Multiple-Antenna Techniques for Wireless Communications – A Comprehensive Literature Survey[†]

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Abstract

The use of multiple antennas for wireless communication systems has gained overwhelming interest during the last decade - both in academia and industry. Multiple antennas can be utilized in order to accomplish a multiplexing gain, a diversity gain, or an antenna gain, thus enhancing the bit rate, the error performance, or the signal-to-noise-plus-interference ratio of wireless systems, respectively. With an enormous amount of yearly publications, the field of multiple-antenna systems, often called multiple-input multiple-output (MIMO) systems, has evolved rapidly. To date, there are numerous papers on the performance limits of MIMO systems, and an abundance of transmitter and receiver concepts has been proposed. The objective of this literature survey is to provide non-specialists working in the general area of digital communications with a comprehensive overview of this exciting research field. To this end, the last ten years of research efforts are recapitulated, with focus on spatial multiplexing and spatial diversity techniques. In particular, topics such as transmitter and receiver structures, channel coding, MIMO techniques for frequency-selective fading channels, diversity reception and space-time coding techniques, differential and non-coherent schemes, beamforming techniques and closed-loop MIMO techniques, cooperative diversity schemes, as well as practical aspects influencing the performance of multiple-antenna systems are addressed. Although the list of references is certainly not intended to be exhaustive, the publications cited will serve as a good starting point for further reading.

Index Terms

Wireless communications, multiple-antenna systems, spatial multiplexing, space-time coding, beamforming.

I. Introduction

How is it possible to design reliable high-speed wireless communication systems? Wireless communication is based on radio signals. Traditionally, wireless applications were voice-centric and demanded only moderate data rates, while most high-rate applications such as file transfer or video streaming were wireline applications. In recent years, however, there has been a shift to wireless multimedia applications, which is reflected in the convergence of digital wireless networks and the Internet. For example, cell phones with integrated digital cameras are ubiquitous already today. One can take a photo, email it to a friend – and make a phone call, of course.

In order to guarantee a certain quality of service, not only high bit rates are required, but also a good error performance. However, the disruptive characteristics of wireless channels, mainly caused by multipath signal propagation (due to reflections and diffraction) and fading effects, make it challenging to accomplish both of these goals at the same time. In particular, given a fixed bandwidth, there is always a fundamental trade-off between bandwidth efficiency (high bit rates) and power efficiency (small error rates).

Conventional single-antenna transmission techniques aiming at an optimal wireless system performance operate in the *time* domain and/or in the *frequency* domain. In particular, channel coding is typically employed, so as to

overcome the detrimental effects of multipath fading. However, with regard to the ever-growing demands of wireless services, the time is now ripe for evolving the antenna part of the radio system. In fact, when utilizing multiple antennas, the previously unused *spatial* domain can be exploited. The great potential of using multiple antennas for wireless communications has only become apparent during the last decade. In particular, at the end of the 1990s multiple-antenna techniques were shown to provide a novel means to achieve both higher bit rates and smaller error rates.[1] In addition to this, multiple antennas can also be utilized in order to mitigate co-channel interference, which is another major source of disruption in wireless communication systems. Altogether, multiple-antenna techniques thus constitute a key technology for modern wireless communications. The benefits of multiple antennas for wireless communication systems are summarized in Fig. 1. In the sequel, they are characterized in more detail.

* * * Fig. 1 about here * * *

A. Higher Bit Rates with Spatial Multiplexing

Spatial multiplexing techniques simultaneously transmit independent information sequences, often called layers, over multiple antennas. Using M transmit antennas, the overall bit rate compared to a single-antenna system is thus enhanced by a factor of M without requiring extra bandwidth or extra transmission power.[2] Channel coding is often employed, in order to guarantee a certain error performance. Since the individual layers are superimposed during transmission, they have to be separated at the receiver using an interference-cancellation type of algorithm (typically in conjunction with multiple receive antennas). A well-known spatial multiplexing scheme is the Bell-Labs Layered Space-Time Architecture (BLAST) [1]. The achieved gain in terms of bit rate (with respect to a single-antenna system) is called multiplexing gain in the literature.

B. Smaller Error Rates through Spatial Diversity

Similar to channel coding, multiple antennas can also be used to improve the error rate of a system, by transmitting and/or receiving redundant signals representing the same information sequence. By means of two-dimensional coding in time and space, commonly referred to as space-time coding, the information sequence is spread out over multiple transmit antennas. At the receiver, an appropriate combining of the redundant signals has to be performed. Optionally, multiple receive antennas can be used, in order to further improve the error performance (diversity reception). The advantage over conventional channel coding is that redundancy can be accommodated in the spatial

[1]Interestingly, the advantages of multiple-antenna techniques rely on the same multipath fading effect that is typically considered detrimental in single-antenna systems.

[2]In other words, compared to a single-antenna system the transmit power per transmit antenna is lowered by a factor of $1/M$.

domain, rather than in the time domain. Correspondingly, a diversity gain[3] and a coding gain can be achieved without lowering the effective bit rate compared to single-antenna transmission.

Well-known spatial diversity techniques for systems with multiple transmit antennas are, for example, Alamouti's transmit diversity scheme [2] as well as space-time trellis codes [3] invented by Tarokh, Seshadri, and Calderbank. For systems, where multiple antennas are available only at the receiver, there are well-established linear diversity combining techniques dating back to the 1950's [4].

C. Improved Signal-to-Noise Ratios and Co-Channel-Interference Mitigation Using Smart Antennas

In addition to higher bit rates and smaller error rates, multiple-antenna techniques can also be utilized to improve the signal-to-noise ratio (SNR) at the receiver and to suppress co-channel interference in a multiuser scenario. This is achieved by means of adaptive antenna arrays [5], also called smart antennas or software antennas in the literature. Using beamforming techniques, the beam patterns of the transmit and receive antenna array can be steered in certain desired directions, whereas undesired directions (e.g., directions of significant interference) can be suppressed ('nulled'). Beamforming can be interpreted as linear filtering in the spatial domain. The SNR gains achieved by means of beamforming are often called antenna gains or array gains. The concept of antenna arrays with adaptive beam patterns is not new and has its origins in the field of radar (e.g., for target tracking) and aerospace technology. However, intensive research on smart antennas for wireless communication systems started only in the 1990's.

D. Combined Techniques

The above families of multiple-antenna techniques are, in fact, quite different. Spatial multiplexing is closely related to the field of multiuser communications and aims predominantly at a multiplexing gain compared to a single-antenna system. Space-time coding is more in the field of modulation and channel coding and aims at a (coding and) diversity gain. Finally, smart antennas and beamforming techniques belong more in the area of signal processing and filtering and aim at an antenna gain, i.e., at an improved SNR or an improved signal-to-interference-plus-noise ratio (SINR). There are also composite transmission schemes that aim at a combination of the different gains mentioned above. However, given a fixed number of antennas, there are certain trade-offs [6] between multiplexing gain, diversity gain, and SNR gain.

[3]If the antenna spacings at transmitter and receiver are sufficiently large, the multipath fading of the individual transmission links can be regarded as statistically independent. Correspondingly, the probability that all links are degraded at the same time is significantly smaller than that for a single link, thus leading to an improved error performance.

In fact, a strict distinction between the above three types of multiple-antenna techniques is sometimes difficult. For example, spatial multiplexing techniques can also accomplish a diversity gain, e.g., if an optimum receiver in the sense of maximum-likelihood (ML) detection is employed. Similarly, spatial diversity techniques can also be used to increase the bit rate of a system, when employed in conjunction with an adaptive modulation/channel coding scheme.[4]

E. Development of the Field

Extensive research on multiple-antenna systems for wireless communications, often called multiple-input multiple-output (MIMO) systems, started less than ten years ago. The great interest was mainly fueled by the pioneering works of Telatar [7], Foschini and Gans [1], [8], Alamouti [2], and Tarokh, Seshadri, and Calderbank [3] at the end of the 1990's. On the one hand, the theoretical results in [7], [8] promised significantly higher bit rates compared to single-antenna systems. Specifically, it was shown that the (ergodic or outage) capacity, i.e., the maximum bit rate at which error-free transmission is theoretically possible, of a MIMO system with M transmit and N receive antennas grows (approximately) linearly with the minimum of M and N.[5] On the other hand, the work in [1]-[3] suggested design rules for practical systems. In [1] the BLAST spatial multiplexing scheme was introduced that accomplished bit rates approaching those promised by theory (at non-zero error rates). In [2], Alamouti proposed his simple transmit diversity scheme for systems with two transmit antennas, and in [3] design criteria for space-time trellis codes were derived. The invention of space-time trellis codes was like an ignition spark. With an enormous amount of yearly publications, the field of MIMO systems started to evolve rapidly. To date, there are numerous papers on the performance limits of MIMO systems, and an abundance of transmitter and receiver concepts has been proposed.[6]

Interestingly, although the period of intensive research activities has been relatively short, multiple-antenna techniques have already entered standards for third-generation (3G) and fourth-generation (4G) wireless communication

[4]If the error rate accomplished by means of spatial diversity is smaller than desired, one can switch to a higher-order modulation scheme or to a channel coding scheme with less redundancy. By this means, it is possible to trade error performance for a higher effective bit rate (since higher-order modulation schemes typically come with a loss in power efficiency). In fact, adaptive modulation and channel coding schemes are employed in most state-of-the-art wireless communication systems.

