

MIMO-OFDM in the TDD Mode

- White Paper -

Abstract— The increasing demand for higher data rates in next generation wireless systems translates into three challenging requirements for the physical layer development: We have to increase both the spectral efficiency and the bandwidth and we shall reduce the costs per bit. A combination of MIMO, OFDM and TDD may be suitable to meet these requirements. Since a substantial amount of spectrum is reserved for TDD systems across the world, this combination could be a promising candidate for the air interface in next generation of mobile communications systems. Initially, the technique could be tested in the next generation of wireless local area networks.

1. INTRODUCTION

Data rates for wireless cellular and local area networks have been steadily increasing in recent years, with an approximate five-fold increase in throughput every four years. With new applications such as wireless multimedia and the replacement of cables for communication purposes in home, office and public access scenarios, we can anticipate this trend to continue. Three challenging requirements arise from the call for higher data rates in next generation wireless systems: we have to increase spectral efficiency, design systems for larger bandwidths, and we shall reduce the costs per bit as well.

Exploiting the rich scattering typical for indoor and urban environments [1], multiple-input multiple-output (MIMO) systems allow for sound gains in the spectral efficiency, thus facilitating the transmission at high data rates in a spectrum which is usually limited by regulation and other factors.

With increasing bandwidth, more and more echoes are resolved in the channel, calling for efficient equalization techniques. Orthogonal frequency-division multiplex (OFDM) is a very attractive option to solving this problem, and the combination of MIMO and OFDM allows a substantially reduced complexity of the spatio-temporal processing [2]. This is due to the fact that the OFDM pre- and post-processing transforms the multi-path channel into multiple flat fading channels for which well-known MIMO detection schemes can be used.

But we still have to exploit the plethora of diversity offered by the multi-path MIMO channel, which is not trivial with MIMO-OFDM. Note that the maximal diversity order in the multi-path MIMO channel is given as the product of the numbers of receive antennas and resolved echoes, when the spatial multiplexing technique is used. In general, space-frequency codes must be designed to realize this diversity, which may be different from the well-known designs for space-time codes [3].

Alternatively, one may attain the capacity by water-filling and related methods, based on channel state

information (CSI) available at the transmitter. With channel-aware pre-processing and adaptive modulation, data are loaded onto the sub-carriers and spatial channels according to the post-processing signal-to-interference-and-noise ratio (SINR). The error bursts typical for fading channels can such be avoided already prior to the transmission. Channel coding is no longer required to realize the multi-path diversity. Consequently, the interleaver size and the corresponding delay can be reduced.

The basic challenge is to make CSI available at the transmitter. This could be achieved by sending feed-back information over the reverse link, but there is a more efficient method in the time-division duplex (TDD) mode. The latter uses the same carrier frequency alternately for transmission and reception. Due to channel reciprocity, we may transmit training sequences in the up-link direction before the data transmission in the down-link. The reciprocal CSI is then used to pre-process the transmitted data, as well as for optimal scheduling in the space-frequency domain (See Fig. 1).

From the system point-of-view, we must consider what is the ultimate gain for the whole system. In the above example, the CSI obviously helps in the downlink optimization. But at the same time, the training sequences eat up valuable resources in the uplink (capacity in the channel, battery power). There is an optimal trade-off point somewhere which needs to be assessed in future research.

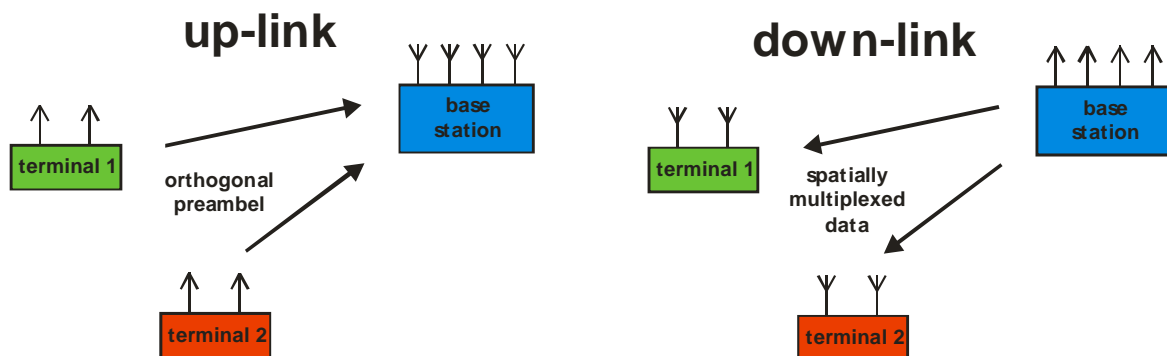


Fig. 1 In the time-division duplex mode, the channel information for the down-link can be made available at the transmitter by using the reciprocal channel information from the up-link, or vice versa.

We feel that this simple principle is the key to realizing the above requirement to reduce the costs per bit while providing a high data rate. With CSI at the transmitter, we gain the flexibility to shift the signal processing effort almost completely to the base station in both, up- and down-link. This allows a simple terminal design. Alternatively, we can share the effort between two mobile terminals in the ad-hoc mode. For each carrier, a simple matrix-vector multiplication at both stations, combined with rate and power control, is sufficient to attain the full capacity (This is called “eigenmode signaling” [4]).

The aim of this White Paper is to identify open research challenges concerning the combination of MIMO, OFDM and TDD which have not been previously addressed, to be able to eventually realize the system concept. The paper is organized as follows: In section 2, application scenarios and

requirements for future wireless systems are described. The system concept for the physical layer is introduced in section 3. The following sections 4-6 summarize the state of the art and analyze open research items in the three component technologies of the combined approach proposed here. Section 7 highlights that a cross-layer optimization is required to achieve the optimal system performance and it addresses the optimal space-frequency scheduling strategy. Section 8 is concerned with the real-time implementation. Finally, conclusions are drawn in Section 9.

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2. APPLICATION SCENARIOS AND REQUIREMENTS

The past years have been marked by two parallel developments that significantly transformed the way people work and live – the advent of the internet and the widespread introduction of personal mobile communications. It is widely anticipated that these two digital industries converge in the next decade, with wireless networks replacing cable-based solutions in home, office and hot spot environments. Seamless interoperability with other communication infrastructure will facilitate user mobility by providing the desired information anywhere at any time. This trend is already visible in the rapidly rising number of Wireless LAN access points in hotels, lounges and offices around the world.

Example applications in this context comprise access to email, intranet and internet, the distribution of multimedia content in home and hot spot environments, replacement of Ethernet networks in offices, and wireless peripheral interfaces for digital equipment. Naturally, customers expect the same high quality of service and ease of use as known from wire based solutions. This translates into a multitude of challenges: high capacity reserves, in order to support the extreme peak data rates, reconfigurability and multi-band operation in order to provide service in a heterogeneous environment, and plug-and-play network configuration in order to enable fast and flexible set-ups.

- Home Environment: The massive use of high quality multimedia applications (streaming audio and video, with data rates in excess of several tens of Mbit/s) for numerous users is one reason for the anticipated need of very high bit rates. Other key requirements in this area are self configuration and zero maintenance features as well as low transmit powers, to minimize exposure of humans to electromagnetic radiation.
- Office and Enterprise Environment: WLAN solutions available to date already enabled office staff to work detached from its desk. However, with high numbers of users accessing a single access point and 100MBit/s Ethernet being state of the art, peak data rates can be expected to be in the order of 1 GBit/s. Moreover, core business applications such as Voice over IP and video conferencing demand very high Quality of Service (including encryption features).
- Hot Sport / Public Access Environment: Large scale coverage in a future heterogeneous wireless access network will be provided by next generation cellular networks whereas high data rate access in urban and hot spot environments will be provided by short range wireless systems. Expected high variations in user data rates and differing service requirements call for a highly flexible MAC. In order to enable user mobility, the system will have to interoperate with other B3G standards.

