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Multiple-input multiple-output (MIMO) technology constitutes a breakthrough in the design of wireless communication systems, and is already at the core of several wireless standards. Exploiting multi-path scattering, MIMO techniques deliver significant performance enhancements in terms of data transmission rate and interference reduction. This book is a detailed introduction to the analysis and design of MIMO wireless systems. Beginning with an overview of MIMO technology, the authors then examine the fundamental capacity limits of MIMO systems. Transmitter design, including precoding and space–time coding, is then treated in depth, and the book closes with two chapters devoted to receiver design. Written by a team of leading experts, the book blends theoretical analysis with physical insights, and highlights a range of key design challenges. It can be used as a textbook for advanced courses on wireless communications, and will also appeal to researchers and practitioners working on MIMO wireless systems.

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To our families.

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Preface

Facies non omnibus una,
Nec diversa tamen
(Ovid, Metamorphoses)

Wireless is one of the most rapidly developing technologies in our time, with dazzling new products and services emerging on an almost daily basis. These developments present enormous challenges for communications engineers, as the demand for increased wireless capacity grows explosively. Indeed, the discipline of wireless communications presents many challenges to designers that arise as a result of the demanding nature of the physical medium and the complexities in the dynamics of the underlying network. The dominant technical issue in wireless communications is that of multipath-induced fading, namely the random fluctuations in the channel gain that arise due to scattering of transmitted signals from intervening objects between the transmitter and the receiver. Multipath scattering is therefore commonly seen as an impairment to wireless communication. However, it can now also be seen as providing an opportunity to significantly improve the capacity and reliability of such systems. By using multiple antennas at the transmitter and receiver in a wireless system, the rich scattering channel can be exploited to create a multiplicity of parallel links over the same radio band, and thereby to either increase the rate of data transmission through multiplexing or to improve system reliability through the increased antenna diversity. Moreover, we need not choose between multiplexing and diversity, but rather we can have both subject to a fundamental tradeoff between the two.

This book addresses multiple-input/multiple-output (MIMO) wireless systems in which transmitters and receivers may have multiple antennas. Since the emergence of several key ideas in this field in the mid-1990s, MIMO systems have been one of the most active areas of research and development in the broad field of wireless communications. An enormous body of work has been created in this area, leading to many immediate applications and to future opportunities. This book provides an entrée into this very active field, aiming at covering the main aspects of analysis and design of MIMO wireless. It is intended for graduate students as well as practicing engineers and researchers with a basic knowledge of digital communications and wireless systems, roughly at the level of [1–4].

The present book gives a unified and comprehensive view of MIMO wireless. After a general overview in Chapter 1, it covers the basic elements of the field in depth, including the fundamental capacity limits of MIMO systems in Chapter 2, transmitter design (including precoding and space–time coding) in Chapters 3 and 4, and receiver design in Chapters 5 and 6. Although the book is designed to be accessible to individual readers, it can also be used as an advanced graduate textbook, either in its entirety, or perhaps in one of two ways: for a course on MIMO Wireless Communication Systems (Chapters 1, 3, 5 and 6) or for a course on Information Theory and Coding in MIMO Wireless (Chapters 1–4).

