pre- and post-filters at the transmitter and receiver to achieve capacity gain [4].

MIMO opens a new dimension, space, to offer the advantage of diversity, and therefore has been adopted in various standards. For instance, MIMO may be implemented in the high-speed downlink packet access (HSDPA) channel, which is a part of the Universal Mobile Telecommunications System (UMTS) standard. Preliminary efforts are also underway to define a MIMO overlay for the IEEE 802.11 standard for WLAN under the newly formed Wireless Next Generation (WNG) group.

MIMO-OFDM

MIMO is known to boost capacity. For high-data-rate transmission, the multipath characteristic of the environment causes the MIMO channel to be frequency-selective. OFDM can transform such a frequency-selective MIMO channel into a set of parallel frequency-flat MIMO channels, and therefore decrease receiver complexity. The combination of the two powerful techniques, MIMO and OFDM, is very attractive, and has become a most promising broadband wireless access scheme.

MIMO-OFDM KEY TECHNIQUES

THE SPATIAL CHANNEL MODEL

Because of the sensitivity of MIMO algorithms with respect to the channel matrix properties, channel modeling is particularly critical to assess the relative performance of MIMO-OFDM systems.

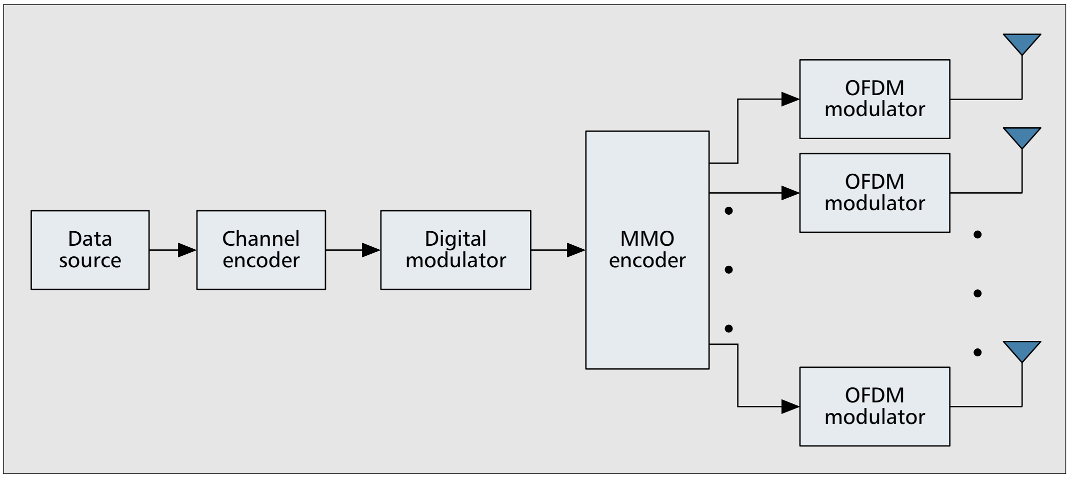
Because of the sensitivity of MIMO algorithms with respect to the channel matrix properties, channel modeling is particularly critical to assess the relative performance of MIMO-OFDM systems. This section briefly describes the key channel characteristics that influence air interface design, such as time selectivity, frequency selectivity, and spatial selectivity.

Time Selectivity — We define the coherence time as the time difference at which the magnitude or envelope correlation coefficient between two signals at the same frequency falls below 0.5. Thus, a signal experiences slow or time-nonselective fading if its symbol period is much smaller than the channel coherence time, and fast or time-selective fading if its symbol period is more than the coherence time. When a signal is slow fading, we can assume that the channel impulse response (CIR) is time-invariant during a block transmission. When the coherence time is in the order of a symbol block interval, we say that the channel is quasi-static fading, which means that the channel fading is assumed to be constant over each block, and changes independently from block to block.

