Smart Antennas:
State of the Art

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Abstract: *Aim of this contribution is to illustrate the state of the art of smart antenna research from several perspectives. The bow is drawn from transmitter issues via channel measurements and modeling, receiver signal processing, network aspects, technological challenges towards first smart antenna applications and current status of standardization. Moreover, some future prospects of different disciplines in smart antenna research are given.*

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Introduction

Smart Antennas (SAs) were born in the early 1990s when well-developed adaptive antenna arrays, originating from radar, were introduced into mobile communications. SAs are also refered as MISO (Multiple Input Single Output) or SIMO (Single Input Multiple Output) systems. In the mid nineties multi-antenna techniques on both sides, i.e., at the receiver and the transmitter—the so-called MIMO systems (Multiple Input Multiple Output)—have been theoretically investigated with rather impressive results, especially in terms of remarkable data rate improvements.

Hence, more than a decade ago the research on multi-antenna techniques began and a large amount of scientific contributions have been published on numerous conferences and in scientific journals. The aim of this article is to summarize the state of the art in smart antennas and MIMO systems from different perspectives and by well-chosen highlights, i.e., transmitter and receiver algorithms, channel measurements and models, network aspects, technology issues and finally SA/MIMO applications and current standardization efforts.

Transmitter

The area of transmitter design and optimisation for MIMO systems has experienced an unprecedented growth in the signal processing and communications research communities. As such, this section does not attempt to summarise the uncountable results in the area that range from information theoretical to prototype implementation, but simply to outline a few specific achievements which we believe are particularly significant.

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Linear Joint Transmit-Receive Design

One of the issues that has always received attention is the design of linear transceivers optimised for a variety of Quality of Service (QoS) criteria when Channel State Information (CSI) is available at both sides of the link. This is often the case in Time Division Duplex (TDD) systems in which channel reciprocity can be applied or under the provision of an appropriate feedback link.

It can be shown that the design efforts for the linear transceiver design in this case concentrate exclusively on the transmitter since the optimal linear receiver can be shown to be independent of the optimisation criterion. The linear receiver simply follows the Minimum Mean Squared Error design (also termed the Wiener filter) possibly incorporating the additional Zero Forcing constraint.

Traditionally, MIMO transmitters were designed based on very simple cost functions, as for example the Mean Squared Error, and more sophisticated QoS requirements demanded specific designs. These schemes were particularly difficult to obtain when involved non-convex or matrix valued variables. Recently, Palomar [1] showed how to solve these problems in an optimal way for the family of Schur-concave and Schur-convex cost functions. Although this is a quite general result, one can think of some interesting QoS requirements that fall out of these categories, such as the minimisation of the average BER when different constellations are used. Reference [2] generalises the previous results to embrace any arbitrary cost function as quality criterion. When the function is convex, the originally complicated nonconvex problem with matrix valued variables can be reformulated as a simple convex problem with scalar variables. This simplified problem can then be addressed under the framework of convex optimisation theory, accommodating and easily solving a great variety of design criteria.

Space-Time Coding Under Imperfect Channel Knowledge at the Transmit Side

Another important situation very often encountered in practice is the one in which the transmitter has access to some limited or imperfect channel state information. Conventional space-time codes do not need any channel knowledge at the transmit side, and this is a clear advantage given the difficulties of acquiring such knowledge, but it may also be a substantial drawback since CSI, when available at the transmit side, can be used to improve performance. A recent work [3] develops the concept of channel side information dependent codes. The conventional way of exploiting the CSI at the transmit side is by the use of beamforming. However, the resulting rank one type of transmission inherent to beamforming (which can be interpreted as assigning only a single preferable direction) is too restrictive when there are imperfections in the channel knowledge. The emitted energy instead should be spread out over several directions, much like in conventional space-time coding. This naturally leads to the concept of channel side information dependent space-time codes, where the codeword matrices depend on the channel side information and the possibly imperfect channel knowledge is taken into account already at the design stage. The idea is to make use of the complementary strengths of both transmission methodologies. Conventional space-time codes are designed to operate without any channel knowledge and hence provide the system with a basic level of performance in the absence of reliable channel state information at the transmitter. Beamforming, on the other hand, is advantageous when the channel knowledge is reliable. Channel side information dependent codes try to combine in an optimal manner the advantages of both schemes.

