# Mimo-Ofdm Wireless Systems: Basics, Perspectives, And Challenges

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**Abstract:** ***Multiple-input multiple-output (MIMO) wireless technology in combination with orthogonal frequency division multiplexing (MIMOOFDM) is an attractive air-interface solution for next-generation wireless local area networks (WLANs), wireless metropolitan area networks (WMANs), and fourth-generation mobile cellular wireless systems. This article provides an overview of the basics of MIMO-OFDM technology and focuses on space-frequency signalling, receiver design, multiuser systems, and hardware implementation aspects. We conclude with a discussion of relevant open areas for further research.***

## I. INTRODUCTION

The key challenge faced by future wireless communication systems is to provide high-data-rate wireless access at high quality of service (QoS). Combined with the facts that spectrum is a scarce resource and propagation conditions are hostile due to fading (caused by destructive addition of multipath components) and interference from other users, this requirement calls for means to radically increase spectral efficiency and to improve link reliability. Multiple-input multiple-output (MIMO) wireless technology [1] seems to meet these demands by offering increased spectral efficiency through spatial multiplexing gain, and improved link reliability due to antenna diversity gain. Even though there is still a large number of open research problems in the area of MIMOwireless, both from a theoretical perspective and a hardware implementation perspective, the technology has reached a stage where it can be considered ready for use in practical systems. In fact, the first products based on MIMO technology have become available, for example, the pre-IEEE 802.11n wireless local area network (WLAN) systems by Airgo Networks, Inc., Atheros Communications, Inc., Broadcom Corporation, Marvell Semiconductor, Inc., and Metalink Technologies, Inc. Current industry trends suggest that large-scale deployment of MIMO wireless systems will initially be seen in WLANs and in wireless metropolitan area networks (WMANs). Corresponding standards currently under definition include the IEEE 802.11n WLAN and IEEE 802.16 WMAN standards. Both standards define air interfaces that are based on the combination of MIMO with orthogonal frequency division multiplexing (OFDM) modulation (MIMO-OFDM). Ongoing fourth-generation mobile cellular system prestandardization efforts in Europe, which are carried out in the context of various "Integrated Projects," funded by the European Commission within its Sixth Framework Program (FP6), also show strong support for a MIMO-OFDM air interface. The goal of this article is to provide a highlevel review of the basics of MIMO-OFDM wireless systems with a focus on transceiver design, multiuser systems, and hardware implementation aspects. The remainder of this article is organized as follows. The next section contains a brief introduction into MIMO wireless and OFDM. We then discuss space-frequency signaling and corresponding receiver design for MIMO-OFDM systems. An overview of multi-user MIMO-OFDM systems is followed by a summary of recent results on the VLSI implementation of a four-stream spatial multiplexing MIMO-OFDM transceiver. Finally, we provide a list of relevant open areas for further research.

## II. MIMO SYSTEMS AND OFDM MODULATION

### Performance Gains In Mimo Systems

Traditionally, multiple antennas (at one side of the wireless link) have been used to perform interference cancellation and to realize diversity and array gain through coherent combining. The use of multiple antennas at both sides of the link (MIMO, Fig. 1a) offers an additional fundamental gain — spatial multiplexing gain, which results in increased spectral efficiency. A brief review of the gains available in a MIMO system is given in the following. Spatial multiplexing yields a linear (in the minimum of the number of transmit and receive antennas) capacity increase, compared to systems with a single antenna at one or both sides

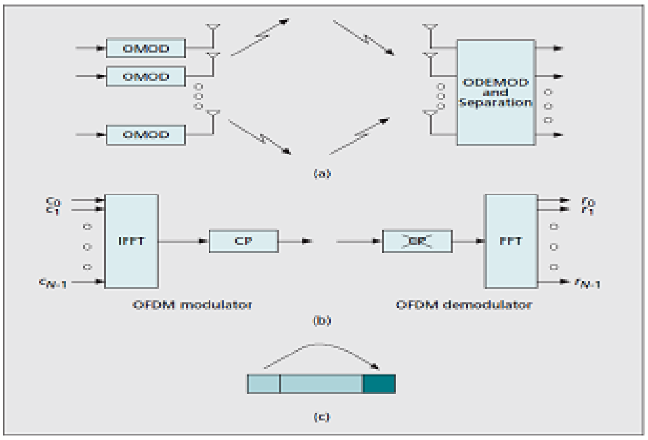


**Figure 1.** (a) Schematic of a MIMO-OFDM system. OMOD and ODEMOD denote an OFDM-modulator and demodulator, respectively; (b) single-antenna OFDM modulator and demodulator; (c) adding the cyclic prefix. of the link, at no additional power or bandwidth expenditure [2–4].

