Preface

The dramatic growth of the wireless communication industry is creating a huge market opportunity. Wireless operators are currently searching for new technologies that can be implemented in the existing wireless communication infrastructure to provide broader bandwidth per user channel, better quality, and new value-added services. Employing smart antennas presents an elegant and relatively economical way to improve the performance of wireless transmission (Winters, 1998; Soni, 2002; Bellofiore, 2002a; Bellofiore, 2002b; Diggavi, 2004).

Deployed at base stations in the existing wireless infrastructure, smart antennas bring outstanding improvement in capacity to radio communication systems, which have severely limited frequency resources, by employing an efficient beamforming scheme (Tsoulos, 1997). New value-added services, such as position location (PL) services for emergency calls, fraud detection, and intelligent transportation systems are also being implemented in real-world applications thanks to the direction-finding ability of smart antennas (Tsoulos, 1999).

Smart antennas can also be efficiently used at mobile terminals. Employed at mobile terminals (e.g., notebook PCs, PDAs) in *ad hoc* networks or wireless local-area networks (WLAN), the direction-finding ability permits the design of packet routing protocols that can determine the optimal manner of packet relaying (Nasipuri, 2000). The beamforming or interference-suppression ability makes it possible to increase throughput at network nodes where it is limited by interference from neighboring nodes (Winters, 2006).

A multiple-input multiple-output (MIMO) wireless communication channel can by built by installing antenna arrays that provide uncorrelated signal outputs at both transmitters and receivers. A MIMO system's capacity for channel information increases with the number of arrayed antenna elements (Telatar, 1999). Transmitting a space-time block coded waveform over a MIMO system dramatically increases the data rate over wireless channels (Naguib, 2000).

To take advantage of smart antennas' potential, recent designs of high-data-rate wireless transmission, distributed sensor networks, wireless network protocols, wireless security, software-defined radio, cognitive radios, and radio frequency identification (RFID) systems have pursued the integration of smart antennas as one of the key technologies.

Researchers in both academia and industry are actively studying smart antenna architectures, algorithms and practical implementations. This handbook aims to provide the readers with a single comprehensive guide to the issues of smart antennas in wireless communication scenarios, covering the wide spectrum of topics related to state-of-the-art smart antenna technologies in wireless systems/networks.

To serve this purpose, this handbook features 25 chapters authored by leading experts in both academia and industry, offering in-depth descriptions of terminologies and concepts relevant to smart antennas in a variety of wireless systems. Furthermore, the handbook explores the challenges facing smart antenna technologies in various wireless propagation environments and application scenarios, including system modeling, algorithms, performance evaluation, practical implementation issues and applications, future research and development trends, and market potential.

The handbook's chapters are organized into four interrelated sections: Algorithms, Performance Issues, Applications of Smart Antennas in Wireless Networks and Systems, and Experiments and Implementations. The following gives an overview of each chapter's contents. The handbook's chapters are organized into four interrelated sections: Algorithms, Performance Issues, Applications of Smart Antennas, and Experiments and Implementations. The following gives an overview of each chapter's contents."

Section I: Algorithms

Chapter I gives a unified analysis of receiver-side beamforming and maximum ratio combining (MRC) algorithms from the viewpoint of eigenbeamforming. Results suggest that the performance of beamforming and MRC fluctuate with the variation in wireless propagation environments. The proposed eigenbeamforming method provides a unified approach to designing smart antenna algorithms.

Chapter II studies the performance of robust Capon beamformers using the max-min optimization method. Results show that the robust Capon beamformers are robust against array-steering vector errors and provide a relatively high output signal-to-interference plus noise ratio (SINR). However, the results also indicate that the robust Capon beamformers still cannot achieve the optimal output SINR.

Chapter III presents detection techniques applying adaptive beamforming for use in multiple-antenna/multi-user systems that employ high-order QAM signaling. A novel minimum symbol error rate (MSER) design for a beamforming-assisted receiver is proposed. Furthermore, an adaptive implementation of the MSER beamforming is examined. Results show that the MSER beamforming design offers a higher user capacity and is more robust in a near-far scenario than the conventional MMSE beamforming design. Moreover, it is shown that the adaptive implementation of MSER beamforming operates successfully in fast fading conditions and consistently outperforms the adaptive LMS beamforming benchmarker.

Chapter IV investigates a sample covariance matrix (SCM)-based beamforming, i.e., sample matrix inversion (SMI) beamforming, for receiver-side interference mitigation in wireless networks where co-channel interference (CCI) is encountered. With the help of a vector space representation, enhanced interfaces between beamforming and signal decoding have been devised for scenarios with block-wise stationary CCI and transmission signals both with and without preambles. Results show that the error rate performance at the decoder output can be significantly improved by employing the SMI-based beamforming on short signal intervals and decoding BICM (bit-interleaved coded modulation) signals.