[5]Again, the underlying assumption is that the individual transmission links are subject to statistically independent fading.

[6]In April 2008, a search with IEEE Xplore® for papers in the general field of multiple-antenna communication systems yielded a total number of more than 14,600 documents.

systems.[7] For example, some 3G code-division multiple access (CDMA) systems use Alamouti's transmit diversity scheme for certain transmission modes [10]. MIMO transmission is also employed in the IEEE 802.11n wireless local area network (WLAN) standard (see [11] for an overview). Further examples include the IEEE 802.20 mobile broadband wireless access system [12] and the 3GPP Long Term Evolution (LTE) of wideband CDMA (W-CDMA) [13].

F. Drawbacks of Multiple-Antenna Systems

Clearly, the various benefits offered by multiple-antenna techniques do not come for free. For example, multiple parallel transmitter/receiver chains are required, leading to increased hardware costs. Moreover, multiple-antenna techniques might entail increased power consumptions and be more sensitive to certain detrimental effects encountered in practice. Finally, real-time implementations of near-optimum multiple-antenna techniques can be challenging. On the other hand, (real-time) testbed trials have demonstrated that remarkable performance improvements over single-antenna systems can be achieved in practice, even if rather low-cost hardware components are used [14].

G. Focus and Outline of the Survey

The objective of this literature survey is to recapitulate the last ten years of research efforts, so as to provide a comprehensive overview of this exciting research field. Focus will be on spatial multiplexing techniques (Section II) and spatial diversity techniques (Section III). Smart antenna techniques will briefly be outlined in Section IV. Finally, alternative categorizations of the available multiple-antenna techniques will be discussed in Section V, and the benefits and requirements of various schemes discussed will be highlighted. Some conclusions are offered in Section VI.

Although the list of references is not intended to be exhaustive, the cited papers (as well as the references therein) will serve as a good starting point for further reading. In particular, there are various tutorial-style articles, e.g., [5], [15]-[21], all of which have quite a different focus.

II. Spatial Multiplexing Techniques

As discussed in the Introduction, three types of fundamental gains can be obtained by using multiple antennas in a wireless communication system: A multiplexing gain, a diversity gain, and an antenna gain (cf. Fig. 1). In this section, we will mainly focus on the multiplexing gain.

[7] In fact, the authors of [9] predict that multiple-antenna techniques will become crucial for system operators to secure the financial viability of their business.

The fact that the capacity of a MIMO system with M transmit and N receive antennas grows (approximately) linearly with the minimum of M and N (without requiring extra bandwidth or extra transmission power) [7], [8] is an intriguing result. For single-antenna systems it is well known that given a fixed bandwidth, capacity can only be increased logarithmically with the SNR, by increasing the transmit power. In [1], the theoretical capacity results for MIMO systems were complemented by the proposal of the BLAST scheme, which was shown to achieve bit rates approaching 90% of outage capacity. Similar to the theoretical capacity results, the bit rates of the BLAST scheme were characterized by a linear growth when increasing the number of antenna elements. The first real-time BLAST demonstrator [22] was equipped with $M = 8$ transmit and $N = 12$ receive antennas. In a rich-scattering indoor environment, it accomplished bit rates as high as 40 bit/s per Hertz bandwidth (corresponding to about 30% of capacity) at realistic SNRs. Wireless spectral efficiencies of this magnitude were unprecedented and can not be achieved by any single-antenna system.

A. Transmitter and Receiver Structure

The idea of spatial multiplexing was first published in [23]. The basic principle of all spatial multiplexing schemes is as follows. At the transmitter, the information bit sequence is split into M sub-sequences (demultiplexing), that are modulated and transmitted simultaneously over the transmit antennas using the same frequency band. At the receiver, the transmitted sequences are separated by employing an interference-cancellation type of algorithm. The basic structure of a spatial multiplexing scheme is illustrated in Fig. 2.

* * * Fig. 2 about here * * *

In the case of frequency-flat fading, there are several options for the detection algorithm at the receiver, which are characterized by different trade-offs between performance and complexity. A low-complexity choice is to use a linear receiver, e.g., based on the zero-forcing (ZF) or the minimum-mean-squared-error (MMSE) criterion. However, the error performance is typically poor, especially when the ZF approach is used (unless a favorable channel is given or the number of receive antennas significantly exceeds the number of transmit antennas). Moreover, at least as many receive antennas as transmit antennas are required ($N \geq M$), otherwise the system is inherently rank-deficient. If the number of receive antennas exceeds the number of transmit antennas, a spatial diversity gain is accomplished.

The optimum receiver in the sense of the maximum-likelihood (ML) criterion performs a brute-force search over all possible combinations of transmitted bits and selects the most likely one (based on the received signals). The ML detector achieves full spatial diversity with regard to the number of receive antennas, irrespective of the number of transmit antennas used. In principle, the use of multiple receive antennas is optional. Yet, substantial

performance improvements compared to a single-antenna system are only achieved when multiple receive antennas are employed. The major drawback of the ML detector is its complexity. It grows exponentially with the number of transmit antennas and the number of bits per symbol of the employed modulation scheme. Due to this, the complexity of the ML detector is often prohibitive in a practical system. However, it can be reduced by means of more advanced detection concepts, such as sphere decoding.

For the BLAST scheme, an alternative detection strategy known as nulling and canceling was proposed. The BLAST detector was originally designed for frequency-flat fading channels and provides a good trade-off between complexity and performance. In contrast to the ML detector, the estimation of the M sub-sequences, called layers in the terminology of BLAST, is not performed jointly, but successively layer by layer. Starting from the result of the linear ZF receiver (nulling step) or the linear MMSE receiver, the BLAST detector first selects the layer with the largest SNR and estimates the transmitted bits of that layer, while treating all other layers as interference. Then, the influence of the detected layer is subtracted from the received signals (canceling step). Based on the modified received signals, nulling is performed once again, and the layer with the second largest SNR is selected. This procedure is repeated, until the bits of all M layers are detected. Due to the nulling operations, the number of receive antennas must at least be equal to the number of transmit antennas (as in the case of the linear receivers), otherwise the overall error performance degrades significantly.[8] The error performance resulting for the individual layers is typically different. In fact, it depends on the overall received SNR, which layer is best. In the case of a low SNR, error propagation effects from previously detected layers dominate. Correspondingly, the layer detected first has the best performance. At the same time, layers that are detected later have a larger diversity advantage, because less interfering signals have to be nulled. Therefore, in the high SNR regime, where the effect of error propagation is negligible, the layer detected last offers the best performance [24]. A detailed performance analysis of the BLAST detector was, for example, presented in [25].

The BLAST detection algorithm is very similar to successive interference cancellation (SIC), which was originally proposed for multiuser detection in CDMA systems. Several papers have proposed complexity-reduced versions of the BLAST detector, e.g. [26]. Similarly, many papers have suggested variations of the BLAST detector with an improved error performance, e.g. [27]. An interesting approach to improve the performance of the BLAST scheme was presented in [28]. Prior to the BLAST detection algorithm, the given MIMO system is transformed into an equivalent system with a better conditioned channel matrix, based on a so-called lattice reduction. The performance

[8]Note that this is a crucial requirement when a simple receiver is desired.

of the BLAST detector is significantly improved by this means and approaches that of the ML detector, while the additional complexity due to the lattice reduction is rather small.

B. Channel Coding

In order to guarantee a certain error performance for spatial multiplexing schemes, channel coding techniques are usually required. Most spatial multiplexing schemes employ a channel coding structure that is composed of one-dimensional encoders and decoders operating solely in the time domain. This is in contrast to space-time coding techniques like [2], [3], where two-dimensional coding is performed in time and space, i.e., across the individual transmit antennas. In principle, three different types of (one-dimensional) channel coding schemes can be used in conjunction with spatial multiplexing: Horizontal coding, vertical coding, or a combination of both. Horizontal coding means that channel encoding is performed after the demultiplexer (cf. Fig. 2), i.e., separately for each of the M layers. The assignment between the encoded layers and the transmit antennas remains fixed, i.e., all code bits associated with a certain information bit are transmitted over the same antenna. At the receiver, channel decoding can thus be performed individually for each layer (after applying one of the above receiver structures). In the case of vertical coding, however, channel encoding is performed before the demultiplexer, and the encoded bits are spread among the individual transmit antennas. Compared to horizontal coding, vertical coding thus offers an additional spatial diversity gain. However, the drawback of vertical coding is an increased detector complexity, because at the receiver all layers have to be decoded jointly.