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The corresponding gain is available if the propagation channel exhibits rich scattering and can be realized by the simultaneous transmission of
independent data streams in the same frequency band. The receiver exploits differences in the spatial signatures induced by the MIMO channel onto the multiplexed data streams to separate the different signals, thereby realizing a capacity gain. Diversity leads to improved link reliability by rendering the channel "less fading" and by increasing the robustness to co-channel interference. Diversity gain is obtained by transmitting the data signal over multiple (ideally) independently fading dimensions in time, frequency, and space and by performing proper combining in the receiver. Spatial (i.e., antenna) diversity is particularly attractive when compared to time or frequency diversity, as it does not incur an expenditure in transmission time or bandwidth, respectively. Space-time coding [5] realizes spatial diversity gain in systems with multiple transmit antennas without requiring channel knowledge at the transmitter. Array gain can be realized both at the transmitter and the receiver. It requires channel knowledge for coherent combining and results in an increase in average receive signal-to-noise ratio (SNR) and hence improved coverage. Multiple antennas at one or both sides of the wireless link can be used to cancel or reduce cochannel interference, and hence improve cellular system capacity.

## III. OFDM MODULATION

MIMO technology will predominantly be used in broadband systems that exhibit frequency-selective fading and, therefore, intersymbol interference (ISI). OFDM modulation turns the frequency-selective channel into a set of parallel flat fading channels and is, hence, an attractive way of coping with ISI. Figure 1 depicts the schematic of a MIMO-OFDM system. The basic principle that underlies OFDM is the insertion of a guard interval, called cyclic prefix (CP), which is a copy of the last part of the OFDM symbol (Fig. 1c), and has to be long enough to accommodate the delay spread of the channel. The use of the CP turns the action of the channel on the transmitted signal from a linear convolution into a cyclic convolution, so that the resulting overall transfer function can be diagonalized through the use of an IFFT at the transmitter and an FFT at the receiver (Fig. 1b). Consequently, the overall frequency-selective channel is converted into a set of parallel flat fading channels, which drastically simplifies the equalization task. However, as the CP carries redundant information, it incurs a loss in spectral
efficiency, which is usually kept at a maximum of 25 percent. In general, OFDM has tighter synchronization requirements than single-carrier (SC) modulation and direct-sequence spread spectrum (DSSS), is more susceptible to phase noise, and suffers from a larger peak-to-average power ratio. While general statements on overall implementation point-of-view comparisons of OFDM, SC, and DSSS are difficult to make, recent industry trends show a clear preference for OFDM-based solutions (e.g., IEEE 802.11n WLANs, IEEE 802.16 WMANs, Flarion Technologies' Flash-OFDM, and the system concept developed in the context of the European FP6 Integrated Project WINNER).

## IV. SPACE-FREQUENCY SIGNALING IN MIMO-OFDM SYSTEMS

The signaling schemes used in MIMO systems can be roughly grouped into *spatial multiplexing* [1], which realizes capacity gain, and *space-time coding* [5], which improves link reliability through diversity gain. Most multi-antenna signalling schemes, in fact, realize both spatial-multiplexing and diversity gain. A framework for characterizing the trade-off between spatial-multiplexing and diversity gains in flat-fading MIMO channels
was proposed in [6]. In the following, we describe the basics of spatial multiplexing and space-time coding with particular emphasis on the aspects arising from frequency-selective fading through multipath propagation and from the use of OFDM.

## V. SPATIAL MULTIPLEXING IN MIMO-OFDM SYSTEMS

The basic idea of spatial multiplexing is described above. It was shown in [3, 4] that the spatial-multiplexing gain or, equivalently, the number of spatial data pipes that can be opened up within a given frequency band, is given by the minimum of the number of transmit and receive antennas, provided the receiver knows the channel perfectly. The transmitter does not need to have channel state information (CSI). While the analysis in [3, 4] was carried out for flat fading MIMO channels, it was shown in [7, 8] that the corresponding results are robust with respect to multipath-induced frequency-selective fading. Moreover, in [8] it was demonstrated that under real-world propagation conditions such as spatial fading correlation (caused, e.g., by insufficient antenna spacing), multipath propagation (leading to frequency-selective fading) can be highly beneficial in terms of spatial-multiplexing gain. Multipath propagation tends to increase the angle spread perceived by the transmitter and the receiver, which, in turn, increases the rank of the channel matrix and hence the spatial multiplexing gain. This comes, however, at the cost of increased receiver complexity due to the need to separate the multipath components or, equivalently, to equalize the (ISI) MIMO channel.