3. OPERATING PRINCIPLE OF THE AIR INTERFACE

The above application scenarios require an air interface which offers a high peak rate, makes the best possible use of the available spectrum, and enables wireless terminals at low cost. Since in the future a significant quantity of applications will be driven by the continuous communication between users rather than by the burst-type internet access, the end-to-end delay becomes increasingly important for the acceptance of new services. In order to meet these requirements, we need an air interface with high spectrum efficiency which operates as close as possible to the information-theoretic limits, but allows a high-bandwidth communication in real time.

From the information-theoretic point of view, there are two approaches with almost equivalent performance limits: There is the classical “blind” transmission scheme, which sometimes overloads the wireless fading channel and repairs the resulting error bursts at the receiver by interleaved channel coding, which unfortunately introduces additional delay between transmission and reception. The second concept is an adaptive scheme based on channel side information at the transmitter avoiding these errors already in advance. We feel that the adaptive scheme fits better to the above requirements, and it has another interesting impact. From the core network perspective it is desired that only error-free data may enter through the wireless-to-wired gateway. With the classical scheme, there is an unavoidable possibility of error over the wireless link. With the adaptive scheme, the throughput may vary in time, according to the time-varying capacity of the wireless channel. Provided that the channel variation can be tracked sufficiently fast at the transmitter, it can be guaranteed that the variable-rate data are free of error when entering the gateway, even under extreme bit error rate constraints in the core network.

The physical and MAC layer are shown in Fig. 2, in the up-link of the infrastructure mode. We assume that each mobile terminal (MT) as well as the access point (AP) feature multiple antennas.

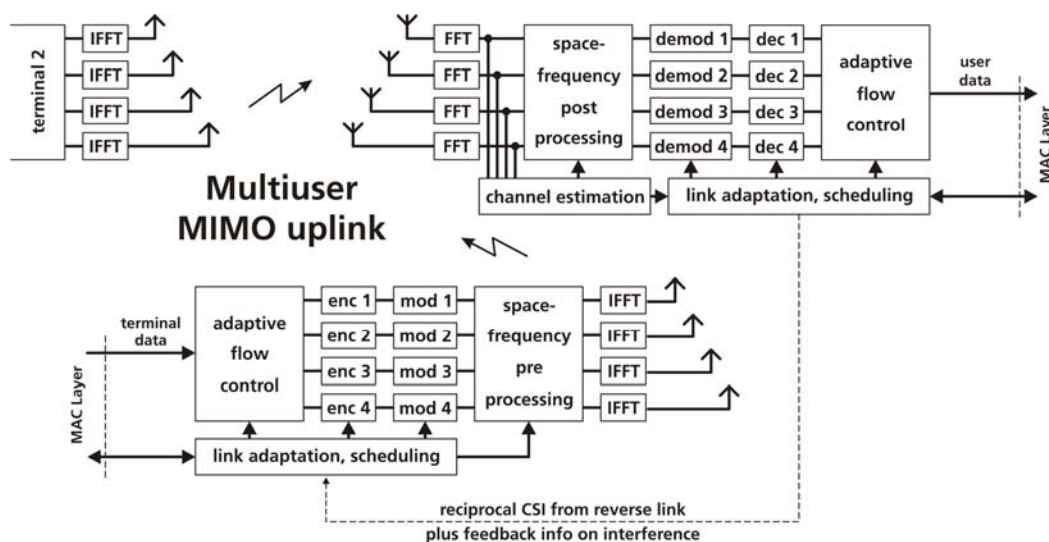


Fig. 2 Concept for the PHY and MAC layers.

Up-link: The MT starts by transmitting pilot sequences for the channel estimation. According to the channel and interference situation at the AP, the scheduler in the AP assigns the required resources in the space-frequency domain to the MT such that the desired quality-of-service requirements (error rates, delay) can be met. The adaptive flow control distributes the data accordingly. Each spatial and frequency channel should at least have individual modulation, steered by the link adaptation unit. Individual coding could be used as well, as indicated in Fig. 2, but might be too complex, eventually. Power control is realized using the joint space-frequency pre-processing after modulation. Finally, the signals are passed through an IFFT, modulated onto the carrier and transmitted over the air. In principle, the corresponding units are used in reversed order at the AP. As in the classical system, it is easy to shift the signal processing effort almost completely to the AP in the up-link, except for power and rate control, which are performed at the terminal but steered from the AP. The (usually complex) MIMO signal processing is performed at the AP.

Down-link: At first, the AP requests the MT to transmit pilot sequences for the channel estimation in the up-link direction and additional information of the current interference scenario at the MT. Using channel reciprocity, the channel state information from the up-link is then correspondingly used to steer the space-frequency pre-coding and to schedule the data transport in the space-frequency domain at the AP, to maximize the throughput and to minimize the latency of the individual users. The data are pre-coded, which means that the MIMO processing is already done at the AP, so that only minor post-processing is required at the MT, such as scaling, demodulation and decoding. The data streams to be multiplexed in space shall already arrive spatially separated at the MT antennas.

Ad-hoc mode: Here the effort is shared between the stations, based on the eigenmode signaling, which results in the minimal total effort for the MIMO processing as well. Initially, the MTs exchange pilot signals for the channel estimation. The space-frequency pre-processing at the transmitting MT is then used to couple the data optimally into the MIMO channel and the post-processing at the receiving MT is used to couple them out. The throughput is optimized by the channel-adaptive space-frequency power and rate control.

Summarizing the above statements, we see that the TDD mode offers the freedom to shift the signal processing effort to wherever it is desired, since it allows us to reuse the channel state information from the UL for the DL, and vice versa, due to channel reciprocity. This particularly enables the design of mobile terminals at reasonable costs, even for very high data rates. Moreover, optimal link adaptation becomes feasible since near-perfect channel side information is available at the transmitter.

4. MIMO

4.1. BROADBAND MIMO CHANNELS

4.1.1 CHANNEL PROPAGATION ISSUES

The mean capacity of an independent and identically distributed (i.i.d.) Rayleigh fading MIMO channel is well known to scale linearly with the minimum of the numbers of transmit and receive antennas [1]. This is perfectly confirmed by the measurement data in Fig. 3 for an indoor non-line-of-sight (NLOS) scenario. When the line-of-sight (LOS) is added, a minor degradation is observed at large numbers of antennas, indicating a minor rank loss of the channel matrix. The huge measured capacities (more than 80 bps/Hz with 16 antennas at 20 dB SNR) are related to the observation that the LOS component is normally not as important compared to the scattered signal, at least indoors with omni-directional antennas. In the general case of MIMO rice channels and non-omni-directional antennas, one has to take into account the trade-off between the multiplexing gain (due to the NLOS scattering environment) and the path loss gain due to the LOS component. The trade-off is mainly a function of the eigenvalue distribution of the mean matrix and the Tx-Rx distance [13, 13b].

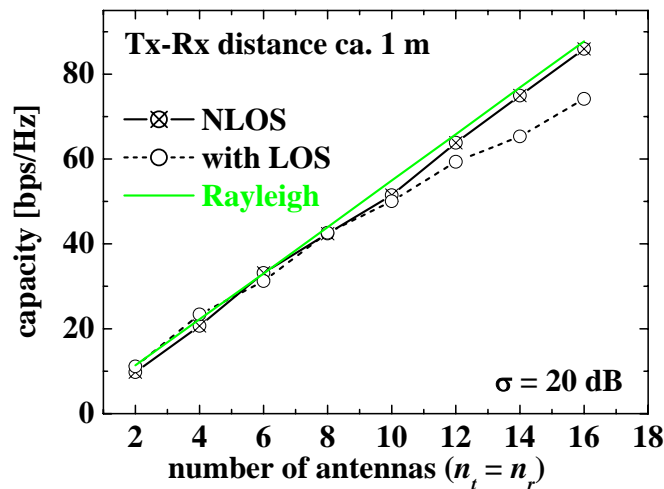


Fig. 3 Measured indoor MIMO capacities versus the numbers of antennas (from [18]).