Diversity-Multiplexing Trade-off Curve for MIMO Channels

From a more theoretical standpoint, and in order to provide an analytical tool for comparison among MIMO systems the concept of diversity-multiplexing trade-off has recently been defined. Multiple antennas have been extensively employed to increase diversity and to compensate channel fading. Each pair of transmit and receive antennas provides an individual channel from the transmitter to the receiver. If the same information is transmitted through different individual channels, multiple *independently faded* replicas of the information are obtained at the receive side and thus the reliability of the reception is improved. That is, diversity on either side of the link can be understood as a procedure to mitigate fading. A different perspective has been recently promoted in relation to the MIMO channel. Fading can in fact be exploited in order to increase the degrees of freedom available for reliable communication. When the individual channels available fade independently

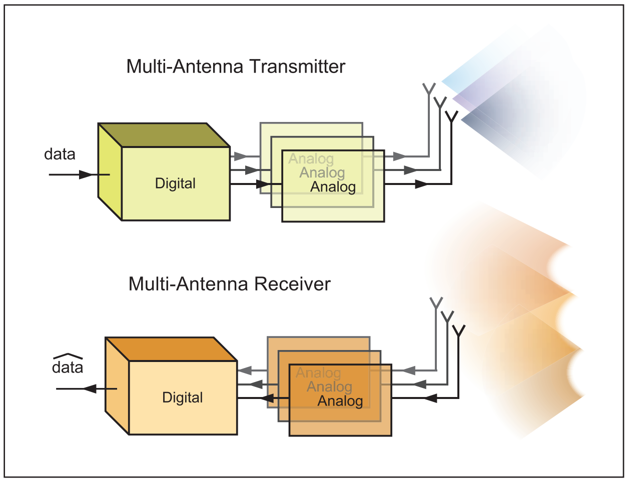

FIGURE 1 MIMO System.

TRANSMITTER DESIGN AND OPTIMISATION FOR MIMO SYSTEMS HAS EXPERIENCED AN UNPRECEDENTED GROWTH IN THE RESEARCH COMMUNITIES.

multiple *parallel* channels can be defined and the data rate can be increased. This effect is known as spatial multiplexing [4].

Most of the available literature on space-time coding concentrates on designs able to extract either maximal diversity gain or maximal spatial multiplexing gain, making a fair comparison difficult. In the high SNR regime this problem has been solved by the diversity-multiplexing trade-off curve presented in [5] as it provides a unified framework to compare the performance of general MIMO systems. Given a MIMO channel, both types of gains can be simultaneously achieved, but there is a *fundamental trade-off* between how much of each type of gain any space-time coding scheme can extract. However, these results are only theoretical, and do not lead directly to a space-time scheme to implement. Nevertheless, by evaluating the performance of a particular scheme by the trade-off it achieves, one can analyse together the capability of the scheme to combat the fading of the channel and its ability to accommodate higher data rate as the SNR increases. Moreover, as the optimal trade-off curve gives a simple characterisation of the best trade-off that can be achieved by any particular scheme, one can always know how far a coding scheme from the optimal coding strategy is.

Channels

As for all wireless systems, knowledge of the propagation channels is a basic requirement for the design, analysis, and simulation of multiple antenna systems, like SA and MIMO [50]. Since those systems make use of the spatial (directional) information, the channel description (including measurement results and models) has to include the DOAs (Directions of Arrival, Ψ) and possibly DODs (Directions of Departure, Ω) of the multipath components (MPCs) and is therefore called "directional" (or "spatial") channels.[1] The channel is thus described by a double-directional impulse response [6]

$$h(\vec{r}_T, \vec{r}_R, \tau, \Omega, \Psi) = \sum_{l=1}^{L(\vec{r})} a_l e^{j\varphi_l} \delta(\tau - \tau_l)\delta(\Omega - \Omega_l)\delta(\Psi - \Psi_l)$$

where $\vec{r}_T$ and receiver $\vec{r}_R$ are the locations of transmitter and receiver, respectively, τ is the delay, a is the absolute amplitude, and φ is the phase of the MPC. A related representation is the channel impulse response matrix $\mathbf{H}$, whose entry $h_{i,j}$ is the impulse response from the j-th transmit to the i-th receive element. It can be obtained from a double-directional (physical model) representation of the channel by adding the contributions from all the MPCs (weighted with the antenna element patterns in the directions of their DOAs and DODs) at the different antenna element locations.

