Smart Antenna Technologies for Future Wireless Systems: Trends and Challenges

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ABSTRACT

The adoption of smart antenna techniques in future wireless systems is expected to have a significant impact on the efficient use of the spectrum, the minimization of the cost of establishing new wireless networks, the optimization of service quality, and realization of transparent operation across multitechnology wireless networks. Nevertheless, its success relies on two considerations that have been often overlooked when investigating smart antenna technologies: first, the smart antennas features need to be considered early in the design phase of future systems (top-down compatibility); second, a realistic performance evaluation of smart antenna techniques needs to be performed according to the critical parameters associated with future systems requirements (bottom-up feasibility). In this article an overview of the benefits of and most recent advances in smart antenna transceiver architecture is given first. Then the most important trends in the adoption of smart antennas in future systems are presented, such as reconfigurability to varying channel propagation and network conditions, cross-layer optimization, and multi-user diversity, as well as challenges such as the design of a suitable simulation methodology and the accurate modeling of channel characteristics, interference, and implementation losses. Finally, market trends, future projections, and the expected financial impact of smart antenna systems deployment are discussed.

INTRODUCTION

The development of a truly personal communications space will rely on the design of next-generation wireless systems based on a whole new concept of fast, reconfigurable networks, supporting features such as high data rates, user mobility, adaptability to varying network conditions, and integration of a number of wireless access technologies, and offering new user-centric flexible service paradigms, relying on the exploitation of new resources such as cross-layer and contextual information. The new challenges require the consideration of certain enabling technologies, such as smart antennas, under new performance objectives and design constraints.

Smart antenna systems consist of multiple antenna elements at the transmitting and/or receiving side of the communication link, whose signals are processed adaptively in order to exploit the spatial dimension of the mobile radio channel. Depending on whether the processing is performed at the transmitter, receiver, or both ends of the communication link, the smart antenna technique is defined as multiple-input single-output (MISO), single-input multiple-output (SIMO), or multiple-input multiple-output (MIMO). Exploitation of the spatial dimension can increase the capacity of the wireless network by improving link quality through the mitigation of a number of impairments of mobile communications, such as multipath fading and co-channel interference, and by increasing the data rate through the simultaneous transmission of multiple streams by different antennas.

Until now, in the design of second- and third-generation wireless systems, smart antenna capability was considered an add-on feature, and optimization of the trade-off between complexity/cost and performance enhancements was not performed during the design phase. Adoption of smart antenna techniques in future-generation wireless systems would require the smart antenna feature to be an inherent part of the system design in order to provide the expected beneficial impact on efficient use of the spectrum, minimization of the cost of establishing new wireless networks, enhancement of the quality of service, and realization of reconfigurable, robust, and transparent operation across multitechnology wireless networks. To this end current research effort in the area is focusing on the following critical issues:

- The design and development of advanced smart antenna processing algorithms that allow *adaptation* to varying propagation and network conditions and robustness against network impairments
- The design and development of innovative smart antenna strategies for *optimization* of

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performance at the system level and transparent operation across different wireless systems and platforms

- Realistic performance *evaluation* of the proposed algorithms and strategies, based on the formulation of accurate channel and interference models, and the introduction of suitable performance metrics and simulation methodologies
- Analysis of the implementation, complexity, and cost efficiency issues involved in realization of the proposed smart antenna techniques for future-generation wireless systems

This article presents a short survey of the latest trends and discusses future directions in the area of smart antennas. In the following section, an overview is presented of the major challenges of mobile radio communications and how smart antennas can improve the performance of mobile communication systems. Then we address the design of smart antenna transceivers. The requirements, challenges, and trends of smart antenna system design for next-generation wireless networks are presented . Finally, the deployment of smart antennas in future wireless systems and the implementation issues associated with this deployment are discussed.

Challenges in Mobile Communications and Benefits of Smart Antennas

Multipath propagation, defined as the creation of multiple signal paths between the transmitter and the receiver due to the reflection of the transmitted signal by physical obstacles (Fig. 1), is one of the major problems of mobile communications [1]. It is well known that the *delay spread* and resulting *intersymbol interference* (ISI) due to multiple signal paths arriving at the receiver at different times have a critical impact on communication link quality. On the other hand, co-channel interference is a major limiting factor on the capacity of wireless systems, resulting from the reuse of the available network resources (e.g., frequency, time) by a number of users.

Smart antenna systems can improve link quality by combating the effects of multipath propagation or constructively exploiting the different paths, and increase capacity by mitigating interference and allowing transmission of different data streams from different antennas. More specifically, the benefits of smart antennas can be summarized as follows [1]:

Increased range/coverage: The *array* or *beamforming gain* is the average increase in signal power at the receiver due to a coherent combination of the signals received at all antenna elements. It is proportional to the number of receive antennas and also allows for lower battery life.