Future wireless systems may occupy bandwidths ranging from several 10 MHz to even 100 MHz. With increasing bandwidth, more and more taps are resolved and the channel offers a high degree of multi-path diversity. When spatial multiplexing is used, the achievable diversity order is equal to the product of the numbers of receive antennas and taps. Broadband spatial multiplexing has then two implications on the channel capacity: Firstly, the mean capacity increases with the number of antennas (see Fig. 3). Secondly, the more taps are resolved, the sharper becomes the capacity distribution (see

Fig. 4), which is a result of the huge amount of diversity offered by the channel [2]. Therefore, broadband MIMO systems not only provide a higher capacity, they also have higher link reliability and promise almost wire-like quality of service (QoS). If we anticipate that the slope of the capacity pdf in Fig. 4 (which is simulated over 10^4 random i.i.d. channel realizations) can be continued (dashed blue line), then the outage probability becomes negligible even when it is measured against figures of merit in the core network.

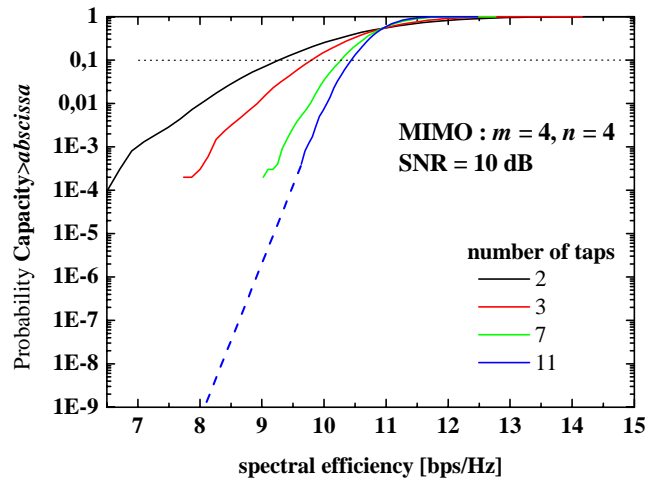


Fig. 4 Broadband MIMO systems promise wire-like quality-of-service (see text).

On the other hand, the spatial structure of the MIMO channel may change as we go from indoor to outdoor scenarios. In Fig. 5, the ordered singular values (SVs) for three scenarios (plotted versus frequency) are compared to the theoretical distributions for the i.i.d. Rayleigh fading channel (The SVs can be considered as the amplitude gains of the spatially multiplexed streams). The random matrix theory predicts an almost equal spacing between the mean SVs. Indoor data agree fairly well with this expectation, and a similar distribution is found at an urban crossing, as well. But on an almost empty parking lot, which is a rather extreme outdoor scenario where the scattering is significantly reduced, the two largest SVs values start to separate from the others. Note that different field directions are addressed in these measurements by four sets of triple antennas addressing different field directions. The two channels with significantly enhanced SVs are due to the polarization, offering multiple spatial channels also in the worst-case line-of-sight scenario.

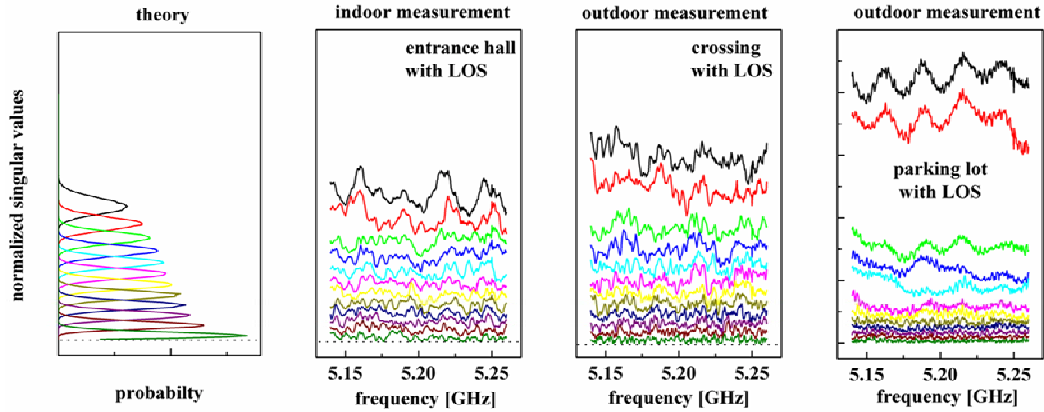


Fig. 5 Singular value distributions in three scenarios, compared to the theory.

Note that the gains of the spatial channels change from frequency to frequency, which is obvious from Fig. 5, and sometimes they become zero for one or more spatial channels at certain frequencies. In order to transmit the data optimally over such arbitrarily conditioned MIMO channels, we need an individual link adaptation at each frequency bin and on each spatial channel. Such a concept may be realistic if we exploit the channel knowledge from the reverse link direction, and when the channel is not too rapidly changing. Of course, we need to signal what transmission mode is used in order to reduce receivers processing load. Then the granularity of this adaptation (in frequency domain, # of different modulations, coding rates etc.) becomes an issue as too fine granularity consumes too much capacity. A proper trade-off between adaptation and signaling granularity is required here.

4.1.2 CHANNEL MODELING ISSUES

The above results point out the necessity of developing a better understanding of the underlying propagation conditions, and more generally the features of the channel critical to communication systems operating in the broadband MIMO OFDM setting for short range and long range scenarios. Of particular importance among these features are the parameters characterizing the eigenmodes/singular modes of the propagation channel, the time-frequency variant structure, the effect of polarization and correlation. In [14], a broadband MIMO model nicknamed Maxent MIMO Model based on information theoretic considerations (maximum entropy principle) was developed and shown to be capacity complying. It includes the time-variant structure as well as the angles of arrival and departure. The maximum entropy principle is a general method which is consistent with one's state knowledge to construct maximum entropy based models. One of the interesting features of the models is their ability to take into account one's state of knowledge and leave in an unconstrained space all the information not provided. The resulting models are mainly based on product of random matrices with Gaussian entries (due to information based on the mean and the variance, otherwise this is not the case) with some pattern mask depending on the relations in the environment. The Maxent model encompasses Sayeed's virtual representation [15], the Kronecker model [16] and the so-called keyhole

channels [17] as special cases. However, the effect of polarization, path loss (for the link budget), the effect of transmit and receiver filters, the effect of the antenna pattern and correlation are still open issues and need to be addressed in light of the transmission techniques to be used in MIMO-OFDM TDD mode.

4.2 MIMO ALGORITHMS FOR TDD

One basic advantage of MIMO-OFDM is that we can reuse the well-known algorithms from the flat fading channel on each carrier. In general, we wish to shift as much signal processing as possible to the AP, to allow economic MTs at high data rates. Next we distinguish between the infrastructure and ad-hoc mode.

Infrastructure up-link: Linear MIMO detection schemes, as the MMSE detector, may have the worst performance at first sight, but they have the proven potential to be implemented in real time for larger numbers of antennas, using parallel multiply-and-accumulate structures realizable in FPGAs and ASICs. The loss of capacity is not as large when a suitable link adaptation is used [3], which is surprisingly efficient also with linear schemes [4]. These adaptive linear algorithms may be extended to the case of MIMO-OFDM [5] where the gap to the optimal schemes reduces further, eventually due to the multi-path diversity. Hence, the linear schemes may serve as a good basis to introduce the new technique in the field. Later, the detectors may be replaced by better schemes, as successive interference cancellation (SIC), lattice-aided detection, sphere decoding or maximum-likelihood detection (MLD). Note that for each of these schemes, a suitable link adaptation must be developed in order to satisfy quality-of-service requirements.

Infrastructure down-link: Recent information theory shows that the down-link capacity region is the same as in the up-link, provided that the channel coefficients are known at the transmitter. This fundamental result is called the up-link/down-link duality [6]. So it is not surprising that the well-known up-link processing schemes have corresponding counterparts for the down-link. For instance, the down-link scheme for the well-known zero-forcing algorithm in the up-link is called channel inversion [7]. Similarly, there are dual algorithms based on the SIC (Tomlinson-Harashima pre-coding [8]), on modulo-lattice reduction [9] and also the sphere pre-coding has recently been reported [10]. The dual scheme for the MLD is the classical “dirty paper” pre-coding which states in principle that known interference signals are not relevant for the channel capacity. But the realization is not yet known. As for the up-link, the better the performance, the higher is the effort.