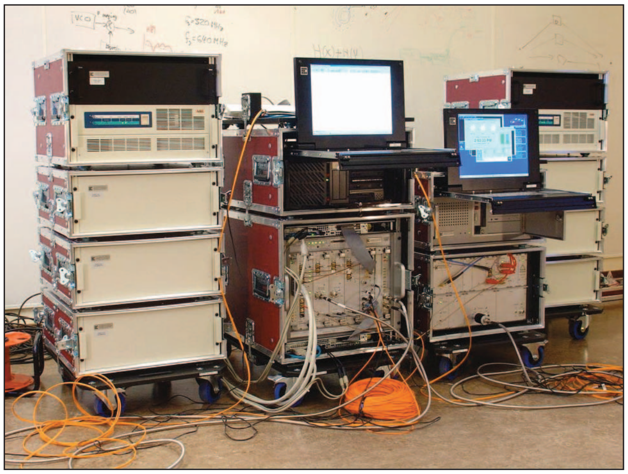

FIGURE 2 Channel Sounder, Lund University.

Much progress has been made in recent years with respect to measuring and modeling those channels. In the following, we give a very brief overview of the main results.

Measurement Techniques

Measurement of spatial channels requires new measurement devices that are able to measure the impulse response in different directions, or at different locations, quasi-simultaneously (i.e., within a time that is shorter than the coherence time of the channel). The most simple approach is the combination of a conventional channel sounder with a directional antenna that is pointed into different directions by a stepper motor, thus directly providing an approximation to the directional impulse response. Alternatively, an omnidirectional antenna can be displaced by mechanical means to provide a virtual antenna array. Such approaches require that the channel stays static while the antenna is moved around mechanically. If this condition is not fulfilled, real antenna arrays arrays (multiple antenna elements that have a complete RF chain and demodulator) or multiplexed arrays (where multiple antenna elements are connected via a fast electronic switch to a single RF chain) are preferable.

Measurement Campaigns

The channel sounders available at different institutions have been used for a large number of measurement campaigns. More campaigns have been performed for single-directional channels, as their

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[1] In the following, we will discuss double-directional channels, i.e., channels for multiple antenna elements at both link ends if not stated otherwise. Single-directional antennas are a straightforward specialization.

application in smart antenna systems raised interest since the mid-1990s. While space restrictions keep us from citing all relevant work, campaigns have been performed in metropolitan macrocells [7], microcells [8], suburban environments [9], rural environments, as well as indoor environments.

For double-directional (MIMO) channels, interest has been focused on urban and suburban macrocells [10], [11], and indoor environments [12]. Those measurements demonstrated that (for arrays with up to 4 elements), the correlations of the fading leads to a 20–30% reduction of the information-theoretic capacity (compared to the uncorrelated case). This performance loss depends (slightly) on the numbers of antennas. Further measurements confirmed the importance of the array orientation, especially in tunnels and corridors.

Deterministic Channel Prediction

Another important tool for the understanding of propagation channels is deterministic channel prediction, which solves Maxwell's equations, or an approximation (ray tracing) thereof. These prediction tools all provide directional information, and can easily provide the large number of results required for statistical evaluation [13].

The accuracy of the predictions of the angles of arrival is not as high as that for the prediction of received power. A good comparison between measurement and ray tracing can be found, e.g., in [14].

Channel Models

Modelling for spatial channels has received great attention in the academic as well as industrial community. One track is the investigation of fundamental modelling approaches, like the generalization of the well-known WSSUS condition to spatial channels [15], [16], as well as the development of the geometry-based stochastic channel model (in the mid 1990s) and generalization to the double-directional case [17].

For single-directional channels, models for the angular spectra were developed, based on measurements. At the base station, the angular spectrum can often be described by a Laplacian function [9]; at the mobile station, different elevation and azimuth spectra are valid for components arriving over the rooftop and guided through streetcanyon. Another important step was the realization that delay spread, angular spread, and shadowing are correlated with each other. A comprehensive model that takes all those effects into account was developed and standardized by the European research initiative COST 259 [18]; related model were also developed by 3GPP and 3GPP2 [19] and IEEE 802.11n [20].