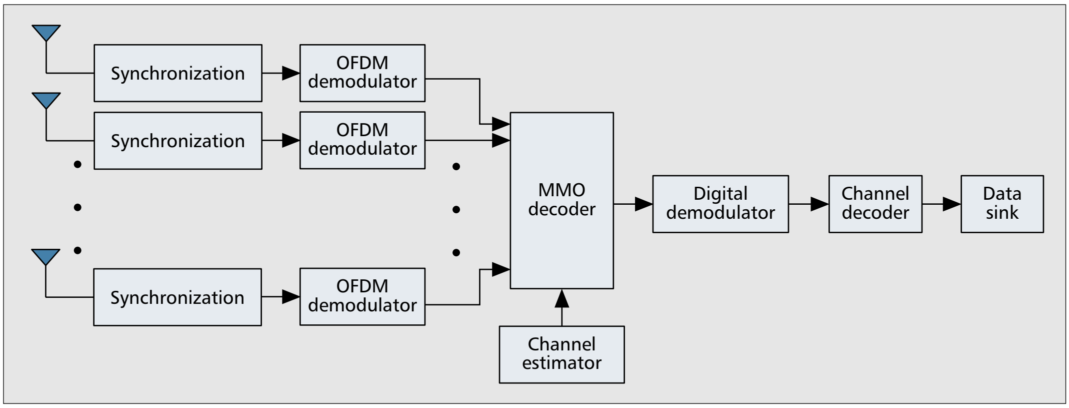
Frequency Selectivity — The coherence bandwidth captures the analogous notion for two signals of different frequencies transmitted at the same time. A signal experiences flat or frequency-nonselective fading if its bandwidth is much smaller than the channel coherence bandwidth, and frequency-selective fading if its bandwidth is more than the channel coherence bandwidth.

Spatial Selectivity — When using multiple-element antennas, the coherence distance represents the minimum distance in space separating two antenna elements such that they experience independent fading. Due to scattering environments, the channel exhibits independent or spatially selective fading. Spatially correlated fading results in lower achievable capacity of MIMO.

K-Factor — The fading signal magnitude follows a Rice distribution, and the ratio of the line-of-sight (LOS) component power to the diffraction component power is defined as the Ricean *K*-



■ **Figure 1.** *A simplified block diagram of a MIMO-OFDM transmitter.*



■ **Figure 2.** *A simplified block diagram of a MIMO-OFDM receiver.*

The frame is structured such that data and pilot symbols are transmitted over sub-carries, which allows the estimation of the above parameters. Once synchronization is obtained, fine timing estimates can be computed from the pilot symbols.

factor. The worst case fading occurs when the power of the LOS component is zero and the fading signal magnitude is regarded as Rayleigh distribution. Spatial channel often becomes more and more correlated as *K*-factor increases, and therefore lower multiplexing gain of MIMO system can be obtained.

MIMO-OFDM SYSTEM MODEL

Transmitter — Figure 1 shows a simplified block diagram of a MIMO -OFDM transmitter. The source bitstream is encoded by a forward error correction (FEC) encoder. After that, the coded bitstream is mapped to a constellation by the digital modulator, and encoded by a MIMO encoder. Then each of the parallel output symbol streams corresponding to a certain transmit antenna follows the same transmission process. First, pilot symbols are inserted according to the pilot patterns. Then the symbol sequence in frequency is modulated by inverse FFT (IFFT) to an OFDM symbol sequence. A cycle prefix (CP) is attached to every OFDM symbol to mitigate the effect of channel delay spread, and a preamble is inserted in every slot for timing. Finally, the constructed data frame is transferred to IF/RF components for transmission.

Receiver — Figure 2 shows a simplified block diagram of a MIMO-OFDM receiver. The received symbol stream from IF/RF components over the receive antennas are first synchronized, including coarse frequency synchronization and timing aided by the preamble. After that, the preambles and CP are extracted from the received symbol stream, and the remaining OFDM symbol is demodulated by FFT. Frequency pilots are extracted from the demodulated OFDM symbol in the frequency domain, and fine frequency synchronization and timing are carried out to extract pilots and data symbols accurately for the following processing. The refined frequency pilots from all the receive antennas are used for channel estimation (CE). The estimated channel matrix aids the MIMO decoder in decoding the refined OFDM symbols. The estimated transmit symbols are then demodulated and decoded. Finally, the decoded source bitstreams are transmitted to the sink.

Frame Structure — Figure 3 shows an example for the frame format of the MIMO-OFDM system. In the time domain, a frame is a minimum transmission unit that includes 10 slots. Each slot consists of one slot preamble and eight OFDM symbols. The preamble is used for time synchronization. Each OFDM in a slot is attached to a CP that is used to reduce ISI, and therefore the design of channel equalizer is simplified. A scattered pilot pattern is used for CE at high mobility.