Ad-hoc mode: Here, the optimal eigenmode signaling can be directly used. It requires simple matrix-vector operations both at the transmitter and at the receiver. There are hints that the eigenmode signaling is sensitive in time-varying channels, since the CSI at transmitter and receiver may differ from each other and this could eventually lead to a confused stream assignment [11]. These effects can be avoided by passing the pilot signals through the pre-coder, which is then considered as a part of the effective channel. So the stream assignment can be restored at the receiver [12].

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5. OFDM

5.1. MOTIVATION AND PRINCIPLE

Proposals for bandwidth usage in current research [1] and standardization efforts [2] as well as large amounts of spectrum allocation for unlicensed operation in the high GHz range are a clear indicator that future wireless systems will use bandwidths ranging from several tens of MHz up to several hundreds of MHz, for wireless broadband applications (i.e., “Gigabit Wireless”).

However, increasing the transmission bandwidth simultaneously increases the sampling frequency of the channel. As the sampling interval becomes shorter, the paths impinging from different scatterers are eventually temporally resolved – the (discrete sampled) channel impulse response is in this case no longer a single Dirac impulse (“tap”) but a sequence of taps – a tapped delay line (TDL), usually described by a power delay profile (PDP) [3].

Traditional single carrier (SC) systems will suffer from strong inter symbol interference (ISI) when transmitting over a frequency selective channel, which makes equalization at the receiver cumbersome. For complexity reasons, it is therefore advantageous to perform equalization in the frequency domain. Two Fourier transforms are required – one of which is done at the transmitter, the other one at the receiver. The aim of this *multi carrier (MC) modulation* is to have a number of parallel sub-carriers high enough such that the bandwidth of one sub-carrier is significantly lower than the channel’s coherence bandwidth and the frequency selective channel is hence transformed into several narrowband frequency flat fading channels. In the time domain, this means that for each individual sub-carrier the symbol time is raised much above the maximum channel delay such that the effects of ISI are negligible.

A commonly used and spectrally efficient [30] technique arising in this context is Orthogonal Frequency Division Multiplexing (OFDM). By means of an Inverse Fast Fourier Transform (IFFT), the transmitter transforms the frequency domain data samples on several sub-carriers (which are equidistantly distributed in frequency domain) into the time domain, adds a prefix/postfix and transmits the resulting signal over the channel. The receiver cancels the prefix/postfix and uses a Fast Fourier Transform (FFT) to transform the received signal back into the frequency domain. We will dwell on the details of pre-/postfixes in the following section. The number of sub-carriers is usually a power of 2, to allow for efficient implementation of the IFFT/FFT.

5.2. OFDM SYSTEM DESIGN

5.2.1. FFT SIZE

One major challenge for the design of an OFDM system is the selection of an appropriate FFT size (number of sub-carriers). In order to avoid OFDM inter-symbol-interference, the length of the guard

interval T_{GI} must be larger than the maximum channel impulse response¹. However, the guard interval is an additional overhead that should not exceed a certain threshold η_{\max} (usually, 25% of the OFDM symbol length). Otherwise, the spectral efficiency would be reduced too much. On the other hand, the OFDM symbol must be short enough such that the temporal variations resulting from relative movements of the transmitter, receiver and/or scatterers do not result in a time-varying channel within one OFDM symbol, which would result in inter-carrier-interference (ICI) and thus significantly deteriorate system performance.

Since sub-carrier spacing and symbol duration are inversely proportional, the former requirement sets a lower bound on the number of sub-carriers: $N_{sc} > B * T_{GI} / \eta_{\max}$, where B is the bandwidth of the channel. It is independent of both carrier frequency and user mobility. The latter requirement sets an upper bound on the number of sub-carriers since at any fixed bandwidth, the OFDM symbol length scales linearly with the number of sub-carriers. If we assume for example a Jakes spectrum and design the OFDM symbol to be shorter than the 99% channel coherence time, then the number of sub-carriers is upper bounded by $N_s < 0.032B / (f_{d,\max} (1 + \eta_{\max}))$, where $f_{d,\max} = f_c v / c$ is the maximum Doppler frequency. The upper bound obviously depends on the carrier frequency as well as on the user mobility. While OFDM carriers are orthogonal, their spectrums do overlap. Doppler shift or, equivalently, insufficient frequency synchronization thus introduce inter-carrier interference (ICI). Doppler spread, or phase noise introduce ICI as well (the effect is a sum of shift effects). Concerning the effect of synchronization on the OFDM performance, the reader is referred to [29]. Usually, a Doppler spread (or phase noise) equivalent to 3%-5% of the carrier spacing may be acceptable. This gives another lower bound on the carrier spacing (and hence an upper bound on the number of sub-carriers). In WiFi, the carrier spacing is rather high to account for cheap oscillators. For future wireless LAN systems in the 60 GHz range, Doppler spread and phase noise considerations may put different requirements.

5.2.2. PREFIX/POSTFIX DESIGN

After fixing the FFT size and the guard interval length, one needs to decide which type of prefix/postfix should be used. The “standard” approach is the use of a Cyclic Prefix (CP). The L last samples of the OFDM symbol are taken and appended to the beginning of the OFDM symbol, where L is the number of samples in the guard interval. The addition of a CP ensures that the convolution of the transmitted signal with the channel impulse response is circular and can hence be diagonalized on a

¹ Note that the length of the guard interval should be designed to take into account the length of the channel impulse response of the *full channel*, i.e., the concatenation of transmitter filters, channel, and receiver filters.

FFT basis. Equalization (and MIMO detection) can thus be effectively performed in the frequency domain on a set of flat channels.

Zero Padding (ZP) [4] follows a different approach by *appending* to the transmitted data sequence a guard interval containing L zero entries instead of *pre-pending* the OFDM symbol with redundant signal copies. Note that the length of the guard interval remains the same and inter-symbol-interference between adjacent OFDM symbols is prevented, as for CP-OFDM. The main advantage is that channel equalization by a simple inversion of the channel is possible even when the channel is badly conditioned, i.e., the channel transfer function has zeros close to or on sub-carriers. The drawback is a higher receiver complexity since the FFT used in conventional CP-OFDM receivers needs to be replaced by a FIR filter bank. However, this complexity increase may be reduced [4].

Recent work [5] proposes to use a pseudo-random-postfix (PRP) as guard interval. The aim is to facilitate low complexity channel estimating for highly mobile environments. The inserted postfix contains a fixed data sequence weighted by a pseudo-random factor in order to avoid stationary effects. Channel estimation can then be assisted by averaging the (un-weighted) received postfix sequence over several OFDM symbols and de-convoluting the resulting vector. Once the channel is known, the postfix can be subtracted from the received data sequence and conventional ZP-OFDM receiver algorithms can be applied to gain knowledge of the transmitted data.

5.2.4. PULSE SHAPING

A first drawback of the standard OFDM waveform is the rectangular pulse shape in the time domain. The corresponding sinc-Spectrum has a bad localization in the frequency domain. This waveform can be modified by an appropriate windowing. But in a conventional OFDM setup, this leads either to the need for either a post-processing equalizer [6], [7] or to the addition of an extra guard interval [8], in order to remove the resulting ISI. Another way to introduce a windowing leading to good frequency localization is to use over-sampled filter banks [9], [10]. The over-sampling increases the spacing between the sub-carriers, and it produces the equivalent of the time-domain guard interval in the frequency domain. So again we have, as for the standard OFDM, a loss in the spectral efficiency.

Another way to introduce the pulse shaping without loss of orthogonality is to include a time-offset when modulating each sub-carrier. For instance, the Offset-QAM (OQAM) modulation format [16] has been used in [15] to get, in the real field, a set of orthogonal waveforms named IOTA (Isotropic Orthogonal Transform Algorithm). IOTA has the nice property to be nearly optimal with regard to the time-frequency localization criterion, i.e. an appropriate criterion when considering transmission over time and frequency dispersive channels. As any OFDM/OQAM scheme, IOTA can reach a maximum spectral efficiency, which is not the case of standard OFDM with CP or ZP. Furthermore, as any modulated transforms, it can be easily and efficiently implemented, thanks to fast Fourier transform (FFT) algorithms. However, compared to classical OFDM, an extra cost is required in order to implement poly-phase pre- and post-filters to generate a waveform that is longer than the simple

rectangular window. However, as shown in the filter bank implementation described in [12], nearly optimal results can be obtained with very short waveforms.