For MIMO channels, modelling efforts have concentrated on the description of the relationship between DOAs and DODs. The so-called Kronecker model [10] assumes that the angular power spectrum at the RX is independent of the transmit direction, and vice versa. This considerably simplifies the mathematical description, and allows to write the impulse response matrix (of a flat-fading channel) in the form $\mathbf{H}_{\text{kron}} \propto \mathbf{R}_{\text{Rx}}^{1/2}\mathbf{G}(\mathbf{R}_{\text{Tx}}^{1/2})^{\text{T}}$ where $\mathbf{R}_{\text{Tx}}$, and $\mathbf{R}_{\text{Rx}}$. are the correlation matrices at TX and RX, respectively, and $\mathbf{G}$ is a matrix with i.i.d. complex Gaussian entries. This model has been in widespread use for the theoretical analysis of MIMO systems. A generalization of the Kronecker model was recently suggested by [17]. Their model preserves the dependencies between DoAs and DoDs. A general channel model that pays special attention to the relationship between DOAs and DODs, and is valid in a large variety of radio environments developed in the COST 273 research initiative.

PROVIDING ACCEPTABLE QOS TO USERS WILL BE ONE OF THE MOST PROMINENT PROBLEMS IN THE DESIGN OF FUTURE WIRELESS NETWORKS.

Receiver

Multi-Antenna Reception

Since multiple Rx antennas dramatically increase the number of parameters to be estimated and to be processed the design of powerful and efficient receivers has become a key issue.

Space-Time Equalization

A straightforward approach to multi-antenna reception is the extension of well-known time domain equalization techniques to the space-time domain. The joint space-time equalization is either based on a SoI (Signal of Interest) or diversity maximization, interference cancellation or a MMSE criterion and versions thereof. Consequently, the extension to spatial (e.g., BLAST) and spatio-temporal decision feedback equalization techniques has been proposed. An overview based on a rigorous theoretical framework has been published recently [21].

Although the extension to space-time equalization seems to be rather natural, it has created plenty of new solutions because of the huge numerical complexity of space-time communication systems and a variety of new transmission strategies as space time coding (e.g., STBC) and spatial multiplexing (Eigenbeamforming) have been proposed. A suboptimum approach to joint space-time receivers are solutions where the spatial and temporal processing is performed in successive processing units.

Subspace Methods

In general the transmission channel offers a rich spatial and temporal structure due to the multipath nature of the propagation environment of wireless communication links which becomes manifest in inhomogenous spectra of the respective transmission operator. In such cases a low rank approximation of the transmission channel can be applied to reduce receiver complexity and to improve the performance of channel estimation and detection [22].

Due to the directivity of multiple antennas which establishes a link to the natural physical propagation environment the spectra of the spatio-temporal correlation functions which characterize the stochastic processes of the SoI and their interfering counterparts are strongly related to physical properties as directions of arrival and power delay profiles. Since in practical applications these channel characteristics generally change very slowly, Rx subspace methods have been proposed which are based on the stationary assumption of the statistical second order spatial moments [22].

Maximum Likelihood Detection

Due to the huge number of parameters in multi-antenna reception a joint ML detector in spatial and temporal domain is generally not tractable, such that suboptimum approaches which guarantee a near ML performance and a considerable lower complexity have been proposed recently. These suboptimum approaches reduce the search space of possible hypotheses either to spheres of reduced volumes (sphere decoding) [23] or lower dimensional manifolds in the space of received codewords (sphere projection) [24].

Iterative Detection

An iterative (turbo) receiver which generally achieves the performance limits consists of an optimum detector and a subsequent decoder exchanging soft information in an interative process. To reduce the computational burden of optimum detection in space-time Rx processing a linear MMSE based solution has been proposed and widely linear processing comes into play [25]. Additionally, it can be shown that a reduced-rank implementation of the linear detection stage offers a convenient trade-off between performance and numerical complexity [26].

Overview

For a completion of the brief introduction in this Section further directions of research should be mentioned. A topic which plays an important role in multi-antenna reception is the robust design of algorithms which takes into account the unrealiability of channel state information at the receiver (CSIR) in realistic systems. Hereby, in mobile communication systems the most crucial feature is the adaptivity of possible robust techniques to different mobilities.