For the BLAST scheme, a combination of horizontal and vertical encoding was proposed, called diagonal coding [1]. Correspondingly, the original BLAST scheme is also known as Diagonal BLAST (D-BLAST). As in horizontal coding, channel encoding is performed separately for each layer. Subsequently, a spatial block interleaver is employed. For a certain time period, the assignment between the encoded layers and the transmit antennas remains fixed, and is then changed in a modulo-M fashion. Thus, the overall coding scheme has a diagonal structure in time and space. In principle, diagonal coding offers the same spatial diversity advantage as vertical coding, while retaining the small receiver complexity of horizontal coding. A comparative performance study of horizontal, vertical, and diagonal coding was presented in [29]. Moreover, several improved channel coding schemes for BLAST can be found in the literature, e.g. [30]. The first BLAST demonstrator [22], coined Vertical BLAST (V-BLAST), was in fact realized without any channel coding scheme.

C. Channels with Intersymbol Interference

The receiver concepts discussed in Section II-A were designed for frequency-flat fading channels, i.e., for channels without intersymbol interference (ISI). However, depending on the delay spread of the physical channel (due to

multipath signal propagation), the employed transmit and receive filter, and the symbol duration, this assumption might not be valid in a practical system. If no counter measures are employed, ISI can cause significant performance degradations (see, for example, [31] where the BLAST scheme was studied in the presence of ISI).

One approach to circumvent the problem of ISI is to use a multicarrier transmission scheme and multiplex data symbols onto parallel narrow sub-bands that are quasi-flat. Transmission schemes developed for frequency-flat fading channels can then be applied within each sub-band. A popular multicarrier scheme is orthogonal frequency-division multiplexing (OFDM) which uses an inverse fast Fourier transform (IFFT) at the transmitter and a fast Fourier transform (FFT) at the receiver, making it simple to implement. Specifically, it is straightforward to combine OFDM with multiple antennas (MIMO-OFDM) [32]. The combination of (an improved version of) the BLAST scheme with OFDM was, for example, considered in [33].

Alternatively, one can also use a single-carrier approach and employ suitable techniques for mitigating ISI. Generally, there are two main classes of techniques, namely transmitter-sided predistortion and receiver-sided equalization techniques. Predistortion techniques require channel knowledge at the transmitter side, e.g., based on feedback information from the receiver. Predistortion for frequency-selective MIMO channels is a rather new research topic, and not much work has yet been reported [34]. In contrast to this, there are many equalization schemes for MIMO systems, most of which are generalizations of existing techniques for single-antenna systems. For example, a low-complexity option is to use a linear equalizer (LE) or a decision-feedback equalizer (DFE) in time domain. In the case of a single-antenna system, these equalizers are usually realized by means of finite-impulse-response (FIR) filters with real-valued or complex-valued filter coefficients. Generalized linear and decision-feedback equalizers for MIMO systems (MIMO-LEs/DFEs) can be obtained by replacing the scalar filter coefficients by appropriate matrix filter coefficients, see e.g. [24], [35]. An alternative to time-domain equalization is frequency-domain equalization (FDE), which is quite similar to OFDM. The major difference is that the FFT and the IFFT operations are both performed at the receiver side. This allows for equalization in the frequency domain by leveling the quasi-flat sub-bands. Like OFDM, FDE can readily be combined with multiple antennas. For example, a combination of the BLAST scheme with FDE was considered in [36].

A high complexity option for mitigating ISI at the receiver is to perform an optimal sequence or symbol-by-symbol estimation, e.g., by means of a trellis-based equalizer. For example, maximum-likelihood sequence estimation (MLSE) can be performed by means of a vector version of the well-known Viterbi algorithm. Alternatively, a generalized version of the Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm can be used to perform symbol-by-symbol maximum a-posteriori (MAP) detection. The complexity of MLSE and symbol-by-symbol MAP detection grows

exponentially with the number of transmit antennas and the number of bits per modulation symbol. Additionally, it also grows exponentially with the effective memory length of the channel. The use of multiple receive antennas is (in principle) again optional. Similar to the case without ISI, the complexity of MLSE can be reduced significantly by means of a sphere decoding approach [37].

Finally, several papers have proposed direct generalizations of the BLAST detection algorithm to ISI channels, e.g. [38]. In essence, the nulling operation is replaced by a set of generalized decision-feedback equalizers for MIMO systems. An iterative extension of [38] was later proposed in [24].

D. Alternative Transmitter and Receiver Concepts

More recently, an alternative receiver concept has been proposed for spatial multiplexing systems (without ISI) [39], which is based on the concept of probabilistic data association (PDA). PDA has its origins in target tracking and has been adopted in many different areas, for example, in multiuser communication systems based on CDMA. The key idea is to use an iterative receiver, which detects the individual layers (or, in a multiuser system, the bit sequences of the individual users) by regarding the other, interfering layers as Gaussian noise (Gaussian assumption). Within each iteration, the mean and the variance of the assumed Gaussian noise are adjusted by exploiting knowledge about already detected bits. When a sufficiently large number of layers is used (and a modulation scheme with moderate cardinality) the Gaussian assumption fits well, and a near-optimum error performance is achieved.[9] The principle of the PDA detector can also be applied for mitigating ISI. A PDA-based equalizer for MIMO systems was, for example, presented in [41]. Further stochastic detection algorithms for spatial multiplexing systems without ISI were proposed in [42]. These are based on the concept of particle filtering and achieve near-ML performance at a reasonable complexity.

There are many connections between spatial multiplexing schemes and multiuser communication systems. Hence the idea to adopt multiple-access techniques for spatial multiplexing is quite obvious. For example, one could use orthogonal spreading codes (also called signature sequences) to separate the individual layers, just as in a direct-sequence (DS) CDMA system. However, if perfect mutual orthogonality between all layers is desired, the maximum possible bit rate is the same as in a single-antenna system, i.e., the advantage of using multiple transmit antennas is sacrificed. On the other hand, relaxing the strict orthogonality constraint causes additional noise within the system (overloaded system). Yet, the use of spreading codes can be beneficial in the case of an unfavorable channel, so as to allow for a separation between a few critical layers [43] (possibly, at the expense of a moderate loss in bit rate).

[9]As shown in [40], four layers are already sufficient to achieve a near-optimum performance with 4-ary modulation and an outer rate-1/2 turbo code.

A promising alternative to DS-CDMA is interleave-division multiple access (IDMA). In contrast to a DS-CDMA system, the orthogonality constraint is completely dropped in IDMA, and hence no spreading code design is required. The individual users or layers are separated solely on the basis of different, quasi-random interleaver patterns. At the transmitter, the information bits are first encoded using a simple low-rate repetition code. Alternatively, a more advanced low-rate channel code may be used. Afterwards, the coded bits (called chips) are permuted using a layer-specific quasi-random block interleaver over multiple code words. In order to separate the individual layers at the receiver, the powerful turbo principle is used. The iterative IDMA receiver uses a Gaussian assumption for the interference stemming from other layers (similar to the PDA detector) and is thus able to efficiently separate the individual layers, even in the case of a significantly overloaded system. In [44], the idea of IDMA was transferred to (single-user) multiple-antenna systems. The ST-IDM scheme in [44] offers an overall bit rate of 1 bit per channel use and is therefore rather a space-time coding scheme. However, by overloading the system the overall bit rate can be increased, so that a multiplexing gain is achieved ('multilayer ST-IDM').[10] Such an (overloaded) ST-IDM system has two major advantages when compared to the conventional BLAST system. First, the number of receive antennas can be smaller than the number of transmit antennas, which is particularly attractive for the downlink of a cellular system, where a simple mobile receiver is desired. Even with a single receive antenna, an overall transmission rate of up to 4 bits per channel use can be achieved with an error performance close to the capacity limit. Second, the ST-IDM scheme is inherently robust to ISI, making it suitable for a large range of wireless applications.

An alternative approach for spatial multiplexing with less receive antennas than transmit antennas was proposed in [45]. It is based on group MAP detection and is applicable for channels without ISI. In [46], a spatial multiplexing scheme called Turbo-BLAST was proposed, which is similar to the (overloaded) ST-IDM scheme. It also uses quasi-random interleaving in conjunction with an iterative receiver structure, so as to separate the individual layers. As in ST-IDM, the number of receive antennas can be smaller than the number of transmit antennas. Moreover, a generalization of Turbo-BLAST to frequency-selective MIMO channels is straightforward.

Spatial multiplexing in the presence of ISI with less receive than transmit antennas can also be performed using a complexity-reduced version of joint detection, e.g., based on the (trellis-based) vector Viterbi algorithm. For example, a (space-time) channel shortening filter can be employed prior to the vector Viterbi algorithm, in order to reduce the effective memory length of the MIMO channel, e.g. [47]. A similar receiver structure has previously been applied in the related field of (single-antenna) co-channel interference (CCI) cancellation, see [48].

[10]In order to accomplish a good error performance, an optimized transmit power allocation strategy is required, however.

III. Spatial Diversity Techniques

In contrast to spatial multiplexing techniques, where the main objective is to provide higher bit rates compared to a single-antenna system, spatial diversity techniques predominantly aim at an improved error performance. This is accomplished on the basis of a diversity gain and a coding gain. Indirectly, spatial diversity techniques can also be used to enhance bit rates, when employed in conjunction with an adaptive modulation/channel coding scheme.