***Noncoherent MIMO-OFDM Systems*** — With perfect CSI at the receiver and no CSI at the transmitter, and fixed transmit power, capacity increases with bandwidth until it saturates and is given by

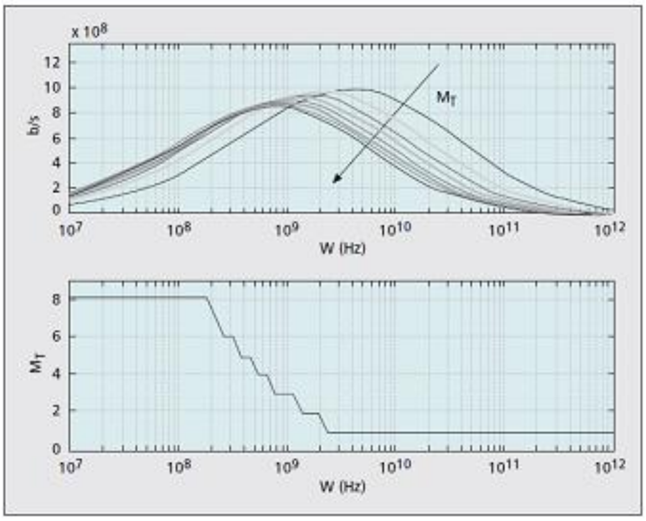


**Figure 2. Top: capacity lower bound for 4 receive antennas and for varying number of transmit antennas MT as a function of bandwidth W. Bottom: corresponding optimum (w.r.t. capacity) number of transmit antennas MT (with a maximum of MT = 8). Figure taken from [20].**

the receive SNR. In the noncoherent case, where neither the transmitter nor the receiver have CSI, the capacity behavior as a function of bandwidth is markedly different: for full-band OFDM systems (i.e., the transmit signal occupies all time-frequency slots), beyond a certain critical bandwidth, "overspreading" occurs, and the capacity goes to zero. The "overspreading" phenomenon was first described in [10] in the context of SISO systems and can be explained as follows. Increasing the bandwidth results in a proportional increase in the number of independent frequency-diversity branches (provided the channel satisfies the uncorrelated scattering assumption). Since the receiver is not assumed to have CSI, these diversity branches contribute to "channel uncertainty" which leads to a capacity penalty. For large bandwidths (and hence small SNR per degree of freedom) this penalty eventually drives the capacity to zero.
In the MIMO case, increasing the number of transmit and receive antennas,



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on the one hand, increases the total number of degrees of freedom for communication and, on the other hand, results in an increase in channel uncertainty. Since the total available transmit power is split uniformly across transmit antennas, increasing the number of transmit antennas results in a smaller SNR per degree of freedom which leads to the existence of a finite optimum (in the sense of capacity maximizing) number of transmit antennas.
Increasing the number of receive antennas, on the other hand, yields an increase in the receive SNR and is hence always beneficial. In summary, for MIMO-OFDM systems operating at bandwidths of several GHz, such as MIMO-based ultra-wideband systems, it is generally not advisable to use a large number of transmit antennas. Figure 2 provides a numerical result illustrating this phenomenon.

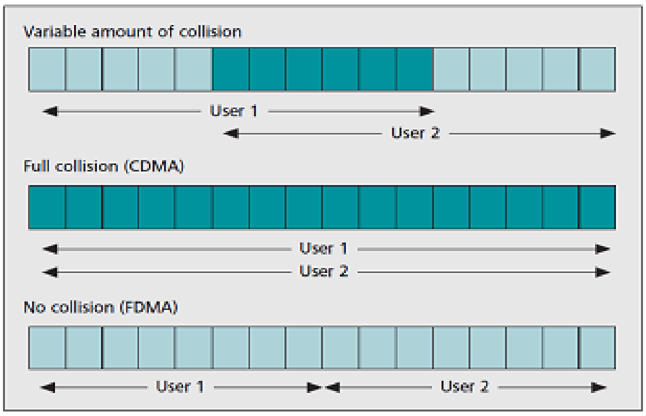


**Figure 3. Multiple access based on variable amount of user collision in frequency (signal space). Figure taken from [17].**