Based on a theoretical analysis [13] it appears that, for transmission over time and frequency dispersive channels, orthogonal waveforms are no longer the best choice and that non orthogonal waveforms have to be used instead. A bi-orthogonal generalization of OFDM/OQAM has already been investigated [11], [14] that could be a candidate for the fourth generation of mobile communication systems.

5.3. IMPLEMENTATION

5.3.1. PEAK-TO-AVERAGE POWER RATIO (PAPR)

The time-domain signal in an OFDM system is the superposition of the signals of a large number of sub-carriers. This results in an approximately Gaussian distribution of the I- and Q-components of the complex base-band signal. Consequently, OFDM systems require transmit and receive signal processing blocks with a high dynamic range. This leads to more costly RF components since amplifiers with a larger linear dynamic range are less efficient than the “switching” amplifiers used in the previous mobile systems, for any given supply voltage level [18].

There are two approaches to reduce this problem: we can either avoid large PAPRs (PAPR reduction) or live with the clipping effects that otherwise occur in the high power amplifier (HPA) of the transmitter. The latter effect is twofold – on the one hand, it distorts the transmitted signal waveforms and thus leads to an increased bit error rate, especially for higher order modulation schemes. On the other hand, the clipping leads to a broadened spectrum of the transmitted OFDM signal – which is the far more damaging effect, since the emission is usually restricted by a spectrum mask.

There has been active research in recent years in the area of pre-processing the OFDM signals for PAPR reduction by coding. However, the additional redundancy of PAPR reduction coding causes a reduction in user data rate and most schemes also lack flexibility. Another approach is to avoid “bad” OFDM words by changing them for equivalent ones. The equivalence is given by changing pseudo-randomly the transmitted word – which however requires channel side information, at least intrinsically. An extensive overview of PAPR reduction schemes is given in [26].

Whenever a broadened spectrum of the OFDM signal is acceptable, one may relax the requirements on RF front-end components, allowing for cheaper power-amplifiers to be used. To appropriately detect the non-linearly distorted signal at the receiver, digital base-band compensation techniques can be employed [27, 28].

5.3.2. PHASE NOISE

The performance of an OFDM system can be strongly degraded by the presence of random phase noise in oscillators, especially if a system targets high data rates at very high carrier frequencies (for instance at 60 GHz). Phase noise causes constellation rotation (common phase error, CPE), and inter-

carrier interference (ICI). Several methods have been proposed to compensate the effects of phase noise. After addressing the problem of estimating the CPE [20, 21], more advanced algorithms were presented which focus on suppressing also the resulting ICI [23]. However, for the carrier frequencies and modulation formats currently envisaged for next generation WLAN systems, phase noise is not (yet) a limiting factor, as long as the subcarrier spacing remains in the order of several hundred kilohertz (e.g. 312.5 kHz as in IEEE 802.11a/n systems).

5.3.3. IQ IMBALANCE

The IQ mismatch must not be overseen when implementing OFDM systems. It is not as widely communicated in the scientific community as other topics, although it is critical for system performance. The FFT processing in the conventional OFDM receiver requires that the IQ mismatch between I- and Q-paths in OFDM transceivers is either absent or sufficiently reduced.

The IQ imbalance is typical for low-cost direct conversion transceivers, where the 90° hybrid for the local oscillator may not be perfect (see Fig. 7, right, where the interior of an IQ modulator is shown). The origin of the phase imbalance is well understood if we compare the precision at which the two mixers can be placed on a printed circuit board (which may be 1 mm), with the carrier wavelength (which is 6 cm in free space at 5 GHz). This would result in a phase error of 6° . Moreover, there are amplitude imbalances, due to the different mixer efficiencies in both branches, which are typically in the order of 1-2 dB. Both effects are narrow-band in their nature, since only the local oscillator phase is affected which has a fixed frequency. But there may be a difference also in the two paths towards the summation point, after the mixers. It becomes critical particularly in broadband OFDM systems. The resulting phase mismatch then becomes frequency-selective, and this error is referred to as the broadband imbalance in the following.

There are several ways out. A simple narrow-band method would be calibration and correction of the time-domain signals. The IQ mismatch is estimated against a perfect normal and corrected out individually, both at the transmitter and at the receiver, to pre-compensate or to restore the complex base-band signals, respectively. This method is reliable as long as the RF parameters can be held sufficiently constant (oscillator and modulation powers).

A second method is to estimate the effect of the IQ imbalance in the frequency domain. The latter causes a cross-talk between equally indexed carriers in the upper and in the lower side-band, depending on the wireless channel as well [31]. Therefore, one may use revised training sequences for the channel estimation. For instance, one could transmit a training symbol only in the upper side-band (USB), and estimate both the correct channel coefficients in the USB and the cross-talk coefficients in the lower side-band (LSB). Then a second symbol is transmitted only in the LSB and the estimation is repeated. With this information, one may perform a joint detection of the equally indexed carrier signals in the USB and LSB. But in the case of MIMO-OFDM, both the dimensions of the channel

matrices and the effort for the reconstruction of the data signals are then increased, and the channel tracking rate is reduced as well.

The problems associated with the approach from [31] arise from the fact that the estimation and compensation of the IQ mismatch is done based on known training symbols within the OFDM signal. The dependence on these training symbols can be avoided, if a blind estimation of the IQ mismatch parameters is performed [32]. In this approach, the estimation and compensation of the quasi-static IQ mismatch is separated from the tracking of the time-variant channel coefficients. Furthermore, the IQ mismatch compensation can be performed for each receive antenna independently, also in the case of MIMO-OFDM. The computational effort no longer scales with the number of transmit antennas.

Both, the narrow- and broadband imbalance can be avoided with digital up- and down-conversion. But this results in a relatively high sampling frequency for the modulated IF signal (>100 MHz), at least at the transmitter, which must provide a sufficient gap, for the purpose of filtering, between the desired and the image frequency after the IF signal is up-converted to the radio frequency domain. The digital technique is truly broad-band, since the analogue origins of the imbalance are no longer present. With commercial components, digital conversion can currently be applied up to 25 MHz bandwidth.

For even higher bandwidth, one must still use the analogue techniques. The broadband imbalance can be avoided by integrating both modulators onto a single chip, which removes the most critical path difference after the mixers. The narrow-band imbalance may then either be calibrated out as described above or almost reduced, by a well-designed 90° hybrid on the same chip. Such components are commercially available, up to carrier frequencies of 2.7 GHz [33] and their performance is calibrated using a multi-tone test signal. The above-mentioned cross-talk between equally indexed carriers is then specified at a mirror frequency distance of -36 dB.

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6. TDD

6.1. RECIPROACITY

Before we start it shall be noted that the Personal Handyphone System (PHS) in Japan already operates in the TDD mode, and it exploits the channel reciprocity for the array processing at the base station. Unfortunately, the technology is driven by a single company (Arraycom) and PHS is no internationally supported standard. Moreover, the PHS is a narrowband system and it does not apply multiple antennas at the MT. Many questions concerning the antenna calibration must be reconsidered for the broadband case until the reciprocity-based technique is applicable to OFDM signals.

For dealing with reciprocity, we must consider two points: Firstly, it requires special (calibrated) RF front-ends to be realized. Secondly, the reciprocity may get lost due to the terminal movement, so that the CSI taken over from the reverse link becomes outdated. Both issues must be considered, separately.

6.1.1. Transceiver calibration

The major advantage of the TDD system is the inherent channel reciprocity, and the presented system concept is fully based on it. But the reciprocity holds only at the antennas, and normally it gets lost in the base-band after the IQ mixer. This becomes obvious from Fig. 7 (left). One usually uses different IQ mixers, amplifiers and path lengths in the separate RF chains at the transmitter and at the receiver. There has been previous work concerning the calibration of the PHS base station array antennas in order to exploit the channel reciprocity [1]. In principle, one of the base station antennas is used as a reference transmitter, and the test signal transmitted from that antenna over the air is measured at the receivers of all other base station antennas for the purpose of calibration. Based on the results of such measurements, a calibration procedure is developed which allows the desired reciprocal processing of the base-band signals of all antenna elements.

