Coding for MIMO Communication Systems

Tolga M. Duman and Ali Ghrayeb

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MIMO Communication Systems

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Preface

Employing multiple transmit and receive antennas, namely using multi-input multi-output (MIMO) systems, has proven to be a major breakthrough in providing reliable wireless communication links. Since their invention in the mid-1990s, transmit diversity, achieved through space-time coding, and spatial multiplexing schemes have been the focus of much research in the area of wireless communications. Although many significant advancements have been made recently in MIMO communications, there is still much ongoing research in this area. Parallel to that, communication companies have already started looking into integrating MIMO systems in their current and future wireless communication systems. In fact, several standards for future wireless communication applications have already adopted MIMO systems as an option.

This book is intended to provide a comprehensive coverage of coding techniques for MIMO communication systems. The contents of this book have evolved over the past several years as a result of our own research in MIMO communications, and the tutorials and short courses we have given at several conferences (including IEEE International Conference on Communications (ICC), Global Telecommunications Conference (GLOBECOM), Vehicular Technology Conference (VTC), and Wireless Communications and Networking Conference (WCNC)). The feedback we have received motivated us to write this book in order to address the fundamentals of MIMO communications in an accessible manner.

At this time, several books have been published on MIMO systems. However, there are a number of factors that differentiate this book from the existing ones. First, we try to stay away from including very complicated derivations, mathematical expressions, and very specific systems. Instead, we focus more on the fundamental issues pertaining to MIMO systems. We use language that is easy to comprehend for a wide audience interested in this topic, including starting graduate or senior undergraduate students majoring in electrical engineering with some limited training in digital communications and probability theory. For certain topics, we present more details with some derivations in an effort to accommodate the needs of a more specific group of researchers or advanced graduate students. However, the book is organized in such a way that these subjects are easy to spot, and thus, these should not overwhelm the rest of the audience. Another major factor that differentiates this book from other books is the breadth of coverage of topics. For instance, in addition to our coverage of basic MIMO communication algorithms, such as space-time block codes, space-time trellis codes, unitary and differential signaling and spatial multiplexing schemes, we include a detailed coverage of turbo codes and iterative decoding for MIMO systems, antenna selection algorithms, practical issues such as spatial correlation and channel estimation, as well as MIMO systems for frequency selective fading channels. Finally, we provide numerous examples – some elementary, some more advanced – on various topics covered, and a large number of references on MIMO communications at the end of each chapter.

Audience

The primary audience of this book is senior undergraduate students, graduate students, practitioners and researchers who are interested in learning more about MIMO systems, or perhaps would like to get into this area of research. For the audience to get the full benefits of the book, it is recommended that they have some background in digital communications, linear algebra and probability theory.

Although this book is intended primarily for researchers and practitioners, it can also be adopted as a textbook for a graduate level, or an advanced undergraduate level, course on "Wireless MIMO Communications." The language, organization, and flow of the material should make this easy. The material could be covered in a one-semester course. In order to facilitate its use as a textbook, the book is also complemented with a set of problems at the end of each chapter which serve the purpose of making the main topics covered in each chapter more clear, and shedding some light on certain aspects that are not provided in detail in the text.