Another solution which makes Rx processing more independent from CSIR, especially in multiuser detection scenarios, exploits fundamental results from random matrix theory for the design of detection algorithms.

A further upcoming approach is the design of detection algorithms based on alternative optimization criteria which are directly related to error-probability measures of transmitted data.

The most comprehensive approaches to Rx processing seem to be iterative algorithms where channel estimation, detection and decoding somehow dissolve for the overall task of information transmission. The most sophisticated solutions hereby seem to be algorithms from factor graph analysis.

In [2] a selection of these receiver oriented concepts and a more detailed overview of proposed Rx processing techniques have been addressed.

Hybrid antenna selection, where the receiver selects, downconverts, and processes only a subset of the signals that are available antenna elements, are a further promising method for reducing the hardware (especially RF) complexity while retaining most of the benefits of having a large number of antenna elements.

Network Aspects

The problem of providing acceptable quality-of-service (QoS) to the users will be one of the most prominent problems in the design of future wireless communications networks. In this context, multiple-input multiple-output transmission techniques will play an important role. This is mirrored in the intensive research activities and discussion on the standardization of physical layer and medium access control for wireless systems beyond 3G (see last section). The general tendency is to develop protocols that support adaptation and optimization across the protocol layers, thereby taking advantages of the interdependences between them [27]. When developing such protocols, researchers resort to communication theory, information theory, queueing theory, the theory of matrices, stochastic processes and dynamical systems. However, although a great deal of research effort has been expanded, the research on network aspects in multiple-user multiple-antenna systems is far away from saturation. Some important problems could not yet be solved or even successfully analytically treated.

Uplink and Downlink Beamforming

Most issues in the design of multiple-antenna systems concern the physical layer, which is consequently the most and longest studied layer. The corresponding theoretical framework has the nice property of being dominated by dualities. The information theoretic duality deals with the capacity regions in the uplink (vector multiple-access channel) and downlink case (vector broadcast channel). In contrast to the well understood vector multiple-access channel, the general broadcast channel case is still an open problem, except the vector Gaussian case, which has been solved recently [28]. More precisely, the results of [28] and [29] show that

THE FIRST BASE STATIONS WITH ADVANCED SPATIAL PROCESSING HAVE BEEN USED IN COMMERCIAL NETWORKS SINCE 1997.

under successive interference cancellation (SIC) in the uplink and so called Costa-precoding in the downlink, the corresponding capacity regions are equal. Another duality applies to the regions of feasible SINR values, which are equal in the sum-power constrained uplink and downlink channels[2] [30], [31]. In the joint optimization of power allocation and beamforming vectors, i.e., interference balancing or sum-power minimization, even the optimal uplink and downlink beamforming vectors are equal. The duality of feasible uplink and downlink SINR regions holds not only in the case of linear spatial filtering at the receiver(s). The SINR regions under SIC in the uplink and Costa-precoding in the downlink exhibit an analogical duality. Nonlinearity of these cases, commonly regarded as undesirable, turns out to be favorable in terms of efficiency of iterative solutions to joint power control and beamforming. The alternating nature of iterative algorithms for the linear case disappears in the nonlinear case and the routines become one-loop [30]. A common conjecture is that the duality property of feasible SINR regions does not hold in the case of multiple antennas at the mobiles.

Multi-User Quality-of-Service Tradeoff

The consideration of QoS measures such as data rate, service delay or effective bandwidth gives rise to the design of access strategies for QoS control. Such policies utilize the knowledge of system and channel parameters to allocate powers and beamforming vectors to the users. Depending on the traffic characteristics, the objective is either to satisfy link-specific QoS thresholds while minimizing the total transmission power or to optimize a certain global function of QoS measures. In both cases, the geometric structure of feasible QoS regions are of great interest for the characterization of the optimum. In systems with no power constraints, the feasible QoS region is completely determined by the spectral radius of a certain matrix describing the system [32], [33]. In particular, the convexity of the spectral radius implies that the feasible QoS region is a convex set, which is strongly desired when developing optimal access control strategies. Recent results of [33] and [34] show that the spectral radius is a convex function if SINR is a bijective and log-convex function of the QoS measure of interest. The log-convexity property has been shown to be necessary in systems with no self-interference when the spectral radius is required to be convex for any multiple access interference scenario. Interestingly, if the self-interference is dominant, in which case the interference matrix is positive semidefinite, the convexity of SINR as a function of the QoS measure is necessary and sufficient for the spectral radius to be convex. In case of symmetric interference matrices, the log-convexity requirement can be also weakened to a less restrictive condition.