Lower power requirements and/or cost reduction: Optimizing transmission toward the wanted user (*transmit beamforming gain*) achieves lower power consumption and amplifier costs.

Improved link quality/reliability: *Diversity gain* is obtained by receiving independent replicas of the signal through independently fading signal components. Based on the fact that it is highly probable that at least one or more of these signal components will not be in a deep fade, the availability of multiple independent dimensions reduces the effective fluctuations of the signal. Forms of diversity include temporal, frequency, code, and spatial diversity obtained when sampling the spatial domain with smart antennas. The maximum spatial diversity order of a non-frequency-selective fading MIMO channel is equal to the product of the number of receive and transmit antennas. Transmit diversity with multiple transmit antennas can be exploited via special modulation and coding schemes [1], whereas receive diversity relies on the combination of independently fading signal dimensions.

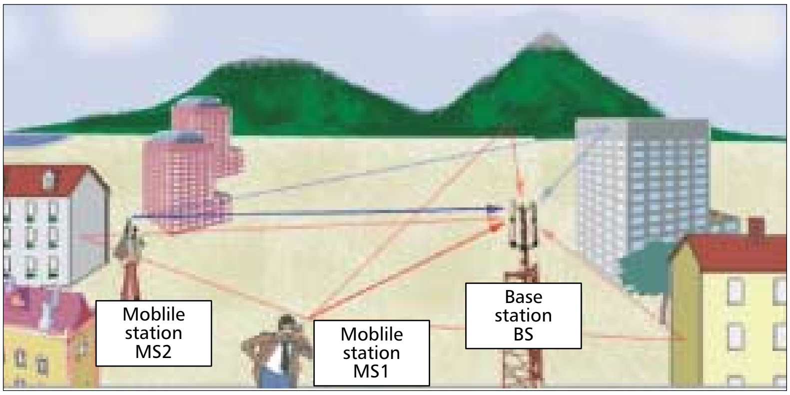


Figure 1. *Multipath propagation and co-channel interference.*

Increased spectral efficiency: Precise control of the transmitted and received power and exploitation of the knowledge of training sequence and/or other properties of the received signal (e.g., constant envelope, finite alphabet, cyclostationarity) allows for *interference reduction/mitigation* and increased numbers of users sharing the same available resources (e.g., time, frequency, codes) and/or reuse of these resources by users served by the same base station/access point. The latter introduces a new multiple access scheme that exploits the space domain, space-division multiple access (SDMA). Moreover, increased data rates — and therefore increased spectral efficiency — can be achieved by exploiting the *spatial multiplexing gain*, that is, the possibility to simultaneously transmit multiple data streams, exploiting the multiple independent dimensions, the so called *spatial signatures* or *MIMO channel eigenmodes*. It was shown [2] that in uncorrelated Rayleigh fading the MIMO channel capacity limit grows linearly with $\min(M,N)$, where M and N denote the number of transmit and receive antennas, respectively.

Traditionally, smart antenna systems have been designed focusing on maximization of one of the above-mentioned gains (beamforming, diversity, and multiplexing gains). Nevertheless, the trade-offs between these gains have been recently studied [3], and smart antenna approaches have been proposed that combine the resulting benefits [4].

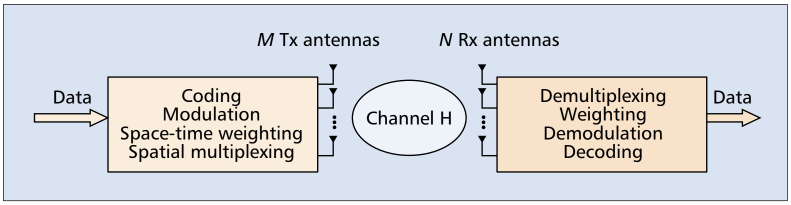


Figure 2. *Smart antenna transceiver architecture.*

SMART ANTENNA TRANSCEIVER ARCHITECTURES

In a multiple-transmit multiple-receive antenna system as illustrated in Fig. 2, the data block to be transmitted is encoded and modulated to symbols of a complex constellation. Each symbol is then mapped to one of the transmit antennas (spatial multiplexing) after space-time weighting of the antenna elements. After transmission through the wireless channel, demultiplexing, weighting, demodulation, and decoding is performed at the receiver in order to recover the transmitted data.