For OFDM systems with multiple transmit antennas, different signals are transmitted from different antennas simultaneously, and consequently, the received signal is the superposition of these signals, which gives rise to challenges for CE.

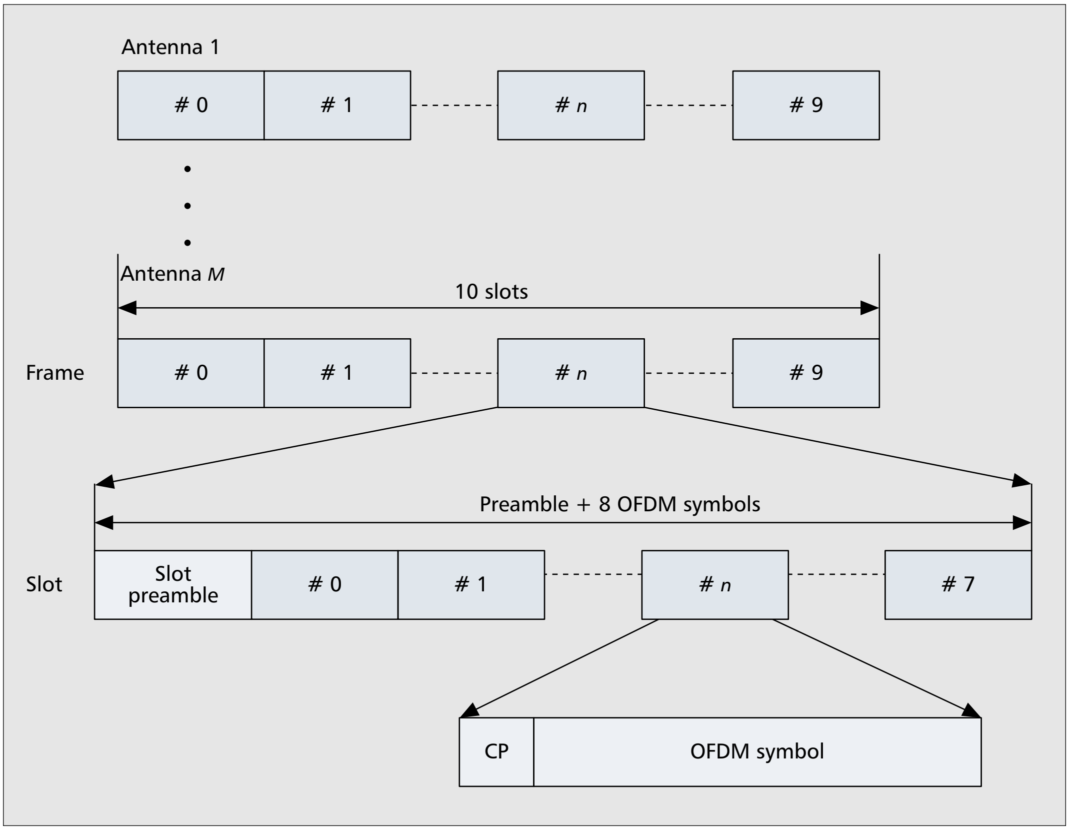


Figure 3. *The frame structure of a MIMO-OFDM system.*

SYNCHRONIZATION

Timing phase, timing frequency, and frequency offset estimation are carried out aided by the preamble of each slot and the pilot symbols in the frequency domain [5]. The frame is structured such that data and pilot symbols are transmitted over subcarriers, which allows estimation of the above parameters. Once synchronization is obtained, fine timing estimates can be computed from the pilot symbols.

CE

MIMO-OFDM is a promising scheme for achieving high data rates and large system capacity over wireless links. To obtain the promised increase in data rate, accurate channel state information is required in the receiver. However, for OFDM systems with multiple transmit antennas, different signals are transmitted from different antennas simultaneously, and consequently, the received signal is the superposition of these signals, which gives rise to challenges for CE. As for pilot patterns, there are three kinds of CE algorithms for MIMO-OFDM system, respectively, based on scattered pilots, orthogonal pilots, and block pilots [6, 7]. Comparatively, the first one adapts to wide applications over fast fading and frequency selective channel. Therefore, we focus on it in the following.