There are two types of spatial diversity, referred to as macroscopic and microscopic diversity. Macroscopic (large-scale) diversity is associated with shadowing effects in wireless communication scenarios, due to major obstacles between transmitter and receiver (such as walls or large buildings). Macroscopic diversity can be gained if there are multiple transmit or receive antennas, that are spatially separated on a large scale. In this case, the probability that all links are simultaneously obstructed is smaller than that for a single link.

Microscopic (small-scale) diversity is available in rich-scattering environments with multipath fading. Microscopic diversity can be gained by employing multiple co-located antennas. Typically, antenna spacings of less than a wavelength are sufficient, in order to obtain links that fade more or less independently.[11] Similar to macroscopic diversity, the diversity gains are due to the fact that the probability of all links being simultaneously in a deep fade decreases with the number of antennas used. A comprehensive survey of the value of spatial diversity for wireless communication systems can be found in [20].

The idea to utilize macroscopic diversity in wireless communication systems is not new. It dates back to the 1970's [49]. Even more so, the use of multiple receive antennas for gaining microscopic diversity (diversity reception) has been well established since the 1950's, e.g. [4]. However, it took until the 1990's before transmit diversity techniques were developed [2].

A. Diversity Reception

Diversity reception techniques are applied in systems with a single transmit antenna and multiple receive antennas. They perform a (linear) combining of the individual received signals, in order to provide a microscopic diversity gain. In the case of frequency-flat fading, the optimum combining strategy in terms of maximizing the SNR at the combiner output is maximum ratio combining (MRC), which requires perfect channel knowledge at the receiver. Several suboptimal combining strategies have been proposed in the literature, such as equal gain combining (EGC), where the received signals are (co-phased and) added up, or selection diversity (SD), where the received signal with

[11] Due to this, the term microscopic diversity was chosen for this type of spatial diversity. This does not imply that the associated performance gains are small. In fact, they can be quite substantial.

the maximum instantaneous SNR is selected (antenna selection), whereas all other received signals are discarded. All three combining techniques achieve full diversity with regard to the number of receive antennas. Optimal combining techniques for frequency-selective fading channels were, for example, considered in [50].

B. Transmit Diversity and Space-Time Codes

The main idea of transmit diversity is to provide a diversity and/or coding gain by sending redundant signals over multiple transmit antennas (in contrast to spatial multiplexing, where independent bit sequences are transmitted). To allow for coherent detection at the receiver, an adequate preprocessing of the signals is performed prior to transmission, typically without channel knowledge at the transmitter. With transmit diversity, multiple antennas are only required at the transmitter side, whereas multiple receive antennas are optional. However, they can be utilized to further improve performance. In cellular networks, for example, the predominant fraction of the overall data traffic typically occurs in the downlink.[12] In order to enhance the crucial downlink it is therefore very attractive to employ transmit diversity techniques, because then multiple antennas are required only at the base station. With regard to cost, size, and weight of mobile terminals this is a major advantage over diversity reception techniques.

An early beginning of transmit diversity schemes was made with two papers that independently proposed a simple technique called delay diversity [51], [52].[13] Another early publication on transmit diversity can be found, e.g. in [54]. However, the value of transmit diversity was only recognized in 1998, when Alamouti proposed a simple technique for two transmit antennas [2]. In the same year, Tarokh, Seshadri, and Calderbank presented their space-time trellis codes (STTCs) [3], which are two-dimensional coding schemes for systems with multiple transmit antennas. While delay diversity and Alamouti's transmit diversity scheme provide solely a diversity gain (more precisely, full diversity with regard to the number of transmit and receive antennas), STTCs yield both a diversity gain and an additional coding gain.

Within the scope of this survey, we will use the generic term *space-time coding scheme* for all transmitter-sided spatial diversity techniques, irrespective of the presence of any additional coding gain. The basic structure of a space-time coding scheme is illustrated in Fig. 3. The preprocessing of the redundant transmission signals is performed by the space-time encoder, which depends very much on the specific scheme under consideration. At the receiver, the

[12]Comparatively large amounts of data may be downloaded from the base station to a single mobile terminal, whereas in the uplink typically little data traffic is required to initiate the download.

[13]Prior to this, there were already publications on transmit diversity schemes that used different modulation parameters at the individual transmit antennas ('modulation diversity'), e.g. [53].

corresponding detection/decoding process is carried out by the space-time decoder.[14] In the delay diversity scheme [51], [52], for example, identical signals are transmitted via the individual antennas, using different delays. This causes artificial ISI, which can be resolved at the receiver by means of standard equalization techniques available for single-antenna systems. In contrast to this, Alamouti's transmit diversity scheme [2] performs an orthogonal space-time transmission, which allows for ML detection at the receiver by means of simple linear processing.

* * * Fig. 3 about here * * *

STTCs [3] may be interpreted as a generalization of trellis-coded modulation to multiple transmit antennas. Optimum decoding in the sense of MLSE can be performed using the Viterbi algorithm. On the basis of simulation results, it was shown in [3] that STTCs offer an excellent performance that is within 2-3 dB of the outage capacity limit. However, this performance comes at the expense of a comparatively high decoding complexity. Motivated by the simple receiver structure of [2], orthogonal space-time block codes (OSTBCs) were introduced in [55], which constitute a generalization of Alamouti's scheme to more than two transmit antennas. OSTBCs are designed to achieve full diversity with regard to the number of transmit and receive antennas. In contrast to STTCs, OSTBCs do not offer any additional coding gain.

STTCs and OSTBCs can be combined with different diversity reception techniques at the receiver side. For example, the performance of STTCs and OSTBCs combined with antenna (subset) selection techniques at the receiver was examined in [56] and [57], respectively.

C. Optimized STTCs and OSTBCs

In [3], general design criteria were derived for STTCs that guarantee a maximum diversity advantage and allow for an optimization of the coding gain (both for high SNR values). These design criteria depend on the number of transmit and receive antennas as well as on the cardinality of the employed modulation scheme. Unfortunately, 'good' STTCs can not be constructed analytically, but have to be found by means of a computer search. An efficient design procedure for STTCs, which is based on simple lower and upper bounds on the coding gain, was presented in [58]. In [3], some examples of optimized STTCs were stated, for certain modulation schemes and certain numbers of transmit antennas.[15] Further examples of optimized STTCs, sometimes based on (slightly) modified design criteria, can be found, e.g., in [58]-[60]. A tight bound on the error performance of STTCs was presented in [61].

[14] All space-time coding schemes discussed in the sequel were designed for frequency-flat fading.

[15] The STTCs constructed in [3] provide the best trade-off between data rate, diversity advantage, and trellis complexity. Specifically, the codes do not cause any rate loss compared to an uncoded single-antenna system.

OSTBCs are based on the mathematical theory of (generalized) orthogonal designs, which dates back to the 1890s. Orthogonal designs are a special class of orthogonal matrices. In general, the use of OSTBCs causes a rate loss when compared to an uncoded single-antenna system. For the case of a real-valued modulation scheme, full-rate (and delay-optimal) OSTBCs for systems with two to eight transmit antennas could be established in [55] (partly based on generalized orthogonal designs). Given a complex-valued modulation scheme, however, the only full-rate OSTBC is Alamouti's transmit diversity scheme [2] for two transmit antennas. In [55] it was shown that half-rate OSTBCs for complex-valued modulation schemes can be constructed for any number of transmit antennas. However, to find OSTBCs with higher rates (and moderate decoding delay) is, in general, not a trivial task. A systematic design method for high-rate OSTBCs was presented in [62], for complex-valued modulation schemes and arbitrary numbers of transmit antennas. Further examples of optimized OSTBCs for different numbers of transmit antennas can be found in [63], [64]. A performance analysis of OSTBCs based on channel capacity and the resulting average symbol error rate can be found in [65] and [66], respectively.

D. Other Families of Space-Time Codes

Since the advent of STTCs and OSTBCs in 1998, various other families of space-time codes have been proposed in the literature. In [67] the family of square-matrix embeddable STBCs was introduced, which includes some of the OSTBCs proposed in [55] as special cases. Similar to OSTBCs, square-matrix embeddable STBCs allow for ML detection at the receiver by means of (generalized) linear processing. A family of non-orthogonal full-rate linear STBCs, called diagonal algebraic STBCs, was constructed in [68]. Diagonal algebraic STBCs provide full transmit diversity and allow for efficient ML detection by means of the sphere decoding approach. Another non-orthogonal full-rate STBC for two transmit antennas, constructed based on number theory, was presented in [69]. For more than one receive antenna, this STBC provides an improved coding gain compared to Alamouti's transmit diversity scheme [2]. In [70], STBCs based on linear constellation precoding were proposed, which provide full rate and full diversity for any number of transmit antennas and perform superior to OSTBCs. For decoding, a sphere decoding approach as well as suboptimal alternatives were considered in [70]. An alternative idea for constructing full-rate STBCs for complex modulation schemes and more than two antennas was pursued in [71]. Here the strict constraint of perfect orthogonality was relaxed in favor of a higher data rate. The resulting STBCs are therefore referred to as quasi-orthogonal STBCs. Due to the relaxed orthogonality constraint, however, quasi-orthogonal STBCs typically offer reduced diversity gains compared to OSTBCs. In addition to the above examples, many other families of STBCs can be found in the literature, some of which were presented in [72]-[74].