A large number of *transmission schemes* over MISO or MIMO channels have been proposed in the literature, designed to maximize spectral efficiency and link quality through the maximization of diversity, data rate, and signal-to-interference-and-noise ratio (SINR). Each of these schemes relies on a certain amount of channel state information (CSI) available at the transmitter and/or receiver side. CSI at the transmitter can be made available through feedback or can be obtained based on estimation of the receive channel. The former approach introduces the trade-off between feedback channel bandwidth and CSI accuracy, whereas in the latter channel reciprocity issues in frequency-division duplex (FDD) systems should be accounted for. CSI at the receiver can be obtained using training-based or *blind* techniques, which exploit other properties of the received signal, such as constant envelope and the finite alphabet.

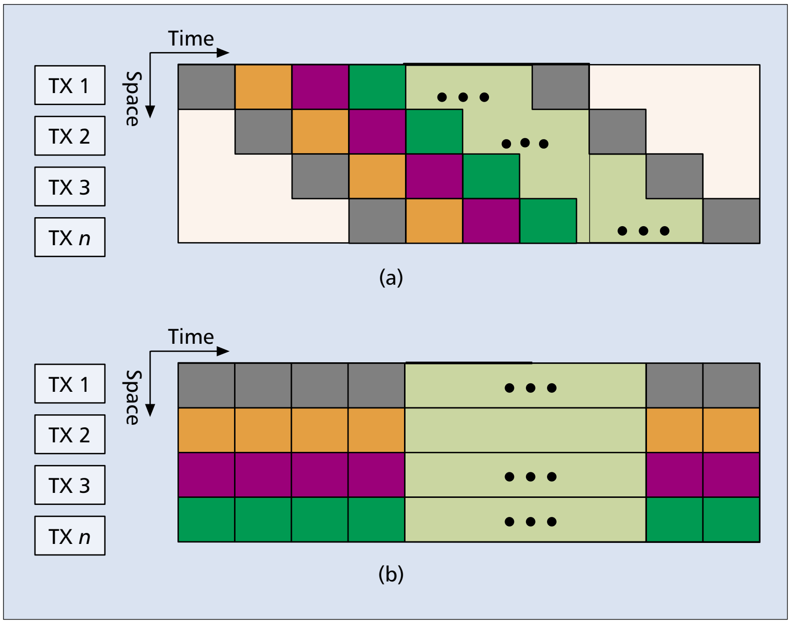


Figure 3. *Layered architectures: a) in diagonal BLAST (D-BLAST) the bitstream/antenna association is periodically cycled; b) in vertical BLAST (V-BLAST) the bitstream/antenna association is fixed.*

Transmission schemes that *do not require CSI at the transmitter* exploit the spatial dimension by either introducing coding on the spatial domain or employing spatial multiplexing gain. The former approach, space-time coding [1], increases redundancy over space and time, as each antenna transmits a differently encoded fully redundant version of the same signal. The received signal is detected using a maximum likelihood (ML) decoder. Space-time codes were originally developed in the form of space-time trellis codes (STTCs), which required a multidimensional Viterbi algorithm for decoding at the receiver. These codes can provide diversity equal to the number of transmit antennas as well as coding gain depending on the complexity of the code without loss in bandwidth efficiency. Space-time block codes (STBCs) offer the same diversity as STTCs but do not provide coding gain. However, STBCs are often the preferred solution over STTCs, as their decoding only requires linear processing. STBCs for two transmit antennas (proposed by Alamouti [5]) have been adopted as part of third-generation (3G) standards. Space-time coding techniques assume in principle perfect CSI at the receiver. Nevertheless, unitary and differential space-time coding has been proposed [6], which does not require CSI at either side of the communication link.

Layered space-time architectures exploit the spatial multiplexing gain by sending independently encoded data streams in diagonal layers as originally proposed in [7] or in horizontal layers, the so-called Vertical Bell Labs Layered Space-Time (V-BLAST) scheme [8], depicted in Fig. 3. The receiver must demultiplex the spatial channels in order to detect the transmitted symbols. Various techniques have been used for this purpose, such as zero-forcing (ZF) that uses simple matrix inversion, but results are poor when the channel matrix is ill conditioned; minimum mean square error (MMSE), more robust in that sense but provides limited enhancement if knowledge of the noise/interference is not used; and maximum likelihood (ML), which is optimal in the sense that it compares all possible combinations of symbols but can be too complex, especially for high-order modulation.

Transmission schemes that require *perfect CSI at the transmitter* optimize SINR by focusing energy in the desired directions, minimizing energy toward all other directions and satisfying transmit power constraints (as illustrated in Fig. 4). Beamforming allows spatial access to the radio channel by means of different approaches, considering either short-term properties (e.g., directional parameters) or long-term properties (e.g., second-order statistics) of the radio channel.