## VI. SPACE-FREQUENCY CODING IN MIMO-OFDM SYSTEMS

While spatial multiplexing aims at increasing spectral efficiency by transmitting independent data streams, the basic idea of space-time coding [5] is to introduce redundancy across space and time to realize spatial diversity gain without the need for CSI at the transmitter. In single-antenna OFDM systems, frequency diversity is obtained by coding and interleaving across tones (and employing appropriate decoding algorithms). In frequency-selective fading MIMO channels, two sources of diversity are available: frequency diversity and spatial diversity. It is therefore sensible to ask how these two sources of diversity can be exploited concurrently. Simply using a space-time code to code across space and frequency (rather than time) was shown in [11], in general, to yield spatial diversity gain only. A straightforward way to realize space-frequency diversity is to combine this approach with forward-error-correction coding and interleaving across tones; most practical systems employ bit-interleaved coded modulation [12]. The problem can, however, be approached in a more systematic fashion through space-frequency codes [11], which essentially spread the data symbols across space (antennas) and frequency (tones), that is, coding is performed within one OFDM symbol and not across OFDM symbols. The resultant code design rules [11], taking the presence of ISI explicitly into account, differ significantly from those for the flat fading case [5]: In the coherent case, where the receiver has perfect CSI, because of ISI, low correlation between shifted versions of the transmitted signal is required in addition to the properties required in the flat-fading case. A framework for designing codes that achieve full rate and full diversity in frequency-selective fading multi antenna channels was proposed in [13]. In the non coherent case, a good code will allow the receiver to implicitly "learn" the channel. Code design for non coherent MIMO-OFDM systems was addressed recently, in a systematic fashion, in [14]. In particular, [14] presents space-frequency code design criteria, taking the presence of ISI into account, and provides explicit constructions of codes that achieve full diversity in space and frequency. Again, the resulting design criteria differ significantly from those for the frequency- flat fading case. Unlike in the coherent case, non coherent space-frequency codes designed to achieve full spatial diversity in frequency- flat fading channels can fail completely to exploit not only frequency diversity, but also spatial diversity, when used in frequency-selective fading environments [14].

## VII. MULTIUSER MIMO-OFDM SYSTEMS

To date, research in the MIMO area has focused predominantly on point-to-point links. The wireless industry has just started to integrate MIMO technology into WLAN, WMAN, and mobile cellular standards. However, little is known about how to optimally leverage the new degrees of freedom resulting from multi-antenna terminals and multi-antenna access points or base stations in a network context. A notable exception is the multi-antenna broadcast channel with perfect transmit CSI [15], where the full-capacity region is known and current research focus is on the design of low-complexity precoding schemes. In the remainder of this section, we briefly review recent results on space-frequency coding and multiple-access in multi user MIMO-OFDM systems.

## VIII. SPACE-FREQUENCY CODING FOR THE MULTIUSER CASE

The main difference between space-frequency coding in point-to-point channels and in multiple access channels (representative of the uplink in a multiuser system) is that in the point-to-point case joint encoding across all transmit antennas is possible, while in the multiple-access case individual users cannot coordinate their transmission. This observation suggests that the space-frequency code-design problem in the multiple-access case is fundamentally different from the point-to-point case, and joint (across users) code designs that take the multiuser aspect explicitly into account will be required in general. We emphasize, however, that even though a joint code book is employed the users will, of course, not cooperate in selecting their codeword. It was recently demonstrated in [16] that, depending on the individual users' transmission rates, joint code designs may or may not be necessary. As a general guideline, the results in [16] allow us to conclude that joint code designs are necessary whenever multiple users transmit concurrently at high rates; in this case, the joint code design has to extend over the corresponding group of users. Otherwise, employing independently chosen codes designed for pointto- point channels for each of the users is optimal (in terms of error probability). The number of receive (base station) antennas plays an important role in delineating the regions where joint code designs are necessary from those regions where independent single-user codes are optimal. Generally, increasing the number of receive antennas for fixed SNR results in an increase of the relative (compared to the capacity region) size of the latter region. This is due to the fact that for a large number of receive antennas there are more spatial degrees of freedom available to separate the individual users' signals so that imposing "separation" through appropriate joint code design is required for a smaller set of (high) rates. We finally note that the discussion in this paragraph pertains to space-time codes as well. Space-frequency code design for broadcast channels (representative of the downlink in a multiuser system) is a largely unexplored area.