Chapter V considers the beamforming issue in *ad hoc* networks with arbitrarily located sensors. Under ideal assumptions such as the absence of mutual coupling and perfect synchronization, results show that such random arrays can form good beam patterns with sharp main lobes and low sidelobe peaks. The probabilistic performance of planar random arrays (or collaborative beamforming) with a view toward application to wireless ad hoc sensor networks is also analyzed.

Chapter VI presents the fundamentals of space-time block coding and, moreover, introduces new codes with better performance. The basic detection algorithms that can be used to detect space-time block codes are discussed. Furthermore, several low complexity pseudo-maximum likelihood algorithms are proposed and discussed. The study proves that these proposed schemes are able to closely match the performance of maximum likelihood detection while only requiring a small fraction of the computational cost.

Chapter VII considers space-time modulated codes (MC) for memory channels, such as those used for multiple-transmit and -receive antenna systems with intersymbol interference (ISI). A joint decoding method for space-time MC encoded channels, i.e., the joint zero-forcing decision feedback equalizer (ZF-DFE), is presented. Analytical and numerical results show that the reliable information rates that can be achieved by the MC coded channels based on standard random coding techniques are larger than those of the channels themselves when the channel SNR is relatively low.

Chapter VIII analyzes the problem of blind channel estimation under space-time block coded transmissions. A new blind channel estimation criterion is proposed. Analysis shows that this technique reduces the problem of extracting the main eigenvector of a generalized eigenvalue (GEV) and does not introduce additional ambiguities. Numerical evaluation shows that the performance of the proposed blind approaches is close to that of a coherent receiver.

Chapter IX studies the adaptive beamforming of a compact array antenna, the electronically parasitic array radiator (Espar) antenna. This antenna has one active element connected to the radio-frequency (RF) port and multiple surrounding parasitic elements loaded with tunable reactance. Beamforming is achieved by tuning the load reactances. A faster beamforming algorithm, based on simultaneous perturbation stochastic approximation (SPSA) theory with a maximum cross-correlation coefficient (MCCC) criterion, is proposed here. Results show that the proposed algorithm achieves sufficient interference suppression.

Chapter X presents Direction of arrival (DoA) estimation with the compact array antenna, the Espar antenna, using methods based on reactance switching. DoA estimation methods by an ESPAR antenna are proposed based on three types of algorithms: power pattern cross correlation (PPCC), reactance-domain (RD) multiple signal classification (MUSIC), and RD estimation of signal parameters via rotational invariance techniques (ESPRIT). These three methods exploit the reactance diversity provided by an Espar antenna to correlate different antenna output signals measured at different times and for different reactance values.

Section II: Performance Issues

Chapter XI takes a look at multi-antenna communication systems from the electromagnetic point of view, ranging from adaptive array antennas to MIMO systems. It shows that when introducing multiple antennas into a system, the electromagnetic effect needs to be considered. Analysis shows that even though the mutual coupling degrades the performance of an adaptive system by destroying the wavefront of the signals, it improves performance by increasing the order of singular values in the channel decomposition for a MIMO system, thus yielding a more reliable multiplexing gain.

Chapter XII describes the underlying principle, evolving techniques, and corresponding industrial applications of transmit beamforming of MIMO systems, which exploits channel state information (CSI) at the transmitter. In particular, it discusses the codebook-based feedback techniques with various quantization complexities and feedback overheads. Application examples of these techniques in 3GPP, IEEE 802.11n, and 80216d/e are studied. Results show that MIMO beamforming delivers more than 2 dB gain for most practical antenna configurations.

Chapter XIII discusses the joint beamforming and space-time coding techniques used to exploit the spatial correlation and diversity gain of MIMO channels, respectively. The beamforming system directly increases the link's signal-to-noise ratio (SNR) while the space-time coding provides the coding gain and diversity gain to improve link performance. The practical implementation issues such as imperfect CSI for these joint beamforming and space-time coding techniques are also discussed.

Chapter XIV analyzes adaptive modulation and coding (AMC) as a practical means of approaching the high spectral efficiency theoretically promised by MIMO systems. Using a generic framework, the study gives a quantitative analysis of the system's multiplexing. In the context of imperfect CSI, an adaptive turbo coded MIMO system is proposed and its performance is evaluated. It is shown that this system achieves a near-capacity performance and is robust against the CSI imperfection.

Chapter XV investigates a class of relaxation detectors that are approximations of the optimal maximum-likelihood detector. The study illustrates how the performance of any detector in this class can be readily quantified through its diversity gain when applied to an independent and identically-distributed (i.i.d.) Rayleigh fading channel. It is shown that the diversity gain is easy to derive based on the geometrical properties of the detector.