In the majority of cases it is reasonable to assume that only *partial CSI is available at the transmitter*. Hybrid schemes that combine space-time coding and beamforming have been proposed; these introduce precoding to exploit the available CSI when optimizing a certain criterion (e.g., pairwise error probability) [9]. *Robust transmit beamforming* schemes have also been proposed that take into account CSI estimation errors and optimize transmission in terms of a performance criterion, such as signal-to-noise ratio (SNR), and mutual information [9, references therein].

At the receiving end of a SIMO or MIMO communication link, the *receiver* or *equalizer* collects the multiple signal paths and reconstructs the transmitted signal [1]. In a frequency-nonselective SIMO channel, the optimal receiver strategy is to perform maximum ratio combining (MRC) and achieve received SNR maximization. For frequency-selective SIMO channels, an ML detector is an optimal receiver but is nonlinear with complexity increasing exponentially with the number of channel dimensions. Linear receivers can be used instead; they have lower complexity at the expense of lower performance. A ZF equalizer is designed to eliminate intersymbol interference (ISI) by employing channel inversion at the expense of noise enhancement. To overcome this drawback a minimum mean square error (MMSE) receiver balances noise enhancement with ISI elimination. A suboptimal nonlinear scheme based on decision feedback (decision feedback equalizer, DFE) can be used to improve the performance of a linear equalizer by using the feedback filter to remove the portion of ISI from the present symbol caused by the previously detected symbols. Both ML and linear equalizers can be extended to the MIMO channel case. A new problem associated with MIMO receivers is the presence of multistream interference (MSI) resulting from the multiple data streams interfering with each other. Nonlinear successive cancellation equalizers, or V-BLAST equalizers as they are commonly known [8], convert the MIMO channel into a set of parallel channels with increasing diversity at each successive stage, but with error performance dominated by the weakest stream. This drawback is overcome by applying ordered successive cancellation, where the strongest stream is decoded first. In D-BLAST a diagonal layer peeling is performed at the receiver.

In the *multi-user case*, where the base station communicates with multiple users who share the available resources (frequency, time, codes, etc.), the design of smart antenna transceivers is more challenging, as it aims to optimize the impact of interference and heavily depends on the specifics of the multiple access scheme employed.

Several nonlinear and linear preprocessing techniques have recently been proposed for transmission in multi-user MIMO systems when (partial or complete) CSI is available at the base station. Tomlinson-Harashima precoding is a nonlinear pre-equalization technique originally developed for SISO multipath channels, where it was used to overcome the error propagation problem of DFE. In [10] it is proposed for the pre-equalization of multi-user interference in MIMO systems.

Block diagonalization (BD) is a linear transmit preprocessing technique for the downlink of multi-user MIMO systems that decomposes a multi-user MIMO downlink channel into multiple parallel independent single-user MIMO downlink channels [11]. BD is more robust to channel estimation errors than nonlinear techniques. The signals of each user are preprocessed at the transmitter using a modulation matrix that lies in the null space of other users' channel matrices.

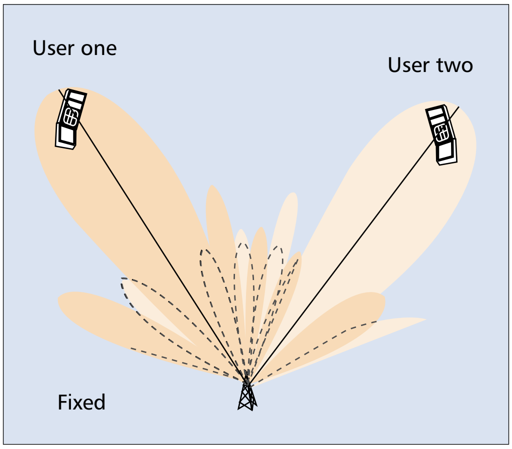
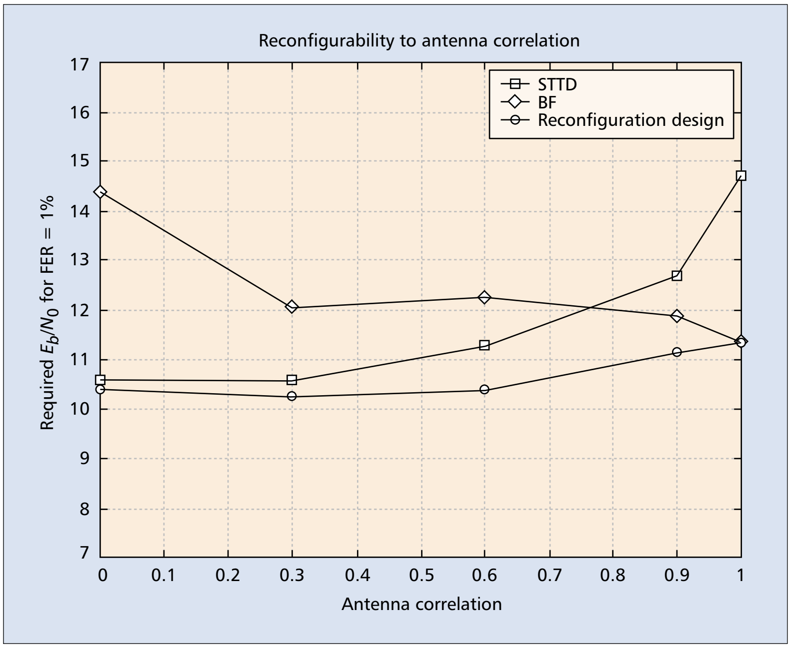