In [75] recursive STTCs were considered. In particular, the parallel concatenation of two identical recursive STTCs

was studied. Here the encoder structure was inspired by the original turbo code proposed by Berrou, Glavieux, and Thitimajshima in 1993.[16] Further examples of concatenated space-time codes can be found, e.g., in [76], [77]. Recursive STTCs are also well suited for a serial concatenation with an outer channel code (with iterative detection at the receiver). In [78], the family of super-orthogonal STTCs was introduced and was later extended in [79] to a larger set of modulation schemes. Super-orthogonal STTCs constitute a systematic combination of OSTBCs with the concept of set partitioning and offer full-rate transmission for two transmit antennas. Moreover, they allow for a trade-off between rate and coding gain. In [80], the concept of super-orthogonal STTCs was extended using quasi-orthogonal STBCs as building blocks. In particular, a full-rate super-quasi-orthogonal STTC for four transmit antennas was constructed. In [81], another class of STTCs called diagonal block space-time codes was proposed. These STTCs are characterized by a special encoder structure (a non-binary block encoder followed by a diagonal space-time transmission scheme), which allows for a systematic design procedure. Further families of STTCs were, for example, presented in [82], [83].

All of the above space-time coding schemes were designed for systems employing linear modulation schemes, such as phase-shift-keying (PSK) modulation or quadrature-amplitude modulation (QAM). Non-linear continuous-phase modulation (CPM) is attractive for practical systems, because its compact spectrum and constant envelope property allows for power-efficient transmitters employing inexpensive amplifiers. Motivated by this fact, space-time coding schemes for CPM systems were, for example, investigated in [84]-[86].

E. High-Rate Space-Time Transmission Schemes

As indicated above, 'conventional' space-time codes such as STTCs and (O)STBCs offer at most the same data rate as an uncoded single-antenna system. In contrast to this, several high-rate space-time transmission schemes with a normalized rate greater than one have been proposed in the literature. These build a bridge between space-time coding and spatial multiplexing techniques.

Some of these transmission schemes explicitly combine ideas of certain space-time codes and the BLAST scheme. For example, high-rate space-time codes that are linear in space and time, so-called linear dispersion codes, were proposed in [87]. Linear dispersion codes provide a flexible trade-off between space-time coding and spatial multiplexing. At the transmitter, the information bit sequence is first split into multiple parallel sub-sequences, similar to spatial multiplexing. Then, linear combinations (in time and in space) of these sub-sequences are simultaneously

[16]Turbo codes, also called parallel concatenated codes (PCCs), are among the most powerful channel codes for additive-white-Gaussian-noise (AWGN) channels.

transmitted. Due to the linear structure of the scheme, detection is very similar to spatial multiplexing schemes, i.e., in principle, any of the receiver structures discussed in Section II-A can be used. At the same time, linear dispersion codes offer a major advantage over spatial multiplexing systems such as the BLAST scheme. They can handle any configuration of transmit and receive antennas, i.e., they do not require a certain minimum number of receive antennas. Moreover, in comparison to an uncoded V-BLAST system they can accomplish an additional coding gain. Further high-rate space-time transmission schemes that combine ideas of space-time coding and the BLAST scheme can be found, e.g., in [88]-[90].

A completely different approach to construct high-rate space-time transmission schemes for MIMO systems is to take channel codes, which are known to provide an excellent performance for single-antenna systems, and to generalize them to the case of multiple antennas. For example, the design of repeat-accumulate (RA) codes for MIMO systems was considered in [91]. In particular, it was shown that RA codes designed for MIMO systems are superior to parallel concatenated codes (PCCs) designed for MIMO systems. As an alternative, one can use low-density parity-check (LDPC) codes and extend them to multiple antennas. LDPC codes designed for MIMO systems achieve a similar performance as RA codes. Like PCCs, RA codes and LDPC codes can be decoded in an iterative fashion, which offers a near-optimum performance at a moderate receiver complexity. In particular, given a certain target SNR value for which convergence of the iterative receiver is desired, the codes can be optimized such that they operate closely to the corresponding capacity limit. This optimization can, for example, be performed by means of the EXIT chart method, which is widely used, in order to design turbo- and turbo-like transmission schemes. Another class of high-rate space-time transmission schemes, which fits into the framework of iterative detection, are the schemes based on IDMA [44] discussed in Section II-D.

A rather new branch of work has originated from a paper published by Zheng and Tse in 2003 [6]. In this paper, it was shown that for any space-time transmission scheme there is a fundamental trade-off between diversity gain and multiplexing gain. In this context, the multiplexing gain was defined as the asymptotic slope of the achieved rate as a function of the (logarithmized) SNR.[17] According to this definition, an adaptive space-time transmission scheme is required, in order to achieve a multiplexing gain greater than zero, because the scheme must be able to scale the transmission rate with growing SNR. Such an adaptive space-time transmission scheme might, for example, be constructed using an STTC or an OSTBC in conjunction with a series of symbol alphabets with growing cardinalities. In fact, for $M=2$ transmit antennas and $N=1$ receive antenna it was shown in [6] that

[17]This definition of the multiplexing gain is very similar to the widely-used definition of diversity order. The diversity order achieved by a space-time transmission scheme is typically defined as the (negative) slope of the frame or bit error rate at high SNRs (in a log-log plot).

Alamouti's transmit diversity scheme [2] achieves the optimal diversity-multiplexing trade-off (however, not for $N>1$ receive antennas). Other space-time transmission schemes that approach the optimal diversity-multiplexing trade-off were proposed in [92]-[94]. Further high-rate space-time transmission schemes not mentioned above can, for example, be found in [95], [96].

F. Outer Channel Codes

In order to further improve the performance of space-time coded MIMO systems, the space-time encoder can be concatenated with an outer channel encoder. This is of particular interest for OSTBCs, which only offer a diversity gain, but no built-in coding gain. A comprehensive survey of such concatenated space-time transmission schemes can be found in [17]. The main focus of [17] is on OSTBCs as inner space-time codes concatenated with different outer channel coding schemes, such as convolutional codes, turbo codes, and (turbo) trellis-coded modulation, among others. Examples of concatenated schemes with inner STTCs are also considered. In all cases, the receiver structure considered in [17] consists of an inner soft-input soft-output (SiSo) space-time decoder (based on the symbol-by-symbol MAP criterion) followed by an outer channel decoder. Alternatively, a turbo-type receiver structure can be employed, where a SiSo space-time decoder and a SiSo channel decoder exchange soft information in an iterative fashion. Examples of space-time coded MIMO systems with outer channel codes (and iterative or non-iterative receiver structures) can be found in [97]-[99].

G. Channels with Intersymbol Interference

All of the above space-time coding schemes were designed for frequency-flat fading, i.e., for channels without ISI. However, as discussed in Section II-C, this assumption might not be valid in a practical system. If no counter measures are employed, ISI can cause a substantial performance loss, compromising the diversity and coding gains achieved by space-time coding. For example, OSTBCs lose their orthogonal property in the presence of ISI, which leads to significant self-interference [100]. Similarly, STTCs suffer from decreased coding gains if ISI is neglected at the receiver (while the diversity advantage is maintained) [101]. As in the case of spatial multiplexing schemes, there are basically three different options to design space-time coding schemes for MIMO channels with ISI. First, one might use a space-time code originally designed for channels without ISI and mitigate the effects of ISI at the receiver using appropriate equalization techniques. Alternatively, one might employ the space-time code in conjunction with a multicarrier scheme (e.g. OFDM), so as to circumvent the problem of ISI. Finally, one might refine or generalize existing space-time codes such that they are suited for ISI channels.

Equalization concepts for OSTBCs were, for example, proposed in [21], [97], [100], [102], [103] (with focus on

Alamouti's transmit diversity scheme [2]). Joint equalization and detection concepts for STTCs in the presence of ISI were presented, e.g., in [102], [104]. The combination of STBCs with MIMO-OFDM was, for example, considered in [19], [105], [106]. MIMO-OFDM systems employing STTCs were considered, e.g., in [16], [107]. In addition to the spatial and the temporal dimension, MIMO-OFDM systems offer a third dimension, namely the frequency domain. Correspondingly, an interesting alternative to space-time coding in MIMO-OFDM systems is to perform two-dimensional coding in space and frequency (i.e., across the individual sub-carriers) or three-dimensional coding in space, time, and frequency. Depending on the properties of the wireless channel, space-frequency (SF) codes or space-time-frequency (STF) codes may offer larger diversity gains than pure space-time coding. Moreover, SF codes sometimes offer certain implementation advantages over space-time coding techniques. SF codes for MIMO-OFDM systems were, for example, considered in [108], [109]. Many SF codes that can be found in the literature were, in fact, constructed using existing STBCs or STTCs as building blocks. Design and performance criteria for STF codes were, for example, presented in [110]-[112].