Chapter XVI discusses different optimization problems of practical importance for transmission in point-to-multipoint networks with a multiple-input transmitter and multiple output receivers. Optimum transmission parameters of these schemes are computed by iterative algorithms involving a complexity that strongly depends on the a priori unknown number of iterations required to reach convergence. To closely approximate the performance of optimum approaches, suboptimum allocation algorithms are presented. Results show that computation of the optimum transmission parameters requires a complexity similar to that of only one iteration of the optimum approaches, and thus users are assigned decoupled spatial dimensions, which makes it possible to reduce the required signaling overhead.

Section III: Applications of Smart Antennas

Chapter XVII studies the performance of smart antennas in a code division multiple access (CDMA) cellular network. An effective analytical model and simulation techniques that provide rapid and accurate assessment of the performance of CDMA systems employing a smart antenna are presented. The close match of the results from the analytical model and from simulation verifies the usefulness of the analytical model. Furthermore, results show that smart antennas play a significant role in improving the performance of cellular CDMA systems.

Chapter XVIII considers a cellular downlink packet data system employing the space-time block coded MIMO scheme. The cross-layer performance of typical scheduling algorithms and a point-to-point power control scheme over a time division multiplexing (TDM)-based shared MIMO channel are evaluated for a CDMA high data rate (HDR) system. Analysis shows that the multi-user diversity gain increases the aggregate throughput and reduces the transmission error rate. It is also shown that space-time block coding/MIMO and one-bit and multi-bit power control improve the physical and media access protocol (MAC) layer performance but may limit the multiuser diversity gain or the potential throughput of schedulers for delay-tolerant bursty data services.

Chapter XIX presents the implementations of multi-beam antenna (MBA) techniques for wireless *ad hoc* network applications. Both multiple fixed-beam antennas (MFBAs) and multi-channel smart antennas (MCSAs) are discussed. The performance in terms of node throughput and the probability of concurrent communications are examined while incorporating two random-access scheduling (RAS) schemes in the contention resolution process for the node priority issue and throughput maximization, respectively.

Chapter XX proposes an application of smart antennas to generating secret keys for encryption of communications over wireless networks. The scheme uses a smart antenna, such as the Espar antenna, at the access point (AP). Intentionally generating random directional beam patterns creates channel fluctuation, which is transformed into a random key for encryption of communications. Experimental results show that the system has the potential to achieve "unconditional security."

Chapter XXI presents the applications of smart antenna technologies to radio frequency identification (RFID) systems. A 3×2-element planar phased array antenna has been designed in a compact package for RFID readers. The antenna covers the 860–960 GHz frequency band with more than 10 dB input return loss, 12 dBi broadside gain, and up to 40° elevation beam scanning with a 4-bit reflection-type phase shifter array.

Section IV: Experiments and Implementations

Chapter XXII gives a comprehensive review of different types of testbeds for MIMO wireless communication systems. Furthermore, the design and development of a 2x2 MIMO testbed that uses antennas built in-house, commercially available RF chips for an RF front end, and a Field Programmable Gate Array (FPGA) for based signal processing are described. The developed testbed is verified and tested with Alamouti quadrature phase shift keying (QPSK) signaling.

Chapter XXIII presents a testbed for implementing directional MAC protocols with smart antennas in wireless networks. The testbed makes it possible to investigate performance of MAC protocols in the real environment. It incorporates a compact array antenna, the Espar antenna, as a practical smart antenna, IEEE802.15.4/ZigBee, global positioning system (GPS) and gyro modules to allow easy installment of different MAC protocols.

Chapter XXIV introduces a wideband spatial beamformer as an alternative approach for a wideband smart antenna without tapped-delay lines and frequency filters. A prototype antenna is developed. Furthermore, an experiment is carried out to verify the concept of the proposed wideband spatial beamformer. The experiment's results show that the wideband spatial beamformer has sufficient beam steering capability with a relatively simple technique and without using filters for the delay lines.

Chapter XXV studies three working modes, omni-, sector and adaptive modes, for a compact array antenna. The Espar antenna is implemented as a representative compact array antenna. Experiments are carried out to verify the omni-, sector and adaptive beam patterns of the Espar antennas.

In these 25 chapters, this timely publication provides an indispensable reference for people interested in smart antennas at all levels as well as for those working within the fields of wireless communications. In short, the handbook was prepared to help readers understand smart antennas as a key technology in modern wireless communication systems. It is our hope that this handbook will not only serve as a valuable reference for students, educators, faculty members, researchers, engineers and research strategists in the field but also guide them toward envisioning the future research and development of smart antenna technologies.

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