Pilot Pattern — The scattered pilot pattern of transmit antennas is designed as follows. The pilot spacing in the time domain is designed to satisfy the sampling theorem, and the channel frequency response (CFR) of the OFDM symbols without pilots can be estimated through time domain interpolation according to the CE results of the adjacent OFDM symbols with pilots. Pilot spacing in the frequency domain should be designed such that the following inequality is satisfied, which is required by the MIMO-OFDM CE algorithm described here:

$$\frac{FFTsize}{PSF \cdot M} > Maximum\ Delay$$

where *PSF* denotes the pilot spacing in the frequency domain, and *Maximum Delay* is the maximum excess delay of the multipath channels between transmitter and receiver in units of sampling time. Figure 4 shows the pilot pattern over a transmit antenna. All the transmit antennas have the same pilot pattern.

MIMO-OFDM CE — We just focus on the processing in frequency domain. The time domain interpolation processing is omitted. The algorithm to estimate CFR of the multi-path channel between one transmit/receive antenna pair is the same as the following steps.

1) Multiply the received pilot sequence with the conjugate sequence of the pilot sequence of the transmit antenna and get the sequence of CFRs over pilots.

2) Make the *FFTsize*/*PSF*-point IFFT for the sequence of CFRs over pilots and get the sequence of CIRs.

3) Divide the sequence of CIRs into *M* segments of the same segment length, where *M* is the number of transmit antennas. Then the *i*th

segment ($i = 1, 2, \ldots, M$) will be the estimated CIR of the transmit/receive antenna pair. Hence, after making the *FFTsize*-point FFT for each segment with zero padding, we get the estimation of all the channels.

Simulation Result — A 3.2 GHz spatially uncorrelated UMTS vehicular A channel with speed of 60 km/h is used [8]. FFT size is 1024, OFDM sampling rate is 11.52 MHz, the pilot interval in the frequency domain is 8, pilots in the time domain are inserted in every OFDM symbol. The number of transmit/receive antennas is (2,2) and (4,4).

Mean square error (MSE) of the developed CE algorithm is shown in Fig. 5. From the figure we can observe that the MSE of the designed MIMO-OFDM estimator has a floor resulting from inter-subcarrier and inter-antenna interference. Related techniques to interference cancellation are desired for MIMO-OFDM system.

SPACE-TIME PROCESSING TECHNIQUES FOR MIMO

Current space-time processing techniques for MIMO typically fall into two categories, data rate maximization and diversity maximization schemes, although there has been some effort toward unification recently.

Spatial Multiplexing — Spatial multiplexing multiplexes multiple spatial channels to send as many independent data as we can over different antennas for a specific error rate. There are four spatial multiplexing schemes: diagonal BLAST, horizontal BLAST, V-BLAST, and turbo BLAST. Of them, V-BLAST is the most promising for its implementation simplicity [3].

The method to detect the transmitted signals consists of three main steps:

1). Estimate the channel matrix. This is often done through training sequence

2). Determinate the optimal detecting order and the nulling vectors

3). Detect the received signals based on the optimal detecting order and successive interference cancellation.

- Zero-forced (ZF) or minimum mean square error (MMSE) nulling: ZF or MMSE estimation of the strongest transmit signal is obtained via nulling out the weaker transmit signals.
- Detecting: The actual value of the strongest signal is detected by slicing to the nearest value in the signal constellations.
- Symbol interference cancellation: The effect of the strongest transmitted signal on the other weaker transmitted signal to be detected is removed from the vector of the received signals, after which we return to nulling in the first step.

Since the spatial multiplexing detector uses some form of channel matrix inversion, a unique solution is only possible if the number of receive antennas is greater than or equal to the number of independent transmit signals. Moreover, spatial multiplexing has poor detection performance over a spatially correlated channel.