In addition to this, several papers have proposed generalizations or refinements of existing space-time coding techniques, so as to enable their use for MIMO channels with ISI. For example, optimized versions of delay diversity for ISI channels were suggested in [100], [113]. Similarly, several papers have proposed optimized or generalized STTCs for MIMO channels with ISI, e.g. [114]. An interesting generalization of Alamouti's transmit diversity scheme [2] to ISI channels, which is based on a time-reversal (TR) block-encoding structure, was presented in [115]. Similar to Alamouti's transmit diversity scheme, simple linear processing is employed at the receiver, which enables subsequent equalization by means of standard algorithms designed for single-antenna systems. An extension to more than two transmit antennas is also possible. A similar transmit diversity scheme for two transmit antennas was also considered in [116]. Moreover, an alternative STBC design for ISI channels was presented in [117].

H. Differential and Non-Coherent Space-Time Transmission Schemes

All of the space-time coding techniques discussed above require some form of channel knowledge at the receiver side. In contrast to this, so-called differential/non-coherent[18] space-time transmission schemes do not require any channel knowledge and are thus of particular interest for practical MIMO systems. Differential space-time transmission techniques can be interpreted as an extension of corresponding single-antenna schemes (e.g., based on differential phase-shift-keying (DPSK) modulation). One of the first differential space-time transmission schemes was proposed in [118]. It is based on Alamouti's transmit diversity scheme [2] and can be employed in systems with two transmit

[18]Purely non-coherent transmission schemes do not employ a differential encoder at the transmitter side.

antennas. Shortly afterwards, two alternative schemes were presented in [119] and [120], which can be employed for any number of transmit and receive antennas. Since then, a considerable number of differential and non-coherent space-time transmission/reception schemes has been proposed in the literature, see e.g. [73], [121]-[124]. Similar to the case of a single-antenna system, differential space-time transmission schemes with conventional differential detection at the receiver lead to a performance loss of about 3 dB, when compared to coherent reception. This performance loss can, for example, be compensated by employing a multiple-symbol differential detection (MS-DD) scheme or a decision-feedback differential detection (DF-DD) scheme at the receiver [122].

All of the above differential/non-coherent space-time transmission schemes were designed for frequency-flat fading channels. In comparison, little work has been done, in order to design corresponding schemes for ISI channels. One option is again to combine the above differential space-time transmission schemes with MIMO-OFDM, see for example [125]. As an alternative, novel differential schemes for MIMO-OFDM were, for example, proposed in [126], [127] employing coding in space, time, and frequency. Another option is to use space-time coding techniques suitable for ISI channels as building blocks. For example, differential schemes that are based on the TR-STBC [115] for two transmit antennas were considered in [125], [128].

I. Practical Aspects

In practical implementations, various detrimental effects can arise that are often not taken into account in the initial design of space-time transmission schemes, such as

- ISI effects (as discussed in Section III-G)
- time-variance of the wireless channel (due to motion of transmitter or receiver)
- carrier frequency offsets (CFOs) between transmitter and receiver (caused by the up-/down-conversion process)
- Inaccurate channel knowledge at the receiver (e.g., due to a low SNR or a rapidly varying channel)
- Spatial correlation effects (due to insufficient antenna spacings or a lack of scattering from the physical environment).

Several papers have studied the impact of such effects on the performance of different space-time transmission schemes. For example, the influence of a time-varying channel and non-perfect channel knowledge on the performance of OSTBCs was investigated, e.g., in [100], [129] (with focus on Alamouti's transmit diversity scheme [2]). Similar investigations for STTCs, as well as improved design criteria, were presented in [3], [130]. The impact of CFOs on the performance of STTCs was, for example, investigated in [131]. Finally, the impact of spatial correlation effects on the performance of STBCs and STTCs was considered in [21], [114], [131], [132]. Further

studies concerning practical aspects of MIMO systems can be found, e.g., in [16], [18], [20], [32], [133].

Another important issue is that the performance gains actually achieved in a practical MIMO system might be smaller than promised in theory, because implementing an optimal transmitter/receiver strategy might be too complex so that one has to resort to suboptimal solutions. For example, the impact of a reduced-state trellis-based equalizer on the performance of the delay diversity scheme [51], [52] was investigated in [100].

J. Cooperative Diversity Schemes

The concept of multiple-antenna systems can be transferred to so-called cooperative wireless networks, where multiple distributed transmitting or receiving nodes cooperate in terms of a joint transmission/reception strategy. In fact, cooperative wireless networks have recently gained considerable attention. On the one hand, cooperating network nodes build the basis of ad-hoc networks, which are envisioned for sensor networks, public safety communication networks, or tactical networks for military applications. On the other hand, cooperating nodes also promise benefits for hierarchical types of networks, such as cellular networks.

Through cooperation, network nodes are able to share their antennas and can thus establish a virtual antenna array. By this means the cooperating nodes, possibly equipped with just a single antenna, can enjoy some of the benefits offered by conventional MIMO systems with co-located antennas. Examples include cooperative diversity schemes, where multiple network nodes share their transmit antennas by employing a distributed space-time-coding scheme, e.g., [134]-[137]. The design of efficient cooperative diversity schemes is currently a hot topic and poses many challenging problems calling for future work.

IV. Smart Antennas and Beamforming Techniques

Multiple antennas offer not only increased data rates and improved error rates. They can also be utilized, in order to improve the SNR at the receiver and to suppress co-channel interference (CCI) in a multiuser scenario, thus improving SINR at the receiver. Both goals can be achieved by means of beamforming techniques.

A. Beamforming

Beamforming can be interpreted as linear filtering in the spatial domain. Consider an antenna array with N antenna elements, which receives a signal from a certain direction. Due to the geometry of the antenna array, the impinging radio-frequency (RF) signal reaches the individual antenna elements at different time instants, which causes phase shifts between the different received signals. However, if the underlying complex baseband signal is assumed to be a narrowband signal, it will not change during these small time differences. If the direction of the impinging

signal is known, the phase differences of the RF signals can be compensated by means of phase shifters or delay elements, before the received signals are added up. As a result, the overall antenna pattern of the phased array will exhibit a maximum in the direction of the impinging signal. This principle is called conventional beamforming in the literature [5].

If only the phases of the received signals are manipulated, the shape of the overall antenna pattern remains unchanged, and solely an angular shift results. Correspondingly, conventional beamforming is equivalent to a mechanical rotation of the antenna array (mechanical beam steering). If the amplitudes of the received signals are also scaled before the combining step, it is possible to modify also the shape of the overall antenna pattern.[19] In particular, an antenna array with N antenna elements provides $(N-1)$ degrees of freedom, i.e., altogether $(N-1)$ angles can be specified for which the overall antenna pattern is supposed to exhibit either a maximum or a minimum (a 'null').

If the above narrowband assumption for the complex baseband signal is not met, the baseband signal can change during time intervals that are as small as the relative delays between the received RF signals. Thus, the individual antenna elements will observe different versions of the complex baseband signal. In this case, broadband beamforming techniques are required that combine narrowband beamforming (i.e., spatial filtering) with time-domain filtering, e.g., in the form of a two-dimensional linear finite-impulse-response (FIR) filter, see e.g. [5].

B. Array Gain

In a wireless communication scenario, transmitted signals often propagate via just a few distinct paths, for example via a line-of-sight path between transmitter and receiver and/or via paths that are associated with significant reflectors and diffractors in the environment (such as large buildings or mountains). If the directions of these dominant propagation paths are known at the receiver side, beamforming techniques can be applied, in order to adjust the receiver beam pattern such that it has a high directivity towards the dominant angles of reception. By this means, significant SNR gains can be accomplished in comparison to an antenna array with an omni-directional beam pattern.[20] Such SNR gains due to beamforming techniques are often called antenna gains or array gains in the literature. Similarly, if the directions of the dominant propagation paths are known at the transmitter side, the

[19]Mathematically, the received signals are weighted by complex-valued antenna weights representing the phase shifts and the scaling of the individual signal amplitudes. Interestingly, these weighting operations (followed by the linear combining step) are very similar to those performed by diversity reception techniques in the baseband domain.

[20]When multiple receive antennas are employed, an SNR gain is always obtained, because the overall average received power is increased. However, SNR gains due to beamforming come on top of that.

transmit power can be concentrated within the corresponding angular regions and is not wasted for directions that do not contribute to the received signal.

Beamforming techniques can also be useful, in order to reduce the delay spread of the physical channel caused by multipath signal propagation. To this end, the transmitter or receiver beam pattern is adjusted such that it exhibits nulls in the directions of dominant distant reflectors. Correspondingly, echoes with excessively large delays are eliminated from the received signal [5]. The basic principle of beamforming is illustrated in Fig. 4. In the considered example, a beamformer is employed both at the transmitter and at the receiver side.

* * * Fig. 4 about here * * *

In a practical system, the directions of dominant propagation paths must be estimated. This can, for example, be done by means of the well-known MUSIC algorithm or the ESPRIT algorithm. Moreover, when transmitter or receiver are moving, the antenna patterns must be updated on a regular basis. Such adaptive antenna arrays are often called smart antennas or software antennas in the literature. Due to the required equipment and processing power, however, the use of smart antenna technologies is currently limited to fixed stations, such as base stations, or mobile stations that are fixed on vehicles. Yet, for future wireless communication systems it is anticipated that smart antennas will also be feasible for hand-held devices employing small phased arrays fabricated by microstrip technology [5].