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Notation

General notation

$\mathbf{X}$	Matrix $\mathbf{X}$ (boldface capital letter)
$\mathbf{x}$	Vector $\mathbf{x}$ (boldface lowercase letter)
$[\mathbf{X}]_{i,j}$	The element on row i and column j of matrix $\mathbf{X}$
$\mathbf{X}^T$	Transpose of $\mathbf{X}$
$\mathbf{X}^*$	Conjugate transpose of $\mathbf{X}$
$\det(\mathbf{X})$	Determinant of $\mathbf{X}$
$\mathrm{tr}(\mathbf{X})$	Trace of $\mathbf{X}$
$\|\|\mathbf{X}\|\|_F$	Frobenius norm of $\mathbf{X}$
$\lambda(\mathbf{X})$	Eigenvalues of $\mathbf{X}$
Λ_X	The diagonal matrix of the eigenvalues of the Hermitian matrix $\mathbf{X}$
Σ_X	The diagonal matrix of the singular values of $\mathbf{X}$
$\mathbf{U}_X$	The eigen- or singular-vector matrix of $\mathbf{X}$
$\mathbf{X} \succcurlyeq \mathbf{0}$	$\mathbf{X}$ is positive semi-definite
$\mathrm{vec}(\mathbf{X})$	Vectorize $\mathbf{X}$ into a vector by concatenating the columns of $\mathbf{X}$
$\otimes$	Kronecker product
$\mathbf{I}$	An identity matrix
$E[\cdot]$	Expected value
$(x)_+$	$= \begin{cases} x & \text{if } x \geq 0, \quad x \in \mathcal{R} \\ 0 & \text{if } x < 0, \quad x \in \mathcal{R} \end{cases}$

Symbols

M_T	The number of transmit antennas
M_R	The number of receive antennas
$\mathbf{H}$	A MIMO flat-fading channel
$\mathbf{H}_w$	A random channel with i.i.d. zero-mean complex Gaussian elements
$\mathbf{H}_m$	The channel mean
$\mathbf{R}$	A covariance of the channel
$\mathbf{R}_t$	Transmit covariance, also called the transmit antenna correlation
$\mathbf{R}_r$	Receive covariance, also called the receive antenna correlation
K	The Ricean K factor
T_c	The channel coherence time
B_c	The channel coherence bandwidth
D_c	The channel coherence distance
(t)	At time or delay t

ρ	Channel temporal correlation function
$\mathbf{F}$	The precoding matrix
p_i	Power loading on beam i
$\mathbf{C}$	A codeword
$\mathbf{Q}$	The codeword covariance matrix
$\mathbf{A}$	The codeword difference product matrix
γ	The signal-to-noise ratio

Abbreviations

APP	*A posteriori* probability
ARQ	Automatic repeat request
AWGN	Additive white Gaussian noise
BC	Broadcast channel
BCJR	Bahl–Cocke–Jelinek–Raviv
BER	Bit-error rate
BLAST	Bell Laboratories space–time
bps	Bits per second
BPSK	Binary phase-shift keying
CCI	Channel covariance information
CDF	Cumulative distribution function
CDI	Channel distribution information
CDIR	Receiver channel distribution information
CDIT	Transmitter channel distribution information
CDMA	Code-division multiple access
CDMA 2000	A CDMA standard
CIR	Channel impulse response
CMI	Channel mean information
CP	Cyclic prefix
CSI	Channel state information
CSIR	Receiver channel state information
CSIT	Transmitter channel state information
dB	Decibels
DDF	Decorrelating decision feedback
DFT	Discrete Fourier transform
DPC	Dirty paper coding
DS	Direct-sequence
DSL	Digital subscriber line
EDGE	Enhanced data rate for GSM evolution
EM	Expectation-maximization
EXIT	Extrinsic information transfer
FDD	Frequency-division duplex
FDE	Frequency domain equalizer
FDMA	Frequency-division multiple access

FER	Frame-error rate
FFT	Fast Fourier transform
FIR	Finite impulse response
GSM	Global system for mobile communications, a second-generation mobile communications standard
IBI	Inter-block interference
IC	Interference cancellation
IEEE	Institute of Electrical and Electronic Engineers
IFC	Interference channel
IFFT	Inverse FFT
iid	Independent, identically distributed
IO	Individually optimal
ISI	Intersymbol interference
JO	Jointly optimal
KKT	Karush–Kuhn–Tucker
LDC	Linear dispersion code
LDPC	Low-density parity check
LLR	Logarithmic likelihood ratio
LMMSE	Linear minimum mean-square error
LMS	Least mean-squares
LOS	Line-of-sight
MAC	Multiple-access channel
MAI	Multiple-access interference
MAP	Maximum *a posteriori* probability
MBWA	Mobile broadband wireless access
MIMO	Multiple-input multiple-output
MISO	Multiple-input single-output
ML	Maximum likelihood
MMSE	Minimum mean-square error
MRC	Maximum ratio combining
MSE	Mean-square error
MU	Multi-user
MUD	Multi-user detection
NAHJ-FST	Noise-averaged Hamilton–Jacobi fast subspace tracking
NUM	Network utility maximization
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access
PEP	Pairwise error probability
PRUS	Perfect root of unity sequences
PSD	Positive semi-definite
PSK	Phase shift keying
QAM	Quadrature amplitude modulation