Cross-Layer Scheduling

In terms of the design of QoS control policies particular interest is in policies based on data link layer objectives, like e.g., minimum delay, minimum buffer occupancy or stability. The cross-layer view of the physical and data link layer consists in the system of bit queues awaiting their transmission over the wireless interface and fed by processes of bit arrivals. The minimum delay and minimum buffer occupancy objectives are suitable for scheduling of real-time traffic or under specific hardware constraints. The corresponding optimal schedulers require the knowledge of the arrival rates. The stability objective is the most favourable objective in the view of the network operator. In broad terms, given some scheduling policy, the queue system is said to be stable if no queue length evolves towards infinity. The policy achieving the largest stability region, i.e., providing stability for the largest set of bit arrival rates, allows the operator to achieve the highest network utility. This is because the set of arrival rates causing infinite queue blow-up and enforcing service abandonment is smallest in such case. The study of stability optimal scheduling presented in [35], [36] was recently extended to the multiple-antenna case [37]. The queue system under stability optimal scheduling was shown to be well-behaved and to allow several bounds and asymptotics on buffer occupancy and convergence rate. The case of multiple antennas is particular in terms of optimization problem behind the stability optimal policy. The insights in the corresponding geometry are crucial and aid the problem understanding and the design of optimization routines significantly ([38] and references therein). An interesting fact is that in terms of stability optimal scheduling under SIC in the uplink or respectively under Costa-precoding in the downlink the time sharing argument turns out to be superfluous. The optimization problem behind stability optimal scheduling is convex, which significantly facilitates the system implementation. Experiments showed, that the implemented routines work efficiently under real-world conditions.

Technology

Antennas

The design of the antenna array plays a crucial role in MIMO systems. The main challenges are found in handheld devices where the small physical dimension can

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[2] The uplink case is assumed here to be sum-power constrained.

FIGURE 3 SmarT Antenna Real Time System (STARS), Testbed of University of Duisburg-Essen, presented at EUSIPCO 2004.

lead to high inter-element correlation, which translates into lower diversity order or reduced multiplexing performance. In this context, conventional approaches are often followed whereby dipoles or inverted-F antennas are used. Crossed dipoles or patch antennas with cross-polarized feeds can provide more spatial (polarization) diversity from independently fading spatial channel. A promising approach to further increase the spatial diversity is the concept of multi-mode diversity [39]: diversity can be achieved with a single antenna with different, independently fed modes. This results in a combination of pattern- and polarization diversity to obtain uncorrelated channel impulse responses for the MIMO channel. Such concept has been applied to the design of spiral or sinuous antennas.

Finally, it should be noted that, for handheld devices, the electromagnetic simulation of the whole handheld housing and antenna array is mandatory to predict the impact of the configuration on the channel capacity [40]. This can and should be extended to the electro-magnetic co-simulation with the RF circuits.

Transceivers (Analog Front-Ends)

Yet another implementation challenge is the MIMO transceiver, basically a (costly) array of parallel transceivers. In order to reduce the cost of the parallel transceiver approach, multiplexing techniques can be envisaged. Time-division, frequency-division and code-division can potentially be used [41]. Although each of these techniques are successfully exploited in wireless multiplexing and multiple access, it appears that their performance for parallel architectures are very different. Of the 3 approaches, code-division multiplex with e.g., Walsh-Hadamard codes has the best performance-complexity trade-off. Its main drawback lies in the necessary bi-phase modulator in each antenna branch and the increased bandwidth resulting from the spreading process. [41] provides a detailed performance comparison but concludes that further system analysis is needed to validate the code-division approach.