C. Co-Channel Interference Suppression and SDMA

Smart antennas are also beneficial in multiuser scenarios, in order to suppress co-channel interference (CCI). Again, both transmitter- and receiver-sided beamforming techniques can be employed for mitigating CCI. When transmitting, each user can adjust his beam pattern such that there are nulls in the directions of other (receiving) co-channel users and a high directivity towards the desired direction(s) of transmission. By this means, the SINR for the other co-channel users is improved as well as the SNR at the desired receiver. Similarly, when receiving each user can adjust his beam pattern such that directions of other (transmitting) co-channel interferers are nulled (or at least attenuated) and desired directions of reception are enhanced. By this means, each user can improve his own received SINR.[21] The use of smart antennas for CCI cancellation offers the opportunity to accommodate multiple co-channel users within the same frequency band. This concept is referred to as space-division multiple

[21]In the case of exact nulling, the directions of all co-channel interferers must be known. Alternatively, it is also possible to optimize the SINR at the combiner output without explicit knowledge of the directions of all co-channel interferers [5]. For example, the well-known Capon beamformer requires solely the direction of the desired source signal.

access (SDMA). For cellular networks, for example, it was shown that network capacity in terms of users per cell can be enhanced significantly by means of SDMA techniques [138].

The concept of antenna arrays with adaptive beam patterns is not new. It has its origins in the field of radar and aerospace technology, especially in applications such as target tracking and high-resolution remote sensing. Early publications on the use of antenna arrays for interference suppression date back to the 1960's [139]. Similarly, publications on adaptive beamforming algorithms can be traced back to the 1970's [140]. However, intensive research on smart antenna techniques for wireless communication systems started only in the 1990's, e.g. [141]. A detailed overview concerning the use of adaptive antenna arrays in wireless communication systems is provided in [5].

D. Combinations with Spatial Multiplexing and Spatial Diversity Techniques

Smart antenna techniques employed for array gains or CCI suppression can readily be combined with spatial multiplexing or spatial diversity techniques. However, in order to achieve a good overall performance, the beamforming scheme should be adapted to the underlying spatial diversity/spatial multiplexing technique. MIMO transmission schemes that combine ideas of beamforming with spatial multiplexing or spatial diversity techniques were, for example, considered in [142] and [138], [143]-[145], respectively. A particularly simple solution is to build a hybrid system, where a switching between the different techniques is possible. At any time, the best transmission strategy can thus be chosen, depending on the current properties of the wireless channel and the requested quality of service (QoS).

E. Limited Feedback Schemes

Generalized transmit beamforming techniques using (possibly imperfect) full instantaneous channel knowledge at the transmitter side were, for example, considered in [7], [142], [143], [146]. Since in practice full channel knowledge at the transmitter might be difficult to acquire, the use of statistical channel knowledge at the transmitter side was investigated, e.g., in [144], [145], [147]. Statistical channel knowledge can be gained quite easily in practical systems, for example off-line through field measurements, ray-tracing simulations or based on physical channel models, or on-line based on long-term averaging of the channel coefficients. Optimal statistical transmit power allocation schemes for spatially correlated MIMO systems were, for example, derived in [145], [147] (with regard to different optimization criteria).

An alternative is to feed back partial (instantaneous) channel state information from the receiver to the transmitter. Here, the challenge is to choose the channel state information feedback such that it can be represented by just a few bits (so as to save resources on the reverse link), but can still efficiently be utilized at the transmitter side, to

provide significant performance improvements. Several such limited-feedback schemes have been proposed in the literature, see e.g., [148], [149]. A particularly simple class of (limited) feedback schemes are MIMO transmission schemes that employ some sort of antenna (subset) selection technique at the transmitter side, see e.g. [150].

* * * Fig. 5 about here * * *

V. Alternative Categorizations of Multiple-Antenna Techniques

As discussed above, transmission and reception techniques for multiple-antenna systems can roughly be divided into spatial multiplexing techniques, spatial diversity techniques, and smart antenna techniques (see Fig. 5 for an overview of the various techniques discussed in the previous sections). In addition to this classification, there are other options for categorizing multiple-antenna techniques:

- *SIMO, MISO, and MIMO techniques*

  Transmission techniques for multiple-antenna systems can be distinguished according to the number of transmit and receive antennas used. Techniques that only utilize multiple receive antennas (such as diversity reception schemes [4]) are referred to as single-input multiple-output (SIMO) techniques in the literature. Similarly, techniques that utilize multiple transmit antennas only are called multiple-input single-output (MISO) techniques. Finally, techniques that require multiple antennas at both ends of the wireless link (e.g., spatial multiplexing techniques such as the BLAST scheme [1]) are called multiple-input multiple-output (MIMO) techniques.

- *Narrowband and broadband techniques*

  Transmission techniques that are designed for frequency-flat fading channels are called narrowband techniques. For example, OSTBCs [55] or the original BLAST scheme [1] are typical narrowband techniques. In contrast to this, transmission techniques that are suitable for frequency-selective fading channels (e.g., multiple-antenna techniques that are based on OFDM) are referred to as wideband or broadband techniques.

- *Open-loop, closed-loop, and non-coherent techniques*

  Transmission techniques for multiple-antenna systems that require no channel knowledge at the transmitter side are referred to as open-loop techniques, because no feedback of channel state information from the receiver to the transmitter is required. For example, space-time coding techniques and spatial multiplexing techniques such as the BLAST scheme [1] are typical open-loop techniques. In contrast to this, transmission techniques that require full or partial channel knowledge at the transmitter (such as the transmitter-sided beamforming techniques [5] or the limited feedback schemes [148], [149] discussed in Section IV) are called closed-loop

techniques. Finally, transmission techniques that require neither channel knowledge at the transmitter nor at the receiver side are called non-coherent techniques. For example, the differential space-time transmission techniques [118]-[120] discussed in Section III-H are an important class of non-coherent multiple-antenna techniques.

- *Co-located and distributed MIMO systems*

  In a conventional MIMO system, the antennas at transmitter and receiver are part of some sort of antenna array (co-located MIMO system). In contrast to this, antennas can also be spatially distributed on a large scale (distributed MIMO system). Examples include virtual MIMO systems employing a distributed space-time coding scheme [134]-[137], cf. Section III-J.

- *Single-user and multiuser MIMO techniques*

  Finally, one can distinguish between single-user and multiuser MIMO techniques, either for broadcast scenarios or for multiple-access scenarios.

The above discussion has shown that the various multiple-antenna techniques available in the literature are quite diverse, in terms of their specific requirements and objectives. In order to provide a final overview, Table I summarizes the prerequisites and benefits of selected multiple-antenna techniques discussed in the previous sections. As earlier, the different schemes are divided into spatial multiplexing techniques ('SM'), spatial diversity techniques ('SD'), and smart antenna techniques ('SA'). In particular, Table I displays whether (i) multiple antennas are required at the transmitter ('Tx') and/or the receiver ('Rx'); (ii) channel state information ('CSI') is required at the transmitter and/or the receiver; (iii) the system bandwidth ('BW') is required to be narrow ('N', frequency-flat fading) or not ('W', frequency-selective fading); (iv) the receiver complexity is typically rather 'low', 'moderate' or 'high'; (v) the achieved gains are multiplexing gains ('MUX'), diversity gains ('DIV'), additional coding gains ('COD'), or antenna gains ('ANT').

VI. Conclusions

This literature survey has offered a comprehensive overview of the field of multiple-antenna techniques for wireless communication systems, which has evolved rapidly during the last ten years. Among other topics, transmitter and receiver structures for spatial multiplexing, spatial diversity, and smart antenna techniques were addressed, outer channel coding schemes were discussed, and solutions for frequency-selective fading channels as well as other practical aspects were stated. Finally, alternative categorizations of multiple-antenna techniques were considered. Although an enormous amount of papers on multiple-antenna systems has already been published, there are still

interesting open problems that deserve further investigation, especially in the area of cooperative diversity schemes, closed-loop MIMO techniques, and multiuser scenarios.