Papers from the scientific community recently propose self-calibration techniques [2, 3a-c]. For instance, a noise source is used as a reference in [3], while the antenna is disconnected from the transceiver. But then the effort in the RF chain is increased, due to additional switches and directional couplers, which all must be perfectly matched. This is likely to increase the costs of the terminal (note that reciprocity is also required at the terminal, at least in the ad-hoc mode).

More recently, a reciprocal transceiver structure has been proposed. The idea is shown at the right side in Fig. 7. In principle, one may re-use the IQ mixer and the low-noise and power amplifiers in the TDD mode, since the terminal does not transmit and receive simultaneously. By using an RF transfer switch, the link direction of the in-line low-noise and power amplifiers can be reversed. Moreover, the IQ mixer is reused, both as a modulator and demodulator. In a hybrid setup, which has already been tested in the lab, a calibration procedure is still required. It directly estimates all the parameters contributing to the residual non-reciprocity (phase errors, amplitude imbalances), based on a precise transceiver model. From the estimated parameters, individual calibration matrices are formed for the

transmitter and receiver modes. The error vector magnitude of the residual non-reciprocity has such been reduced down to -30 dB. Currently, the calibration is narrow-band, and it is useful in a 20 MHz bandwidth. But we like to point out that a careful integration of the amplifier and the transfer switch, combined with digital up- and down-conversion or an analogue IQ mixer with negligible imbalance could make these transceivers calibration-less. This is desirable, at least at the mobile terminal [4].

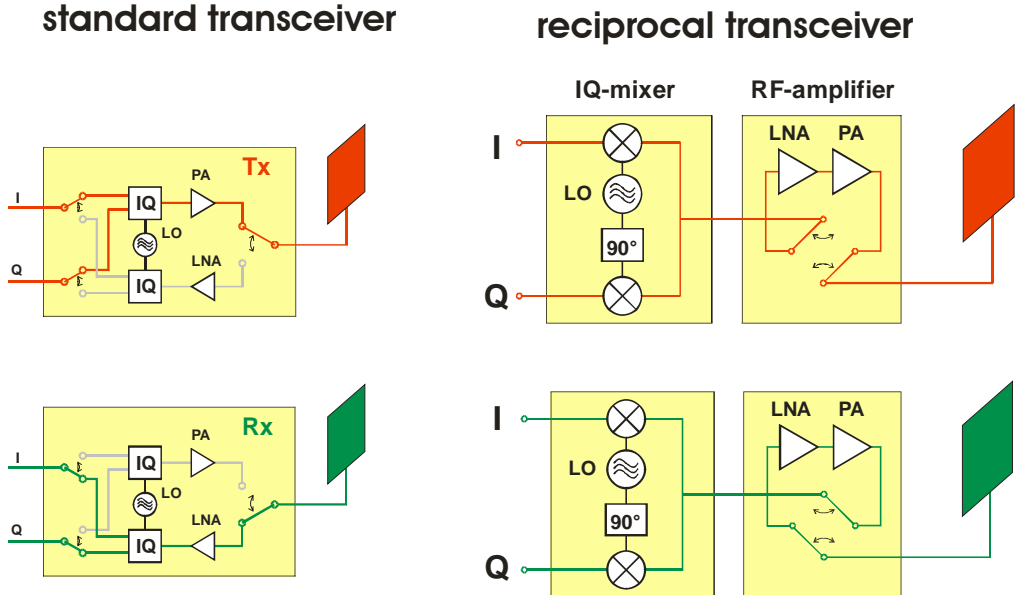


Fig. 7 Standard transceivers lose the reciprocity in the base-band (left). A reciprocal transceiver may re-use all components in both link directions, using a transfer switch (right).

Guaranteeing reciprocity in wireless communication devices can pose additional constraints from the point-of-view joint antenna and printed circuit board design. This is clear from the fact that in the event that a non-negligible amount of signal energy enters the receiver at points other than the front-end (i.e. behind the antennas, Switches, LNAs and power amplifiers) the composite channel will not be reciprocal. This could easily happen in RF subsystems which separate the front-end from the up/down-conversion circuits for ease of deployment of the equipment.

6.1.2. Time-variant channels

Of course, the wireless channel must itself be reciprocal as well. It is easy to prove this with two antennas and a network analyzer in the lab, by alternately measuring the channel in both directions. The reciprocity is given even in indoor scenarios, where the scattering is rich. But as soon as antennas move faster than the channel is updated, time variation destroys the channel reciprocity. Hence, time variation must be negligible while the channel coefficients are estimated in the up-link and the pre-coded data are then transmitted in the down-link.

At low mobility, this requires a simple change in the OFDM burst structure, where the pilot signals for the channel estimation are initially transmitted from the MT to the BS. At higher mobility, the changes

in the link direction must be realized very fast. The challenge is then to still identify the signals from different antennas, to estimate the channel with good quality and still to transmit a useful amount of data in a fraction of the channel coherence time. But these requirements may not be much stricter than in conventional wireless systems which use the channel information only at the receiver. We need to transmit the pilot signals only from the terminal towards the base station, either in the up-link (as in the conventional system) or prior to the down-link and receive the data within the coherence time. Such a roundtrip needs two times the propagation delay ($2 \mu\text{s}$ for a distance of 300 m), which is shorter than one OFDM symbol if the number of sub-carriers and the length of the guard interval are properly designed as described in section 5.

6.2. INTERFERENCE

Interference is the true headache in cellular TDD systems. It arises from many reasons (uplink-downlink synchronization, intra- and inter-cell interference) and it is handled with additional interference management functionality.

Synchronization-related interference: A major promise of the TDD mode in UTRA is the flexible load distribution between up-link and down-link. However, the results in [5] clearly indicate that the switching point between up- and downlink must be synchronized in adjacent cells, particularly in the down-link, while the up-link is less affected.

Intra-cell interference: When a continuous CDMA signal is transmitted over a multi-path fading channel, the spreading codes are no longer orthogonal, which causes multiple-access interference as well as interference between consecutive CDMA symbols. Both can be removed with rather complex receiver structures (see e.g. [6]), which is critical at the mobile terminal.

The OFDM signaling waveforms remain orthogonal also in multi-path channels. Provided that a suitable guard interval is used, and that the synchronization of the MTs is well established, there may be no intra-cell interference, at least in the down-link.

In the up-link, each terminal must be individually synchronized. This is straightforward, when the terminals are operated in the TDMA mode, as in the HiperLan/2 standard. With OFDMA in the up-link, the synchronization becomes an issue to be addressed, in particular when multiple users must be supported at a single carrier, as suggested by the information theory.

Inter-cell interference: Reusing the carrier frequency in adjacent cells became popular with the CDMA systems where it was claimed that all interference can be suppressed by the processing gain. But the exemplary results in [5] indicate that this approach might be wrong, since no cooperation between adjacent base stations is realized. The performance in a given cell depends strongly on the load in the adjacent cells, and it is obvious that the inter-cell interference is a limiting factor when the system load is high, even with optimal receiver structures.

Interference management: Cooperation between the base stations might be a principal way out. Joint detection and transmission techniques have been discussed in the context of base station antenna

arrays since a decade or so. Multiple base-stations may form a virtual array by means of optical fiber or microwave/free-space optical interconnects between them. The drawback of this approach is that the infrastructure costs rise significantly. But any sort of cooperation is economical for a cluster of cells, where the system is frequently used at high load.