MIMO transceiver non-idealities deserve a significant trade-off analysis when a real-time wireless system must be implemented. Whereas non-idealities in SISO systems are well documented, their impact on the performance of MIMO transmission is now becoming the subject of growing interest, due to the imminent introduction of MIMO in wireless standards [42]. It is worth mentioning the following non-idealities and their possible cure:

- A/D and D/A converter quantization: interestingly, the RX requirements are usually tougher, e.g., to allow some margin for the AGC
- I/Q imbalance, can be completely eliminated in indirect conversion receivers with digital quadrature generation. For low-cost direct conversion receivers, calibration techniques are usually needed, especially with high order modulation and/or multi-carrier transmission
- phase noise, can be partially mitigated with a tracking loop in the receiver. For ease of tracking in MIMO systems, a common local oscillator and sampling clock is mandatory at both the transmitter and receiver
- Power amplifier non-linearity: the transmit waveform of non-constant-envelope modulation and multi-carrier transmission exhibit a high peak-to-average-power ratio (PAPR). For a given amplifier non-ideality, input back-off is often resorted to, at the expense of power efficiency. TX processing usually requires more back-off.

Very importantly, the impact of analog non-idealities varies considerably for different MIMO transmission schemes. The following trends can be observed:

- Spatial multiplexing is more sensitive than combining diversity techniques because of multi-stream interference (MSI). Another reason is that fully loaded multiplexing schemes usually require a higher SNR for a given BER, hence less distortion noise is allowed. For STBC or STTC, since different symbols are simultaneously transmitted, a higher sensitivity is also observed.
- Joint TX-RX processing schemes are usually less sensitive because of the special structure of the pre- and post-filter that are usually unitary matrices.

Transmit processing with TX channel knowledge can also impact the Transceiver design. When the channel is reciprocal (TDD, slowly varying channel), it can be estimated in the reverse link. However, the reciprocity of the transceiver must also be guaranteed, which can be achieved by specific calibration techniques [43].

Demonstrators and Testbeds

Demonstrators and testbeds are very important for MIMO since they allow verifying the channel model and assumptions (including the antenna array), checking the front-end effects, assessing complexity and real-time requirements and are useful for validating and "marketing" new concepts. Many institutions have or are developing their own platform, with off-line or on-line processing. For on-line platforms, the signal processing part is mostly a hybrid combination of FPGA and programmable DSP or CPU to cope with the high processing requirements, flexibility and great variety of MIMO algorithms. More than 25 MIMO demonstrators or testbeds are known to the authors, which, in view of the development effort, is an amazingly high number [44]. This illustrates the huge interest of the scientific and industrial communities in MIMO technologies.

Applications and Standardisation

Albeit impressive progress in multi-antenna research has been demonstrated in the past 15 years, SA/MIMO techniques do not yet sucessfully penetrate the market despite the obvious benefits shown in the previous sections. The reasons might be manifold, e.g., higher implementation cost, higher power consumption, severe size limitations at the terminal side, lack of adequate protocols, lack of low-complexity algorithms, lack of world-wide standards, or, maybe even most convincingly, no current market need for high-data rate systems escorted by economy slow-down. However, there seems to be no doubt about the future success of multi-antenna technique because of the two major advantages: coverage extension and data rate improvement. Since both benefits can be traded-off to some extent, we will focus our discussion for the moment on data rate only. In analogy to Moore's law, the so-called Edholm's law of data rates has been proposed recently [45]. It says that data rates increase *exponentially* with time, independent of wireline, nomadic, or wireless type of systems. Taking into account a today's maximum rate of 1–2 Mbit/s for outdoor systems and 10–50 Mbit/s for indoor systems, we may expect in five years data rates of up to 20 Mbit/s for outdoor and up to 500 Mbit/s for indoor systems. While the progress in digital implementation is endorsed by Moore's law, a similar empirical rule does not exist for analog implementations. For example, in order to increase data rate, higher level modulation schemes (more than 64-QAM for indoor or more than 16-QAM for outdoor systems) may impose too strict requirements on the analog frontend. Hence, there is a need for alternative technologies within the next years and multi-antenna techniques seem to be well suited to serve both indoor and outdoor requirements. For a continuative discussion among scientists and industrial representatives on the need of SA/MIMO see [46].

In the following we will briefly discuss the different standardization efforts and present a few proprietary SA/MIMO solutions. Several standardization bodies, e.g., WLAN's (IEEE 802.11), WMAN's (IEEE 802.16) and 3GPP, 3GPP2, consider multi-antenna techniques as viable extensions to current single-antenna standards, which indirectly confirms an adequately mature multi-antenna technology in the future.