QCI	Quantized channel information
QPSK	Quadrature phase-shift keying
QSTBC	Quasi-orthogonal STBC
RF	Radio frequency
RLS	Recursive least squares
RSC	Recursive systematic convolutional
RV	Random variable
SAGE	Space-alternating generalized EM
SC	Single carrier
SIMO	Single-input, multiple-output
SINR	Signal-to-interference-plus-noise ratio
SISO	Single-input, single-output
SI/SO	Soft-input/soft-output
SNR	Signal-to-noise ratio
SPA	Sum–product algorithm
ST	Space–time
STBC	Space–time block code
STC	Space–time coding/space–time code
STTC	Space–time trellis code
SU	Single user
SVD	Singular-value decomposition
TCP	Transport control protocol
TDD	Time-division duplex
TDMA	Time-division multiple access
36PP	36 Partnership project
TWLK	Tanner–Wieberg–Loeliger–Koetter
UEP	Unequal error protection
V-BLAST	Vertical BLAST
WCDMA	Wideband code-division multiple access
WiMAX	IEEE 802.16 standard
WLAN	Wireless local area network
WMAN	Wireless metropolitan area network
ZF	Zero-forcing
ZMSW	Zero mean spatially white

Contents

1 Introduction

1.1 MIMO wireless communication

The use of multiple antennas at the transmitter and receiver in wireless systems, popularly known as MIMO (multiple-input multiple-output) technology, has rapidly gained in popularity over the past decade due to its powerful performance-enhancing capabilities. Communication in wireless channels is impaired predominantly by multi-path fading. Multi-path is the arrival of the transmitted signal at an intended receiver through differing angles and/or differing time delays and/or differing frequency (i.e., Doppler) shifts due to the scattering of electromagnetic waves in the environment. Consequently, the received signal power fluctuates in space (due to angle spread) and/or frequency (due to delay spread) and/or time (due to Doppler spread) through the random superposition of the impinging multi-path components. This random fluctuation in signal level, known as fading, can severely affect the quality and reliability of wireless communication. Additionally, the constraints posed by limited power and scarce frequency bandwidth make the task of designing high data rate, high reliability wireless communication systems extremely challenging.

MIMO technology constitutes a breakthrough in wireless communication system design. The technology offers a number of benefits that help meet the challenges posed by both the impairments in the wireless channel as well as resource constraints. In addition to the time and frequency dimensions that are exploited in conventional single-antenna (single-input single-output) wireless systems, the leverages of MIMO are realized by exploiting the spatial dimension (provided by the multiple antennas at the transmitter and the receiver).

We indicate the kind of performance gains that are expected from the use of MIMO technology by plotting in Figure 1.1 the data rate versus the receive signal-to-noise ratio (SNR) in a 100 kHz channel for an $M \times M$ (i.e., M receive and M transmit antennas) fading link with $M = 1, 2, 4$. The channel response is assumed constant over the bandwidth of interest for this simple example. Assuming a target receive SNR of 25 decibels (dB), a conventional single-input single-output (i.e., $M = 1$) system can deliver a data rate of 0.7 Mbps (where Mbps denotes Mbits per second). With $M = 2$ and 4 we can realize data rates of 1.4 and 2.8 Mbps respectively. This increase in data rate is realized for no additional power or bandwidth expenditure compared to the single-input single-output system. In principle, the single-input single-output system can achieve the data rate of 2.8 Mbps with a receive SNR of 25 dB if the bandwidth is increased to 400 kHz, or