In view of reducing the complexity of the system management as well as signaling overhead between nodes in the radio access network (either base station or radio network controllers), algorithms allowing mitigation of inter-cell interference in a decentralized mode are of particular interest. Such algorithms may exploit two fundamental features of wireless data access communications: First, data traffic is not continuous but bursty. In order to prevent buffer overflow, base stations typically operate at a fraction of the nominal physical layer capacity. At the physical frame/slot level, this translates into a utilization ratio of less than 100% of the physical resource (time slots and frequency subcarriers in a TD-OFDMA access system). It is possible to exploit this property with the aim to reduce interference by using a smart “frame filling algorithm” [7]. One example is the so-called left-right algorithm whereby a given cell fills up the temporal frame from the left-most slot toward the right, while the neighboring cell fills up the frame with traffic from the right to the left. On average, several slots are unused by one of the base stations, thus are not subject to any interference. Joint power control and antenna beamforming can be used to further enhance interference mitigation, by finding rules to allocate interference-prone slots to strong users and interference-mitigated slots to weakest users. More general frame filling rules can be researched that will lead to a reduced interference level.

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7. CROSS-LAYER DESIGN

7.1 MULTIPLE ACCESS FOR MIMO: SINGLE VS. MULTIPLE LINK OPTIMIZATION

In wireless single user links, one applies multiple antennas in order to increase the spectral efficiency and the performance. Many results and techniques are well known that can achieve a certain performance and that can guarantee a certain spectral efficiency [1]. Furthermore, the properties of the multiple antenna channel and their impact on the performance was analyzed [3].

On the other hand, in multiuser scenarios, the MIMO multiple access channel (MAC) appears in the uplink transmission from multiple users to the multi-antenna base station. In general, the optimal transmit strategies depend crucially on the applied performance metric. Different power constraints can be imposed: The sum power of all users can be constrained to limit inter-cell interference. The transmit powers of each user can be constrained or the transmit power of each antenna of each user can be bounded. In addition to the power constraint, the type of channel state information (CSI) at the mobiles and at the base plays an important role. In the proposals for High Speed Uplink or Downlink Packet Access (HSDPA, HSUPA), the multiuser transmit as well as receive strategy depend on the channel quality and on the quality-of-service (QoS) requirements of the users. To apply results for the MIMO MAC to the MIMO BC, the duality theory in [14,15] can be used. The capacity regions of both multiuser systems are equal. The perfect CSI assumption is crucial for the duality theory and for the following results.

Each user who participates in the MAC or BC, has its own performance which depends on its own transmit strategy as well as on the transmit strategies of all other users. A popular overall performance metric is the sum of all individual performances of all users. This leads to the sum capacity which can be used as a measure of total throughput. For the single-antenna multiuser case, the sum capacity has been analyzed in [4] and it turned out that the optimal strategy is to allocate power to only the user with the best channel quality. The corresponding optimal multiple access scheme is simple TDMA. The result has led to the development of opportunistic downlink scheduling algorithms [5]. If multiple antennas are applied, the sum capacity optimization problem is solved by iterative waterfilling [6] and power allocation [7]. For fixed channel matrices and for a fixed sum power constraint, the algorithm proposed in [7] provides the optimal transmit covariance matrices and their respective transmit powers of all users. The higher the SNR, the more users are active. In general, it is necessary to support more than one user at a time to achieve the sum capacity [8]. This result necessitates the development of

multiple access schemes that distribute the available temporal and spectral resources not exclusively to one best user, but to a set of active users. The important point to note here is that multiple access schemes that are optimal for single-antenna systems can be highly suboptimal in multiple antenna multiple user systems. The multiuser and spatial diversity offered by the underlying multiple antenna physical layer (PHY) has to be taken into account when designing the multiple access scheme.

In contrast to the sum performance optimization, there has been some effort to analyze the complete performance region of the MIMO MAC and BC [8]. Since each user has his individual performance, the set of performances that are simultaneously achievable can be used to design multiple access strategies which support a certain point in the performance region. The boundary of the performance region is of major interest because of its power efficiency. In [9], the capacity region of the single-antenna MAC has been derived and its intrinsic polymatroid structure has been explored. It turns out, that the optimal transmit strategy that achieves a certain point on the boundary of the performance region requires more than one user to be active, i.e. TDMA is suboptimal, except at the point which achieves the maximum sum-rate. The suboptimality of TDMA even for small SNR values was observed in [10].

7.2 QUEUING THEORETIC ANALYSIS: STABILITY AND CAPACITY

With the expected increasing proliferation of new services, which require low delay and high-rate uplinks, like e.g. image/video-upload, is associated a need for flexible uplink transmission design. Hence, the issue of efficient uplink scheduling is gaining increasing importance in the design of e.g. HSUPA radio link scheme proposed for future use. Recently, a number of multiple access scheduling policies based on combined optimization of the bursty data-packet traffic of the data-link layer and the information flow of the PHY has been presented [16]. Such scheduling design constitutes a distinct field of cross-layer design of the network communication stack [2]. The idea behind cross-layer design is to allow for the combined optimization of different objectives throughout the communication stack, which can result in increased network efficiency. In [11], the combination of information theory and queuing theory has been demonstrated. The need for a kind of cross-layer optimization was recognized in [12]. The goal of cross-layer scheduling policies is to choose such physical layer transmit strategy, which optimizes a desired measure of efficiency of packet traffic in the multiple access data link layer (DLL). Hence, the goal can be e.g. the minimization of mean or maximal bit queue length or achieving stability (finite length at any time) of bit-queues at all transmitters.

The scheduler can optimize different objective criteria. An important criterion from the DL point of view is the stability of the bit queues of the users. In [13], it is shown that the stability region of arrival rates corresponds with the ergodic capacity region of the MIMO MAC. All arrival rate vectors which lie inside the capacity region of the MIMO MAC can be supported without infinite waiting time (or bit queue size). Furthermore, the optimal scheduling algorithm was developed in [13]. Interestingly, the optimal SIC order depends only on the bit queue length and not on the channel realizations. Other

important properties of the capacity region based on polymatroidal theory [9] lead to a complete characterization of the optimal transmit strategy. Currently, the computational efficient implementation of the optimal scheduling algorithm is under investigation.

7.3 MINIMIZING DEPENDENCY TOWARDS CHANNEL STATE INFORMATION

Optimal multi access transmission strategies require a complete channel state information to be available at the transmitter/scheduler to form the correct precoding matrices, power allocation. In view of the uncertainty surrounding the channel estimation at the transmitter due to the non-full reciprocity of the TDD channel, it is of interest to investigate scheduling techniques which either are more robust to errors in transmit channel state information (TCSI) or reduce the need for it. Recently, it was proposed a reduced feedback scheme for multiuser diversity in single transmit antenna systems [17,18] which reduces the feedback needs by as much as 90% while maintaining 90% of the system capacity. The technique is based on a channel quality thresholding principle used to discard certain users from the competition in accessing the channel. This type of techniques is currently being investigated for extension to the MIMO case with SDMA.

7.4 DYNAMIC RESOURCE ALLOCATION FOR DETERMINISTIC CHANNEL USE

A key advantage of wideband OFDM(A) systems is the possibility of performing multiuser waterfilling both in time and frequency. Although the ergodic capacity region is not increased by the wideband resources [9], the additional dimensions potentially allow for a more fair use of the channel due to the increased randomness in the system. This randomness can be beneficial if constraints are placed in order to guarantee a certain instantaneous bandwidth. As mentioned earlier, the latter are particularly important for today's circuit-switched applications (e.g. voice, real-time video) if they are to be run effectively on wireless packet networks. In the context of a cross-layer view, we are interested in wideband resource allocation strategies guaranteeing the peak queue length as opposed to average queue length for a given link. In [19,20] orthogonal allocation and power control strategies guaranteeing a deterministic channel use (i.e. guaranteed instantaneous bit-rate) are considered for parallel (e.g. OFDMA) slowly fading channels with multiple-antennas. Although clearly sub-optimal from the point-of-view of the delay-limited capacity region [21], which to-date remains an open-problem for frequency-selective multi-antenna channels, it is shown that reasonably simple orthogonal allocation strategies can yield both multiuser diversity and spatial multiplexing, without the need for phase information at the transmitter. These strategies are thus very appealing for slowly-fading TDD systems since exploiting amplitude reciprocity does not pose significant constraints on electronics design. The achievable rates approach those of the ergodic sum-rate, however with strict guarantees on channel use.