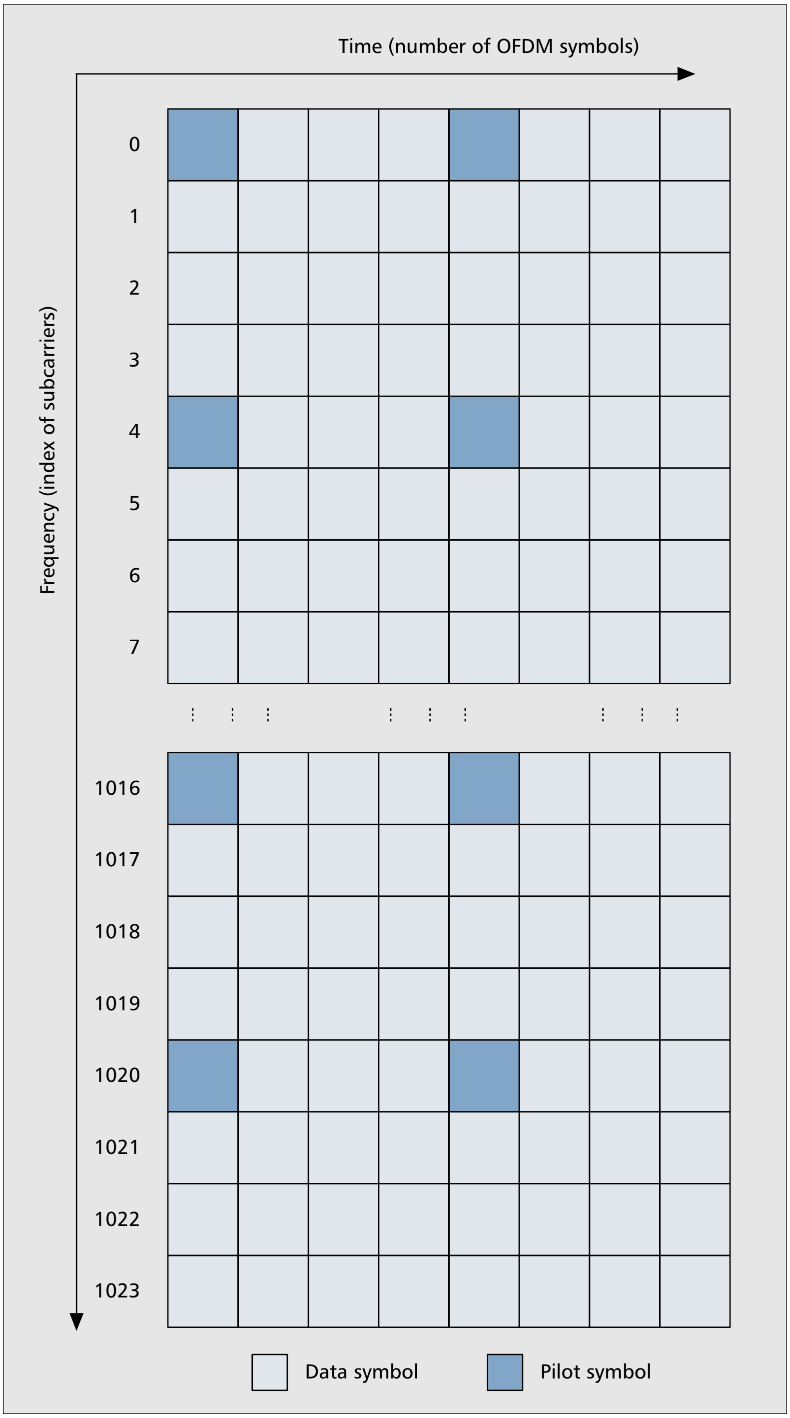


Figure 4. *An example of the pilot pattern over a transmit antenna.*

Space-Time Coding — Space-time coding jointly encodes the data streams over different antennas, and therefore aims to maximize diversity gain. Two main space-time coding schemes, STBC [1] and STTC [2], are mentioned here. STTC obtains coding and diversity gains due to coding in space-time dimension. But its decoding complexity increases greatly as the size of modulation constellations, state number, and code length increase. STBC based on orthogonal design obtains full diversity gain with low decoding complexity, and therefore has been widely