## IX. MULTIPLE ACCESS IN MIMO-OFDM SYSTEMS

Multiple access and broadcasting is fundamentally different in systems with multi-antenna terminals and base stations compared to systems with single-antenna terminals, base stations, or both. The underlying reason is that realizing spatial-multiplexing gain requires





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the users to collide (interfere) in signal space. This favours collision-based (non orthogonal) multiple-access schemes such as code division multiple-access (CDMA) over orthogonal multiple-access schemes such as frequency division multiple access (FDMA) or time division multiple-access (TDMA). In OFDM-based systems it is particularly simple to realize variable amounts of collision in signal space by assigning different subsets of the available OFDM tones to different users. The corresponding multiple-access or broadcast schemes, commonly referred to as OFDMA, range from FDMA (each OFDM tone is assigned to at most one user) to CDMA (each OFDM tone is assigned to all users). The situation is depicted schematically in Fig. 3. Note that here the terminology CDMA is used solely to indicate that all users collide on all tones. Spreading, which introduces redundancy, yields an inferior capacity performance compared to a CDMA scheme according to our definition. The impact of variable amount of collision in OFDM based multiple-access schemes was analyzed in detail in [17]. The main findings, assuming that joint decoding is employed, can be summarized as follows: the capacity region obtained for any amount of collision is outer-bounded by the capacity region obtained for a fully collision based multiple-access scheme (i.e., CDMA). This result holds, irrespective of the number of antennas at the terminals and the base station. One may now be tempted to conclude that there is no case for multiple-access schemes other than one with full collision. In practice, however, minimizing the amount of collision in frequency is desirable, as this minimizes the receiver complexity incurred by having to separate the colliding (interfering) signals. In summary, there is a trade-off between capacity and receiver complexity. The following (rough) rules of thumb, applicable in the high-SNR case, may serve as practically relevant guidelines for system design: • When the users are spatially well separated, as measured by their spatial signatures induced

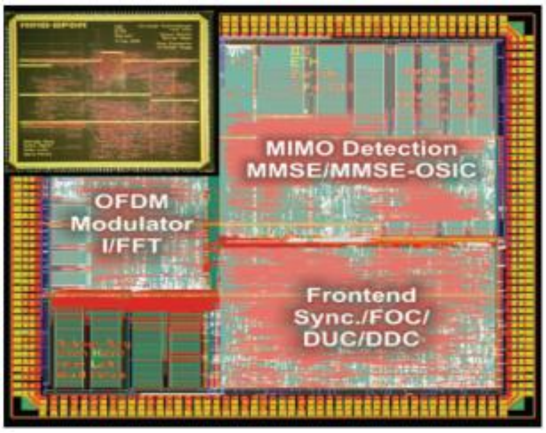


**Figure 4.** Layout and chip micrograph (upper left corner) of the MIMO-OFDM baseband signal processing ASIC [18] manufactured in 0.25 □m 1P/5M 2.5 V CMOS technology.

at the base station, and the number of base station antennas is high, collision in frequency is crucial to maximize the system (i.e., sum) capacity.

• For poor spatial separation or a small number of base station antennas, or both, the impact of collision on system capacity is small. More detailed design guidelines can be found in [17], which furthermore reveals that, when considering system capacity, the number of base station antennas is typically the limiting factor. Based on this result, one may be tempted to conclude that there is no point for multi antenna terminals. This is, however, not the case, as using multi-antenna terminals will result in higher individual data rates and improved per-user link quality. An analysis of the impact of variable amount of collision in broadcast channels does not seem to be available at this point.

## X. HARDWARE IMPLEMENTATION ASPECTS

The gains achievable in MIMO (-OFDM) systems come at an (often significant) increase in hardware complexity. Little is known about suitable VLSI architectures for MIMO (-OFDM) systems and the corresponding silicon complexity. The first commercial MIMO (-OFDMA) chip set was developed by Iospan Wireless, Inc. In 2002 for a proprietary fixed wireless system. This chip set supported two-stream spatial multiplexing
and space-time coding. Several companies have announced MIMO-OFDM chip sets for the

| Component | Area (mm$^2$) | |
|---|---|---|
| | SISO | 4X4 MIMO |
| DDC, DUC | 0.5 | 1.9 |
| AGC | 0.1 | 0.4 |
| FOE.FOC,FSD | 0.3 | 1.3 |
| Modulator,I/FFT | 0.9 | 1.4 |
| Frame buffer | - | 3.3 |
| Ch. Est. and ch. Mem. | <0.1 | 1.12 |
| QR decomposition | - | 1.29 |
| QR memory | - | 1.23 |
| MIMO detector | - | 0.9 |
| Total | 1.9 | 12.8 |