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8. REAL-TIME IMPLEMENTATION

The system concept in Fig. 1 is based on full channel information at the transmitter. Since the wireless channel may change rapidly, in particular when the terminal is moving, we need to adapt to the current channel realization already prior to transmission. The long-term channel variation is not predictable in rich scattering scenarios. This might be possible only in cases where the LOS component is dominant. So the adaptation to the channel must take place in a fraction of the coherence time. Typical values both for Wireless LANs and cellular systems are in the order of a few ms, even though a higher mobility is required for cell phones. Note that the proper frame length depends on the SNR at which a system operates. After an initial estimate of the channel, the time variation causes an interference rising with a slope of 20 dB per decade in time. Once this interference becomes comparable to the noise, a new estimate is needed. Wireless LANs operate at much lower noise and interference levels than cellular systems, and so they may be similarly sensitive to the time variation of the channel, even if the mobility is much lower [1].

All operations concerning the transmitted signal (spaced-frequency pre-coding and scheduling) must be properly adapted in this short time. So the algorithms must strictly satisfy real-time constraints while performing close to optimal, which is the basic challenge in the system concept considered here. Most principle problems in the real-time implementation of MIMO-OFDM have already been solved separately, but the system integration has not yet been fully finished. Regarding the up-link, the definition of orthogonal pre-amble, the corresponding low-complexity channel estimation, the fast weight calculation and at least the linear data reconstruction have already been integrated and successfully tested over the air in a number of prototypes, almost simultaneously [2-5].

In the following, we refer to [2]. Fig. 6 (left) shows part of the reconstructed BPSK data signals (I and Q signals for two antennas) after the spatially multiplexed transmission over the air at 5.2 GHz, estimating the channels for all 48 used sub-carriers, calculating the weight matrices and reconstructing the data signals using the linear MMSE algorithm, which all is done in real time. The minor cross-talk between the I and Q branches is due to the IQ imbalance in the three receiver chains. The right part of Fig.6 shows the effect of the multi-path fading, which is resolved in the frequency domain with OFDM. Using the channel-aware MIMO-OFDM concept described above, the corrupted carriers in the upper side-band would not be loaded with data, while the lower side-band will carry most of the traffic. Concerning the complexity, the 3-antenna receiver for 2 transmitted data streams fits into a Virtex II/8000 FPGA, where the channel estimation and data reconstruction are performed. The limitation comes from the dedicated BlockRAMs needed to store the channel and weight coefficients close to either the correlation circuits for the channel estimation or to the multipliers in the matrix-vector multiplication unit used for the data reconstruction, respectively. An additional TI 6713 DSP is occupied with tracking the channel sufficiently fast. The OFDM signals are continuously transmitted and reconstructed, and the data transmission is only interrupted by the inserted preambles for the synchronization and channel estimation.

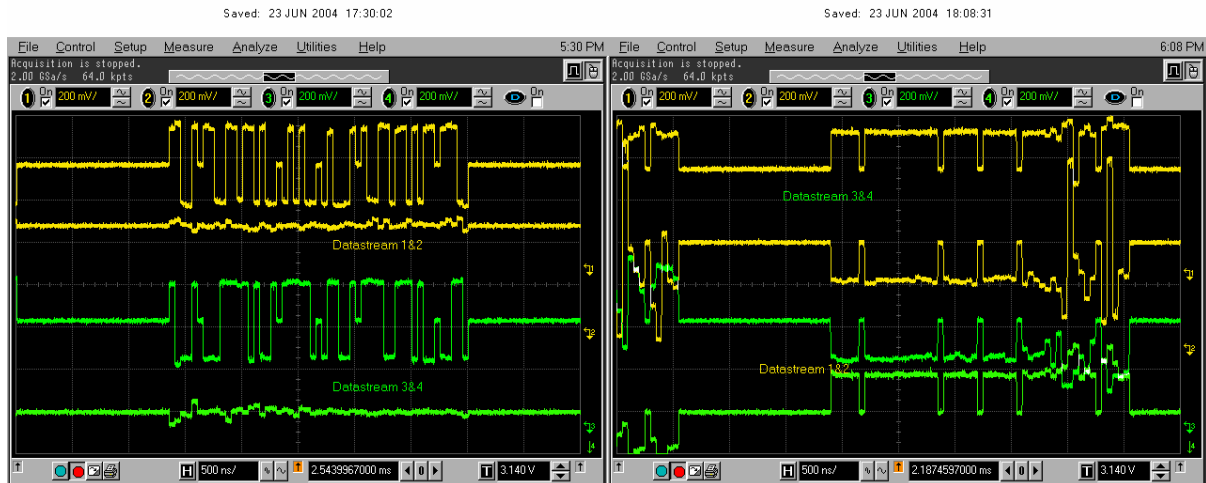


Fig. 6 Left: Reconstructed data signals after reordering them in the frequency domain (yellow: antenna 1, green: antenna2). Right: In the captured channel, the multi-path fading corrupts the signals in the upper side-band, while it provides good conditions in the lower side-band.

The combination of adaptive modulation and linear MIMO detection has recently been demonstrated with a flat-fading MIMO detector. It may be straight forward to implement the adaptation for multiple carriers as well [6]. The down-link is in principle very similar. For a single carrier, the linear precoding and the interference-free signal reception at multiple mobile terminals has already been demonstrated, based on the channel side information obtained over a perfect feed-back link [7]. The principle of a calibration-free TDD transceiver which is reciprocal in the base band has recently been reported (section 6). The challenge is now to integrate all these techniques.

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9. CONCLUSIONS AND MAIN R&D CHALLENGES

We have worked out that a combination of MIMO, OFDM and TDD approaches might fulfill the requirements of the next generation of wireless systems. Customers increasingly expect the same high quality of service and ease of use as known from wired solutions, which implies a high bandwidth, ease of use, robustness in fading environments, negligible latency and low-cost terminals. It has been illustrated that the broadband MIMO channel promises wire-like quality of service over the wireless link, as long as the user is inside the coverage area. There is a plenty of MIMO measurements in the literature but we need more broadband data also at longer ranges which are relevant for cellular applications. In order to reduce the delay and to approach the channel capacity also in arbitrarily conditioned MIMO channels, we have proposed an adaptive system concept, based on channel side information at the transmitter. The latter is realistic in the TDD mode, due to the inherent channel reciprocity. A wide range of transmission and detection techniques is already known. The challenge here is the real-time constraint due to the channel-aware transmission. At least the most simple techniques have already been implemented and tested in real-time, but we need further research to develop more efficient algorithms with the potential of real-time implementation. The OFDM system is highly developed, since it is already used in multiple standards and commercial products. Its inherent drawbacks are widely known and have mostly already been addressed. Alternative schemes not loosing spectral efficiency due to the cyclic prefix or guard interval may need further research, also in the context of MIMO. There are principal ways to realize the reciprocity in the base-band, but both the calibration and the removal of the IQ imbalance are not yet addressed satisfactory, at least in the broadband case. Also the aspect of interference in such an adaptive concept must still be evaluated in a multi-cellular scenario. Also we may need a guideline from the information theory concerning the optimal scheduling and link adaptation in the multi-user broadband MIMO case. The dramatic progress, which is due to significant world-wide research efforts in this field, may indicate that the system concept described above can eventually be realized.

Contributors

Volker Jungnickel, Eduard Jorswiek	Fraunhofer Institute for Telecommunications, Heinrich-Hertz Institut, Germany
Ernesto Zimmermann, Peter Zillmann, Denis Petrovic, Marcus Windisch	Vodafone Chair Mobile Communication Systems, TU Dresden, Germany
Olivier Seller, Pierre Siohan	France Telecom R&D
Merouane Debbah, David Gesbert, Raymond Knopp	Institut Eurécom, Sophia Antipolis
Kari Kalliojarvi	Nokia
Liesbet van der Perre	IMEC Belgium

Coordinating Editor: Volker Jungnickel

contact: Fraunhofer Institute for Telecommunications, Heinrich-Hertz Institut, Einsteinufer 37, D-10587 Berlin, Germany, Tel +49 30 31002 768, email: jungnickel@hhi.de