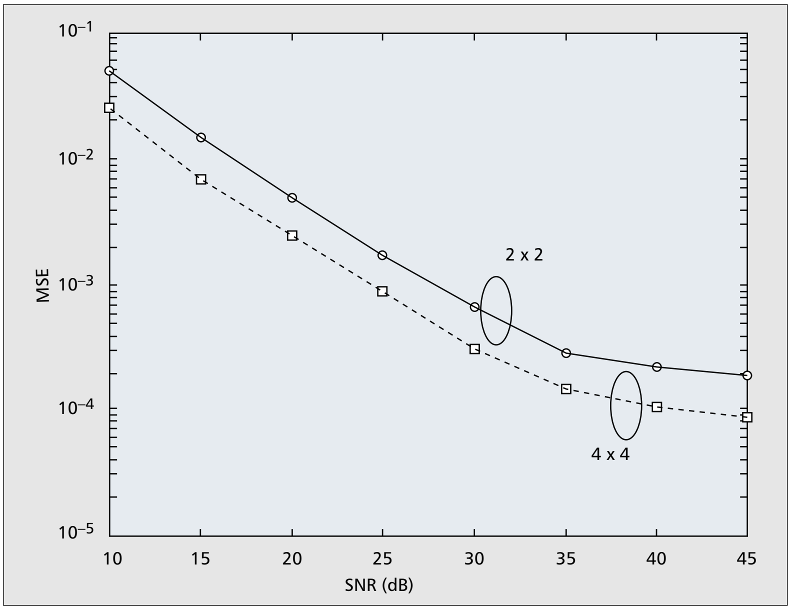


Figure 5. *MSE of the CE.*

MIMO candidates	SFBC/STBC	Spatial multiplexing
Data rate	U → High S → Low	S → High U → Low
Diversity gain	S	U
Spatial correlated channel	S	S → Low U → High
Frequency selective channel	S → MIMO-STBC	S
Fast fading channel	S → MIMO-SFBC	S
Channel estimation error	Insensitive	Insensitive → Low Sensitive → High
LOS	S	U
Antenna configuration	S → 2 Tx	S → Tx ≥ Rx

S: Suitable
U: Unsuitable

Table 1. *Comparisons of STC and spatial multiplexing.*

used. The well-known Alamouti code is just a special case of STBC with double transmit antennas [9]. Space-frequency block code (SFBC) is based directly on space-time codes (with time reinterpreted as frequency).

STBC is optimally designed under the assumption that the fading channel is quasi-static. Therefore, the time or frequency selectivity degrades the performance of STBC and SFBC. Between SFBC and STBC, one is selected based on the selectivity of the channel in the time or frequency domain. Whatever the delay spread of the channel, STBC is chosen only if the channel is slowly varying in the time domain when the terminal moves slowly. Similarly, at whatever speed the terminal moves, SFBC is chosen only if the channel is slowly varying in the frequency domain when the delay spread of the channel is small.

Comparisons of STC and Spatial Multiplexing — Based on the algorithms above, STC and spatial multiplexing are compared by analysis and simulations here. Advantages and disadvantages of STC and spatial multiplexing are listed in Table 1.

Data rate: SFBC/STBC is only suitable for low-data-rate service. Here, low data rate is just relative to the very high data rate achieved by spatial multiplexing. Thus, in order to achieve very high bandwidth efficiency up to the future 10 b/s/Hz, spatial multiplexing is a better choice.

Diversity gain: There is no coding in the time or space domain for spatial multiplexing, and it is not suitable for achieving diversity gain. If a system is designed to achieve better QoS for average data rate, STBC/SFBC is a better choice.

Spatially correlated channel: Over a weak spatially correlated channel, both SFBC/STBC and spatial multiplexing can work well. Over a spatially correlated channel, STBC/SFBC is preferred because spatial correlation leads to much less performance degradation for STBC/SFBC than spatial multiplexing.

Frequency-selective channel: Spatial multiplexing and STBC can work well in a frequency-selective channel at low mobility. At high mobility, only MIMO spatial multiplexing or SFBC can work well.

Fading channel: Both spatial multiplexing and SFBC can work well in a fast fading channel only if the channel is not frequency-selective. Over a frequency-selective channel such as UMTS vehicular B channel, spatial multiplexing is better.

Channel estimation technique: SFBC/STBC is not as sensitive to channel estimation error as spatial multiplexing. Thus, if a CE technique with low accuracy is used for low channel resource cost and low implementation complexity, SFBC/STBC is a better choice.

Channel with LOS: A channel with LOS is spatially correlated, and the receiver often has higher received SNR. Therefore, SFBC/STBC can work well due to high received SNR, while spatial multiplexing fails to work in the LOS case due to spatial correlation.

Antenna configuration: For a configuration with more than two transmit antennas, either two of the transmit antennas are chosen for SFBC/STBC, or spatial multiplexing is used. For more than two transmit antennas, full or higher rate SFBC/STBC are desired.