Figure 4. *Optimizing transmitted power with beamforming.*

Thus, the interference this user represents for the others is set to zero. In order to derive a closed form solution of the problem of minimum transmit power subject to achieving an arbitrary rate for each user, the zero interference constraint is relaxed. The proposed algorithm, named *successive optimization* (SO), has better performance than any BD solution at low signal-to-noise ratios (SNRs) or for different user power levels or rate requirements (near-far problem).

Depending on the multiple access scheme, different receiver strategies have been proposed in the multi-user case, from theoretically optimal strategies to practical ones like parallel or successive interference cancellation (PIC or SIC) and joint detection. When the same resources (frequency, time, codes, etc.) are reused by two or more users, in this case only spatially separable through their spatial channel signatures, SDMA allows for further capacity enhancement at the expense of harsh intracell interference conditions. In the multi-user multicell case, spectral efficiency can be increased by increasing the resources (frequency, time, codes, etc.) reuse factor between cells. In this case interference conditions are even more challenging, as the interfering users being served by different base stations cannot be controlled, as in the SDMA case. Space-time co-channel interference (CCI) mitigation techniques [1] at the receiving end of the SIMO or MIMO channel are classified as *training-based*, where training information known at the receiver is used to estimate the channel and detect the transmitted signal by employing a linear (e.g., MMSE) or nonlinear (e.g., ML) receiver, or *blind*, when other properties of the transmitted signal (e.g., constant envelope, finite alphabet, cyclostationarity) are exploited. At the transmitting end of a MISO or MIMO channel, CCI mitigation is performed in the form of reducing the generated interference by employing SINR balancing beamforming subject to transmit power constraints. Multi-user designs are highly dependent on higher-layer issues, such as scheduling, which need to be taken into account in the optimization of smart antenna systems, as further discussed in the next section.

Performance metrics for the characterization of smart antenna transceivers are the mean square



■ **Figure 5.** *Reconfigurability to antenna correlation for a two-transmit one-receive antenna system. STTD is Alamouti space-time block coding, and BF is transmit beamforming toward the direction of the strongest correlation matrix eigenvector.*

error (MSE), SINR, bit error rate (BER), achievable throughput, required transmit power, and channel capacity. Transmission schemes and receivers are designed to optimize one of these criteria.

In summary, four key MIMO transceivers design parameters can be identified:

- CSI reliability at the transmitter and receiver
- Characteristics of the transmitted signal: modulation, multiplexing, and training information
- Performance metrics to be optimized
- Computational complexity and its partitioning between transmitter and receiver

SMART ANTENNA STRATEGIES FOR NEXT-GENERATION WIRELESS SYSTEMS

Next-generation wireless systems require signal processing techniques capable of operating in a wide variety of scenarios with respect to propagation, traffic, interference, user mobility, antenna configuration, radio access technology, and CSI reliability. Exploitation of the enhancements achieved by smart antennas and optimization of the trade-off between complexity and performance would require consideration of the smart antenna feature in the initial phase of next-generation systems design. To this end, current research efforts focus on identifying the most promising approaches, and the requirements and challenges associated with their incorporation in future wireless systems design.

In this section some of the major trends and challenges in the area of smart antennas for future wireless systems design are introduced.

RECONFIGURABILITY AT THE PHYSICAL LAYER

In order to allow wireless communication transceivers to operate in a multiparametric continuously changing environment, *reconfigurable* adaptive techniques to adjust the structure and parameters of transceivers and achieve the best possible performance in a variety of scenarios need to be devised.

Reconfigurability in smart antenna transceivers can be viewed as the capability of intelligent switching between transceiver architectures with varying performance in a certain parameter of interest (e.g., CSI reliability at the transmitter, antenna correlation). One example could be the design of an algorithm that exploits the fundamental trade-off between spatial diversity and multiplexing in MIMO channels [3]. Novel approaches have been proposed recently that achieve reconfigurability by introducing parameterization in the transceiver design with respect to the parameters against which reconfiguration is to be performed, such as antenna correlation and CSI reliability [12] (Fig. 5).