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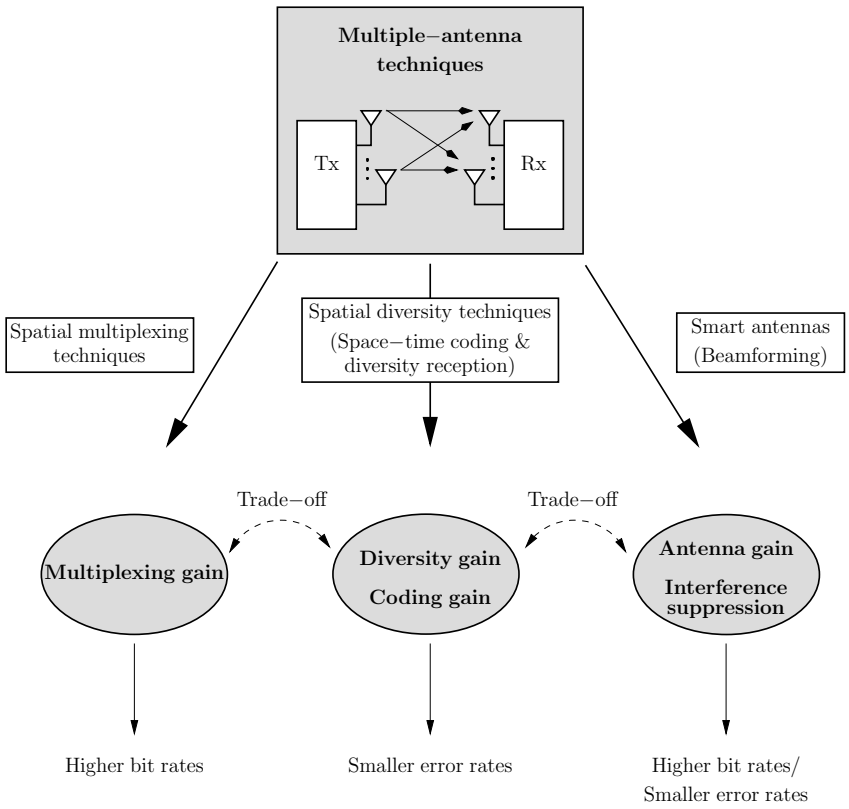

Fig. 1. Benefits of multiple-antenna techniques for wireless communications.

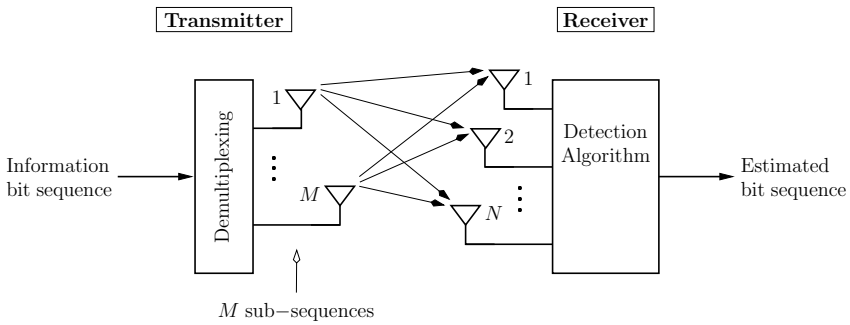

Fig. 2. Basic principle of spatial multiplexing.

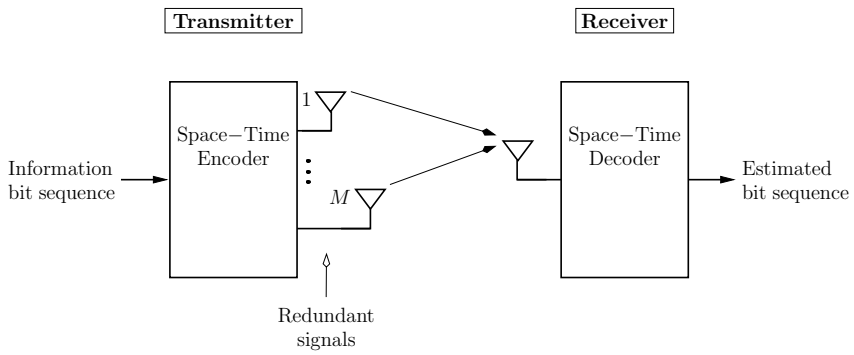

Fig. 3. Basic principle of space-time coding.

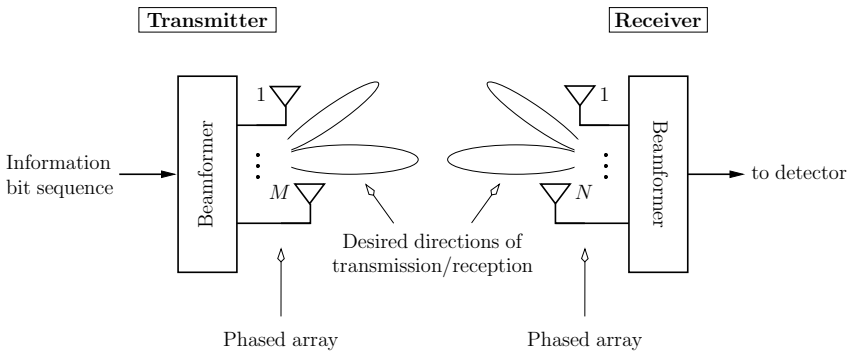

Fig. 4. Basic principle of beamforming.

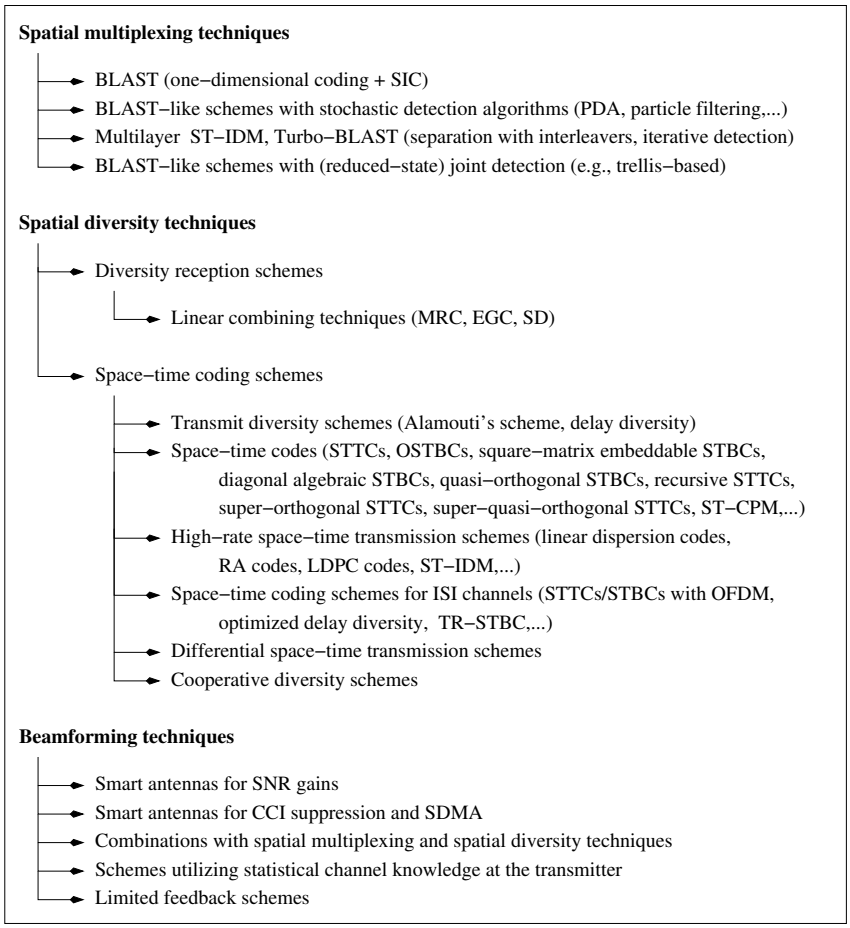

Fig. 5. Overview of multiple-antenna techniques.

TABLE I

PREREQUISITES AND BENEFITS OF SELECTED MULTIPLE-ANTENNA TECHNIQUES

Scheme (with example references)		**Prerequisites**				**Benefits**
		Mult. Ant.	**CSI**	**BW**	**Rx Compl.**	
SM	V-BLAST [22]	Tx & Rx ($N \geq M$)	Rx	N	moderate	MUX
	D-BLAST [1]	—- ” —-	—- ” —-	N	moderate	MUX & DIV
	Turbo-BLAST [46]	Tx & Rx ($N < M$)	—- ” —-	N/W	moderate	MUX & DIV
SD	Diversity reception (MRC) [4]	Rx	Rx	N	low	DIV
	Alamouti’s scheme [2] / OSTBCs [55]	Tx (Rx optional)	—- ” —-	N	low	DIV
	Delay diversity [51], [52]	—- ” —-	—- ” —-	N	moderate/high	DIV
	STTCs [3]	—- ” —-	—- ” —-	N	high	DIV & COD
	Quasi-orthogonal STBCs [71]	—- ” —-	—- ” —-	N	low	DIV
	Super-orthogonal STTCs [78], [79]	—- ” —-	—- ” —-	N	moderate/high	DIV & COD
	Linear dispersion codes [87]	—- ” —-	—- ” —-	N	moderate	DIV and/or MUX
	ST-IDM [44]	—- ” —-	—- ” —-	N/W	moderate	DIV
	SF/ STF codes [108]-[112]	—- ” —-	—- ” —-	W	varies	DIV (& COD)
	TR-STBC [115]	—- ” —-	—- ” —-	W	moderate/high	DIV
	Differential ST schemes [118]-[120]	—- ” —-	no CSI	N	varies	DIV (& COD)
SA	Rx beamforming [5]	Rx	Rx	N/W	low	ANT
	Tx beamforming [5]	Tx	Tx & Rx	N/W	low	ANT
	Limited feedback schemes [148], [149]	Tx (& Rx)	Tx (lim.) & Rx	N	varies	ANT & DIV or MUX