ITERATIVE DECODING

Channel coding undoubtedly plays an important role in modern digital communications. A reasonable coding scheme is always related to the requirements of a particular communication system. GSM supplies low-bit-rate speech service and some data service; a combination of block coding and convolutional coding is used on important bits. 3G mobile communications are expected to provide a wide range of user services spanning from voice to high-rate data, so besides convolutional code, turbo code is used for the first time.

For the limit of transmit power according to the consideration of 4G, decoders will work at low SNR. To improve the decoding performance, all the features known to decoder should be used, such as interleaving, soft decisions, channel state information, and concatenation. On the other hand, the dramatic increase of integrated circuit capacity makes sophisticated error control methods possible. Two kinds of codes, turbo code and low density parity check (LDPC) code, which have very good error correction performance, are promising candidates for an FEC scheme in 4G.

Turbo Code — In 1993, decoding of two or more concatenated codes was proposed using soft iterative decoding. The basic concept of this new coding scheme is to use a parallel concatenation of at least two codes with an interleaver between the component encoders. Decoding is based on alternately decoding the component codes and passing the extrinsic information to the next decoding stage. Even though very simple component codes are used, the turbo coding scheme is able to achieve performance close to Shannon's capacity bound, at least for a large interleaver and at BER of approximately 10^{-5}. Long latency due to large interleaver size and the performance floor at high SNR are two disadvantages related to turbo code.

Another near-optimum turbo code, turbo product code (TPC), is built on 2D or 3D arrays of extended Hamming codes, and works with hard decision or soft decision. The iteration is made between row and column. The advantages of TPC are summarized as followed:

- A single low-cost TPC encoder/decoder can support code rates from 1/5 to 19/20 with excellent performance at high code rates.
- Near zero latency can be attained, and no tailing bits are required.
- Any packet size is supported.
- There is no error floor for TPC.

LDPC — LDPC, proposed by Gallager in 1962, is a linear block code whose parity check matrix is composed of 0 elements dominantly. LDPC code shows good error correction capacity with soft iterative decoding by the sum-product algorithm or belief propagation (BP) algorithm. LDPC codes possess several advantages over turbo codes:

- BP decoding for LDPC codes can be implemented fully parallel and can potentially be implemented at a significantly faster speed.
- LDPC codes have better block error performance.
- There is no error floor for LDPC codes.

Recently, some researchers have investigated the performance of LDPC applied to OFDM systems. The good error rate performance obtained makes it a candidate access method for 4G.

ADAPTIVE MODULATION AND CODING

Time-varying wireless channel conditions and therefore time-varying system capacity are two important features of wireless and mobile communication systems. Accordingly, future systems should have a high degree of adaptivity on many levels in order to achieve desired performance. Examples of such adaptivity are information rate adaption, power control, code adaptation, bandwidth adaptation, antenna adaptation, and protocol adaptation. AMC is a kind of information rate adaptation, and is used presently in HSDPA and IEEE 802.16.

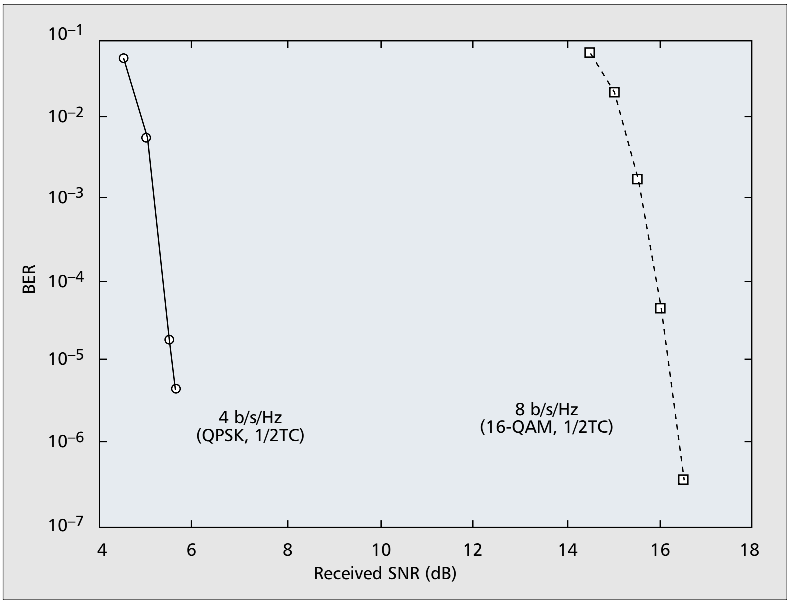


Figure 6. *BER performance of a MIMO-OFDM spatial multiplexing system with bandwidth efficiency of 4 b/s/Hz and 8 b/s/Hz.*

The principle of AMC is to change the modulation and coding format in accordance with instantaneous fluctuation in channel conditions, subject to system restrictions. Channel conditions should be estimated based on feedback from the receiver. For a system with AMC, users close to the cell site are typically assigned higher-order modulation with higher code rates. On the other hand, users close to the cell boundary are assigned lower-order modulation with lower code rates.