THE FIRST PROPRIETARY MIMO CHIP-SET FOR WLANS WERE LAUNCHED IN LATE 2003.

Indoor

The term *Wi-Fi* (Wireless Fidelity) is widely spread for WLAN's. Wi-Fi is a generic term to summarize the single-antenna IEEE standards 802.11a, b, g and to make them all comfortable to costumers. With a coverage of about some ten meters Wi-Fi represents the major category of current indoor systems.

In 2003, standardization efforts towards a physical layer peak rate of 150 Mbit/s have been initiated by the IEEE 802.11n task group. An optional part of this standard may even consider data rates of up to 500 Mbit/s. In order to allow full compability with Wi-Fi, the occupied bandwidth per channel is 20 MHz but also 40 MHz are under discussion. MIMO technology seems to be a favorite approach to tackle the targeted challenges mainly because of its high spectral efficiency. The 802.11n standard might be adopted in 2005, so that first MIMO products can be expected for the mass market in 2006.

Beside the standardization issues, a first proprietary MIMO chip-set for WLANs has been launched in late 2003 by the Californian company Airgo and, according to recent press reports, are under manufacturing by Asken and Taido Yuden. Companies like Atheros, Vivato, Hermes, and Motia announce comercially-available smart antenna products within 2004. Moreover, multi-antenna techniques may become a must in order to satisfy the required quality of service for VoIP because of the worse wireless channel. In contrast, for data services, laptops will probably become the first commercially relevant multi-antenna carrier device. Once the costumer get used to high and reliable MIMO data rates, MIMO equipped laptops could pave the way for multi-antenna technology also for outdoor systems. All these facts demonstrate the technically and economically mature MIMO indoor systems in the near future.

Outdoor

Compared to indoor systems the progress in multi-antenna based outdoor systems is slower. Standardization efforts are partly far behind the targeted schedule, i.e., only some transmit diversity techniques have been considered in 3G yet. More sophisticated WCDMA MIMO extensions are under discussion in UMTS Release 6, but only a channel model has been adopted yet. However, several MIMO proposals have been submitted and a final decision is expected soon.

The first base stations with advanced spatial processing and complying with the PHS standard have been used in commercial networks since 1997 and were developed by ArrayComm. The first complete commercial 802.16 compatible MIMO outdoor product was developed by Iospan Wireless (a Stanford University spin-off, recently acquired by Intel Corporation) in 2001. In 2002, Lucent technologies also developed a proprietary MIMO chip set, and Sanyo and Ericsson had already demonstrated their SA/MIMO pre-standard products in 2003. Recently, the IEEE 802.16d task group has accepted several MIMO proposals and a first release is expected in 2005. The Californian company Zyray announces the first MIMO HSDPA chip set in the end of 2005.

Future air interface ("4G," IEEE 802.20) will likely select a combination of multi-carrier (MC), spread-spectrum (CDMA) and Multi-antenna technique, with the following benefit: basically the frequency-selective channel is first equalized in the frequency-domain by the MC approach and DS-CDMA is applied on top of the equalized channel, keeping the interesting orthogonality properties of the codes. The DS-CDMA signals are either spread across the OFDM carriers, leading to multi-carrier MC-CDMA or along the carriers, leading to multi-carrier block-spread (MCBS-CDMA). The cyclic-prefixed single-carrier counterparts (SC-CDMA) and single-carrier block-spread CDMA (SCBS-CDMA) have also been proposed and are especially suited for the uplink since they reduce the problem of high PAPR transmit waveform at the terminals. Multi-antenna techniques (multiplexing, transmit and combining diversity and beamforming) will be key to achieving the expected performance of these advanced physical layer scheme [47].

Conclusions

In this contribution major aspects of smart antenna research and technology are highlighted. Although multi-antenna techniques were repeatedly demonstrated to be mature, smart antennas did not successfully penetrate the market yet. However, a recent report [48] states that wireless operators will profit from smart antennas once the demand for high-data rates meets limited spectrum resources. This situation will occur rather soon for fixed and nomadic wireless communication systems, e.g., in wireless local area networks or in wireless metropolitan area networks. Moreover, a recent study claims that the smart antenna market will reach $1.6 billion in sales globally in 2008 [49]. In conclusion, after more than a decade of research in smart antennas, its economic breakthrough seems to be not far away.

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