CROSS-LAYER OPTIMIZATION

Overall system performance can be enhanced by interacting with the higher layers of the open systems interconnection model of the International Standards Organization (OSI/ISO) protocol stack. Smart antenna techniques can be developed combining parameters in the physical, link (medium access control, MAC; data link control, DLC; scheduling, etc.), and network layers (radio resource management, routing, transport, etc.); that is, in a cross-layer fashion rather than attempting to optimize the designs in isolation from one another. A layer-isolated approach often proves inefficient when the performance evaluation takes into account higher layers. For example, the enhancements achieved by space-time block coding techniques are reduced or even disappear in the presence of scheduling. Furthermore, layer-isolated approaches can prevent the physical layer innovations from being incorporated in the standardization effort and eventually adopted in the implementation phase.

The information to be exchanged among the functionalities residing in different OSI layers can be classified as follows:

- **CSI**, that is, estimates for channel impulse response, location information, vehicle speed, signal strength, interference level, interference modeling, and so on
- **QoS-related parameters** including delay, throughput, bit error rate (BER), packet error rate (PER) measurements, and so on
- **Physical layer resources** including spatial processing schemes, number of antenna elements, battery depletion level, and so on

It is also important to carefully consider the cross-layer optimization criteria. In practical systems, the link quality when employing smart antenna techniques is determined not only by the performance of data detection methods, but also by the specific coding scheme being used, the MAC/DLC functionalities adopted in the link layer, or even the performance of protocols in the upper layers of the protocol stack. Thus, all these blocks should optimally be designed to achieve the highest possible overall system throughput including all links instead of the highest data rate for a single link (channel capacity maximizing approach).

For delay-tolerant services, the combination of smart antenna architectures, such as V-BLAST, with hybrid automatic repeat request (H-ARQ) schemes turns out to be a promising field for research [13]. Cross-layer designs open the space for novel strategies for mapping transmit data on specific streams, alternative methods to adjust frame size, as is the case of the 3G Partnership Project (3GPP) high-speed data packet access (HSDPA) standard, or new antenna selection methods on the transmit and/or receive side. An example of antenna selection based on the maximization of throughput or capacity when different ARQ protocols are used is shown in Fig. 6.

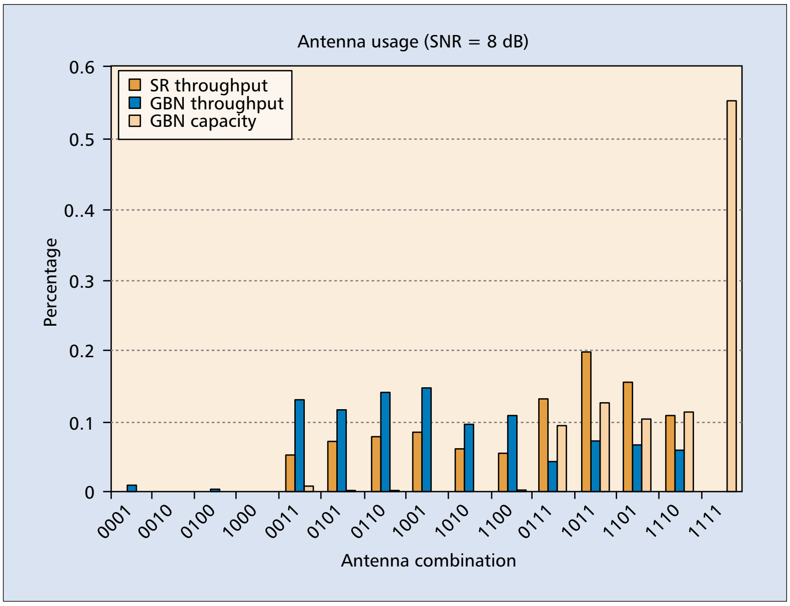


Figure 6. *Transmit antenna selection according to the ARQ protocol in use: GBN throughput stands for Go-Back-*N *protocol with throughput maximization; b) SR throughput stands for selective repeat protocol with throughput maximization; c) GBN capacity stands for Go-Back-*N *protocol with capacity maximization. In the horizontal axis, 0: antenna OFF; 1: antenna ON (source: [13]).*

Multi-User Diversity

In a multi-user context, so-called opportunistic approaches have recently attracted considerable attention. The basic idea is to multiplex users by granting the channel to those with higher chances of completing a successful transmission. In the end, overall (rather than individual link) throughput maximization is pursued. For specular spatial channels, opportunistic beamforming approaches point at the user with the highest SNIR out of those present in the system. On the other hand, in rich scattering scenarios opportunistic approaches will implicitly exploit fading by granting access to those with highest instantaneous capacity ([14, references therein]. Instead of traditional strategies aimed at stabilizing individual links against channel (or interference) fluctuations by using multiple antennas, artificial fading may need to be introduced for slowly time-varying channels on the transmit side by randomly changing transmit weights. More sophisticated multiple access can be derived by combining space and code diversity. In that case, additional issues like efficient user grouping arise.