The implementation of AMC offers several challenges. First, AMC is sensitive to channel measurement error and delay. In order to select appropriate modulation schemes, the scheduler must be aware of the channel quality. Errors in the channel estimate will cause the scheduler to select the wrong data rate, and transmit at either too high power, wasting system capacity, or too low power, raising the block error rate. Delay in reporting channel measurements also reduces the reliability of the channel quality estimate. Furthermore, changes in interference also increase measurement errors.

One objective of AMC is to greatly improve the MIMO channel capacity with the help of turbo-like codes.

INTERCARRIER INTERFERENCE CANCELLATION

For a traditional OFDM communication system, the frequency offset caused by oscillator inaccuracies or Doppler shift results in ICI that degrades the BER performance of the system greatly. Although frequency synchronization is used, the residential frequency offset causes a number of impairments including attenuation and rotation of each of the subcarriers and ICI

Parameter	Value
Sampling factor (MHz)	11.52
FFT size	1024
Carrier frequency (GHz)	3.2
Mobile speed (km/h)	250
Antenna configuration	4 × 4
Spatial correlation model	Independent Identical Distribution
Multipath fading channel	UMTS Vehicular A
Mobile speed (km/h)	60
Spatial multiplexing detector	MMSE
Turbo code length (bits)	5000
Turbo code rate	0.5
Modulation type	QPSK, 16-QAM
Random interleaving length (ms)	40
Synchronization and CE	Perfect
Spatial channel model	Link level channel model C [8]

■ **Table 2.** *Simulation parameters.*

between subcarriers. Similarly, MIMO-OFDM is also sensitive to Doppler shift and carrier frequency offset that destroy orthogonality of subcarriers and give rise to ICI. ICI mitigation (e.g., a time-domain filtering scheme [10]) is needed to increase the achievable data rates over the wireless medium.

PAPR

The main limitation of OFDM-based transmission systems is the high PAPR of the transmitted signals, and large peaks will occasionally reach the amplifier saturation region and result in signal distortion. Several PAPR reduction schemes have been proposed and investigated; of them, the partial transmit sequence (PTS) scheme is an efficient approach and a distortionless scheme for PAPR reduction by optimally combining signal subblocks. Selective mapping (SLM) is also a good approach, in which some statistically independent sequences are generated from the same information and the sequence with the lowest PAPR is transmitted. Both techniques provide improved PAPR statistics at the cost of additional complexity.

SIMULATION RESULTS

In Fig. 6 we show the BER performance of a MIMO-OFDM spatial multiplexing system with bandwidth efficiency of 4 b/s/Hz and 8 b/s/Hz. The simulation parameters are listed in Table 2. The results show that for BER of 10^{-5}, bandwidth efficiency of 4 b/s/Hz can be achieved at SNR of 5.5 dB, and bandwidth efficiency up to 8 b/s/Hz can also be achieved at a reasonable SNR of lower than 16.2 dB. These encouraging results show that MIMO-OFDM creates a new way to achieve high bandwidth efficiency without sacrificing additional power or bandwidth.

CONCLUSIONS

In this article MIMO-OFDM key techniques are introduced. Some of our considerations in MIMO-OFDM system design are also given, focusing on frame structure, CE, and comparisons of STC and spatial multiplexing. The proposed frame structure with scattered pilots is especially suited for high-data-rate transmission at high mobility. Based on comparisons of STC and spatial multiplexing, qualitative criteria in terms of data rate, application environment, and antenna configuration are proposed to choose STC or spatial multiplexing. Link level simulation results for the designed MIMO-OFDM spatial multiplexing system present encouraging performance. The high bandwidth efficiency obtained shows that MIMO-OFDM is a potential candidate for future broadband wireless access.

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BIOGRAPHIES

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