**Table 1.** Chip area of baseband functional blocks in 0.25 μm CMOS technology (FOE,FOC, and FSD stand for frequency offset estimation, frequency offset compensation, and frame start detection, respectively). Taken from [18].

upcoming IEEE 802.11n WiFi standard. Airgo Networks, Inc. offered a prestandard chip set earlier in 2005. In the mobile WiMAX area (IEEE 802.16e), Beceem Communications, Inc. has developed MIMO-OFDMA chip sets supporting two-stream spatial multiplexing, spacetime coding, and beamforming. A four-stream (four transmit and four receive antennas) MIMO-OFDM WLAN physical layer testbed has recently been developed in a collaboration between the Integrated Systems Laboratory (IIS) and the Communication Technology Laboratory (CTL) at ETH Zurich. Next we briefly summarize the main features of this testbed. The basic system architecture of the testbed is based on the SISO IEEE 802.11 a/g OFDM physical layer (FFT length 64, CP length 16, FFT bandwidth 20 MHz, symbol duration 4 μs, support of BPSK, QPSK, 16- QAM, and 64-QAM, and rate 1/2 convolutional coding) and is, therefore, most relevant to the upcoming IEEE 802.11n standard. Further specifics of the testbed are as follows: with an intermediate frequency (IF) of 20 MHz, the (direct IF) sampling rate of the A/D and D/A converters is 80 Msamples/s, which is digitally downconverted to a baseband sampling rate of 20 Msamples/s. Each receive RF chain contains a gain control element. The ASIC described in [18] and shown in Fig. 4 contains the baseband digital-signal-processing functional blocks of the PHY layer described above, including an MMSE ordered-successive interference- cancellation (OSIC) MIMO receiver. It operates at 80 MHz clock frequency and achieves uncoded data rates of up to 192 Mb/s in a 20 MHz channel, which corresponds to a spectral efficiency of 9.6 b/s/Hz. The die area breakdown of the ASIC according to functional blocks along with die area figures for a corresponding SISO system, is summarized in Table 1. Compared to a SISO transceiver, the 4 × 4 MIMO transceiver requires the four-fold replication of most functional blocks and, in addition, a channel- matrix preprocessor for MIMO detection
and the MIMO detector itself; as a result, the overall chip area increases by a factor of 6.5. The main bottleneck in implementing the 4 × 4 MIMO system was found to be the latency incurred by preprocessing the channel matrices for MIMO-OFDM detection.



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We therefore conclude that algorithms for computationally efficient MIMO-OFDM channel matrix preprocessing, such as those described in [9], are of utmost importance for practical implementations.

## AREAS FOR FUTURE RESEARCH

We conclude this survey article with a brief discussion of open problems in the area of MIMOOFDM that need to be addressed so that the gains promised by the technology can be fully leveraged in practical systems. As mentioned above, multiuser MIMO systems are largely unexplored. Making progress in the area of multiuser MIMO systems is of key importance to the development of practical systems that exploit MIMO gains on the system level also. The recently launched EU FP6 STREP project MASCOT (Multiple-Access Space-Time Coding Testbed) is aimed at developing, analyzing, and implementing (in hardware) concepts and techniques for multiuser MIMO communications. Specific areas of relevance in the context of multiuser MIMO systems include multiple-access schemes, transceiver design (including precoding), and space-frequency code design. In particular, the variable amount of collision-based framework for multiple access, introduced in [17], needs to be further developed to account for the presence of out-of-cell interference and to allow for variable amounts of collision in space, time, and frequency. Flarion Technologies' Flash-OFDM system can be seen as a special case of such a general system. Even though it probably constitutes one of the most important areas in MIMO wireless that remain to be addressed, the MIMO community has seen relatively little work on hardware implementation aspects arising in MIMO transceiver design. An exception is the recent Ph.D. thesis [19], which reports, among other results, the ASIC implementation of a sphere decoder. Hardware implementation problems of significant current interest include efficient algorithms for (soft-)sphere decoding and for channel preprocessing in MIMO-OFDM systems. To date most of the work on (multiuser) MIMO has focused on physical layer aspects. Understanding the impact of MIMO technology on the higher layers and, in particular, the development of link adaptation, scheduling, and retransmission algorithms that make explicit use of the MIMO nature of the system are of significant interest.

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