Opportunistic approaches go beyond the physical layer and exploit *multi-user diversity* as a complement to code, time, frequency, or space diversity. This clearly has an impact on the design of MAC protocols, which are forced to abandon the collision avoiding paradigm (e.g., Aloha) and evolve toward multi-user schemes, reinforcing the need for cross-layer designs.

Realistic Performance Evaluation

The adoption of smart antennas in future wireless systems relies on two main investigation approaches to be performed:

- Consideration of the smart antenna features early in the design phase of future systems (*top-down compatibility*)
- Realistic performance evaluation of smart antenna techniques according to the critical parameters associated with the future systems requirements (*bottom-up feasibility*)

The latest trends that fall in the former approach have been discussed in the previous paragraphs of this section. The latter investigation approach consists in performance evaluation based on suitable simulation methodology with accurate modeling.

Simulation Methodology — Link-level simulations provide an assessment of a single communication link performance of a smart antenna transceiver in terms of frame error rate (FER) in various propagation environments, interference scenarios, and modulation and coding schemes, and under certain assumptions (ideal or realistic) on implementation losses, but fail to introduce the effects of multi-user multicell scenarios, where higher-layer parameters may play a decisive role. On the other hand, system-level simulations generate certain traffic patterns within a network of cells and provide an assessment of the overall multicell system performance by evaluating metrics such as capacity, throughput, and SINR distribution. Simulation complexity constraints impose a trade-off between the amount of higher-layer system functionalities (e.g., ARQ, scheduling, handover) to be reflected in system-level analysis and the accuracy of the representation, especially in the smart antenna case, where space diversity introduces an additional dimension [12]. In order to optimize this trade-off, an interface between link- and system-level studies can be devised (Fig. 7), relying on a carefully selected interface parameter that uniquely characterizes both link and system performance. The closer to one-to-one this mapping is, the more accurate the interface. Under the assumption of Gaussian interference, the MIMO channel capacity can be proved to be an accurate interface metric.

Modeling — The efficiency of smart antenna techniques depends on the characteristics of a highly variable environment in terms of propagation, antenna array configuration, traffic patterns, service profiles, user behavior, interference scenarios, availability of signaling bandwidth,

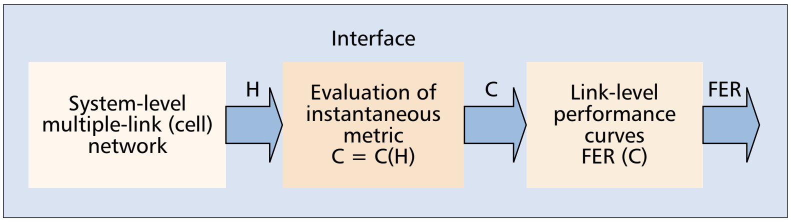


Figure 7. *Link- to system-level interface based on performance metric C, a function of channel matrix H.*

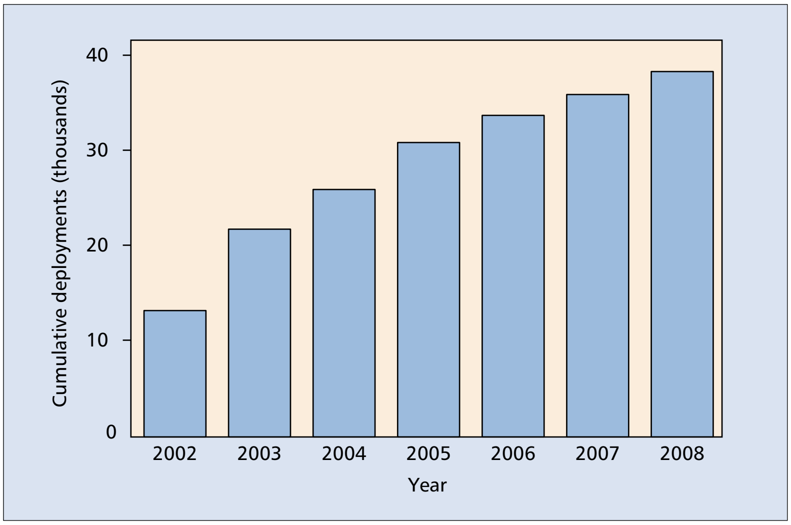


Figure 8. *The global market for smart antennas growth (source: Visant Strategies.*

and QoS requirements. It is therefore critical to develop realistic MIMO channel models for the characterization of a highly variable propagation environment; representative interference models for adequate evaluation of baseband signal processing techniques in multiple-antenna multiuser multiservice multitechnology radio networks; and implementation loss models for realistic assessment of performance in a practical communication system.

MIMO channel modeling has been intensively investigated in the literature in an effort to optimize the trade-off between simulation complexity, accuracy, and flexibility in parameterization. Depending on whether the channel models are based on a detailed reproduction of the actual physical wave propagation process or reproduced by statistical means, they can be characterized as *deterministic* or *stochastic*, respectively [15]. *Full-wave models* discretize the space on a lattice and calculate the electromagnetic field values at each lattice point. In stochastic models limited representation of physical reality is traded for computational simplicity. In an effort to optimize this trade-off, *geometry-based stochastic models* have been introduced that provide a statistical approach based on geometrical considerations in the scattering environment.

Interference modeling has been traditionally used in the analysis of smart antenna transceiver performance as a variable rather than a working assumption. This bottom-up approach offered limited insight on the practical problems associated with interference and the real value of the interference mitigation capability of smart antenna transceivers. It has recently become obvious that interference modeling must be based on system-level simulation results, where the intra- and intercell impact of smart antenna techniques, nonuniformity of traffic (e.g., hot spots), and mixed service scenarios are accounted for.

Finally, *modeling of implementation losses*, such as channel estimation errors, feedback quantization and delay, realistic antenna patterns, and mutual coupling, needs to be considered in order to identify the critical parameters and directions for further implementation improvements.

Deployment of Smart Antennas in Future Systems Implementation Issues

According to recent studies[1] smart antenna technology is now deployed in one of every 10 base stations in the world, and the deployment of smart antenna systems will grow by 60 percent in the next four years, as illustrated in Fig. 8. It was shown in the same study that smart antenna technology has been successfully implemented for as little as 30 percent more cost than similar base stations without the technology.

Smart antennas are already part of current releases of 3G standards (e.g., Alamouti STBC), and more sophisticated approaches are considered for future releases. Furthermore, there is currently increasing interest in the incorporation of smart antenna techniques for IEEE wireless LAN/MAN (802.11n and 802.16[2]).

However, implementation costs can vary considerably, and cost-effective implementation is still the major challenge in the field. At the base station of particular importance is the development of improved antenna structures (possibly employing micro-electromechanical system, MEMS, technology, e.g., micro-switches, or left-handed materials), improved cabling structures, and efficient low-cost radio frequency/digital signal processing (RF/DSP) architectures. At the terminal the application of smart antenna techniques can have a significant impact, in terms of not only system performance but also cost and terminal physical size (Fig. 9). Promising areas for further research are efficient smart antenna algorithm design, small low-power RF structures, and viable low-power DSP implementations. Moreover, antenna structures, RF architectures, and DSP implementations are expected to operate efficiently within a wide variety of air interface scenarios, both separately and in parallel. To this end, innovative development flow methodologies jointly covering the RF and baseband parts of complex wireless systems-on-a-chip should be studied. A key output of this area of study is an understanding of the base technologies that are required to make the future use of smart antennas viable.

The financial impact of the deployment of smart antenna technologies in future wireless systems was studied in [16] for cdma2000 and UMTS. The results showed that smart antenna techniques are key to securing the financial viability of operators' business, while at the same time allowing for unit price elasticity and posi-

[1] US analyst firm Visant Strategies

[2] http://grouper.ieee.org/groups/802/11/

■ **Figure 9.** *A terminal with 16 antennas mounted on a laptop.*

tive net present value. They are hence crucial for operators that want to create demand for high data usage and/or gain high market share. Based on this type of analysis, technology roadmaps along with their associated risks can be concluded that will enable appropriate technology intercept points to be determined, resulting in the development of technologies appropriate for each application area.

CONCLUSIONS

In this article an overview of the benefits of and most recent advances in smart antenna transceiver architectures is given. The successful adoption of smart antennas relies on considering the particular features of the technology at an early stage in the design of future systems. In this context the major trends in the area of smart antennas, such as reconfigurability to varying channel propagation and network conditions, cross-layer optimization, and multi-user diversity techniques, have been discussed. Moreover, challenges such as the design of a suitable simulation methodology and the accurate modeling of channel characteristics, interference, and implementation losses have been presented along with market trends, future projections, and the expected financial impact of smart antenna systems deployment.

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