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Notation

$\approx$	approximately equal to
$\triangleq$	defined as equal to
$\gg$	much greater than
$\ll$	much less than
$\cdot$	multiplication operator
$\arg\max_x [f(x)]$	the value of x that maximizes the function $f(x)$
$\arg\min_x [f(x)]$	the value of x that minimizes the function $f(x)$
$\exp(x)$	exponential of x (i.e., e^x)
$\text{Im}\{x\}$	the imaginary part of x
$\text{Re}\{x\}$	the real part of x
$Q(x)$	Gaussian Q-function $\left(\frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt\right)$
$\mathbb{R}$	the field of all real numbers
$X \sim p_X(x)$	the random variable X has p.d.f. $p_X(x)$
$E[X]$	the expected value of random variable X
$H(X)$	the entropy of random variable X
$H(Y\|X)$	the conditional entropy of random variable Y given random variable X
$I(X; Y)$	the mutual information between random variables X and Y
$\|x\|$	the absolute value of the complex number x
$\angle x$	the angle of the complex number x
x^*	the conjugate of a scalar or vector quantity
$\boldsymbol{x}$	the vector $\boldsymbol{x}$
$\\|\boldsymbol{x}\\|$	the norm of vector $\boldsymbol{x}$
$\boldsymbol{x}^T$	the transpose of vector $\boldsymbol{x}$
$\boldsymbol{x}^H$	the Hermitian (conjugate transpose) of vector $\boldsymbol{x}$
$\boldsymbol{A}$	the matrix $\boldsymbol{A}$
$\boldsymbol{A}^T$	the transpose of matrix $\boldsymbol{A}$
$\boldsymbol{A}^H$	the Hermitian (conjugate transpose) of matrix $\boldsymbol{A}$
$\boldsymbol{A}^*$	the conjugate of matrix $\boldsymbol{A}$
$\boldsymbol{A}^{-1}$	the inverse of matrix $\boldsymbol{A}$
$\\|\boldsymbol{A}\\|$	the Frobenius norm of the matrix $\boldsymbol{A}$ (i.e., sum of absolute value squares of all the entries of $\boldsymbol{A}$)
$\det(\boldsymbol{A})$	the determinant of matrix $\boldsymbol{A}$
$\text{trace}(\boldsymbol{A})$	the trace of matrix $\boldsymbol{A}$

$\boldsymbol{I}_N$	the $N \times N$ identity matrix
$\mathbf{0}_N$	the $N \times N$ all zero matrix
$\mathbf{0}_{M\times N}$	the $M \times N$ all zero matrix
$diag\{a_1, a_2, \ldots, a_N\}$	the diagonal matrix with elements $a_1, a_2, \ldots, a_N$ on the main diagonal
N_t	number of transmit antennas
N_r	number of receive antennas
$h_{i,j}$	channel coefficient between the ith transmit and jth receive antennas
$h^{(l)}(k)$	ISI channel coefficient for the lth tap at time k
$h_{i,j}^{(l)}(k)$	channel coefficient from the ith antenna to the jth antenna at time k for the lth channel tap
$\boldsymbol{H}$	MIMO channel matrix
$\boldsymbol{X}$	transmitted signal
$\boldsymbol{Y}$	received signal
$\boldsymbol{N}$	AWGN noise
ρ	average signal-to-noise ratio at each receive antenna
L	number of intersymbol interference taps
L_r	number of selected antennas at the receiver side
L_t	number of selected antennas at the transmitter side
R_c	code rate
P_b	bit error probability
P_e	probability of error
T	coherence time in number of symbols
N	frame length at each transmit antenna
$\log_x \det[\boldsymbol{A}]$	the log, base x, of the determinant of matrix $\boldsymbol{A}$
$\mathrm{sinc}(x)$	the sinc function $(\sin(\pi x)/\pi x)$
$X \sim \mathcal{CN}(0, 1)$	the random variable X is circularly symmetric complex Gaussian with zero mean and variance $1/2$ in each dimension
W	bandwidth of a signal
$C(f; t)$	time-varying frequency response of a wireless channel
$c(\tau; t)$	impulse response of a wireless channel
T_m	multipath spread
B_D	Doppler spread
B_C	coherence bandwidth
$(\Delta t)_c$	coherence time (in seconds)
$S(\tau; \lambda)$	scattering function

Abbreviations

APP	a posteriori probability
AWGN	additive white Gaussian noise
BP	belief propagation
BICM	bit interleaved coded modulation
BLAST	Bell Laboratories layered space-time
BPSK	binary phase shift keying
BSC	binary symmetric channel
c.d.f.	cumulative distribution function
CSI	channel state information
DBLAST	diagonal Bell Laboratories layered space-time
DFE	decision feedback equalization
DFT	discrete Fourier transform
DPSK	differential phase shift keying
DSTC	differential space-time code
EGC	equal gain combining
EM	expectation maximization
FFT	fast Fourier transform
FS	frequency selective
FSK	frequency shift keying
HBLAST	horizontal Bell Laboratories layered space-time
HDD	hard decision decoding
IFFT	inverse fast Fourier transform
IIR	infinite impulse response
ISI	intersymbol interference
LAPP	log a posteriori probability
LDPC	low density parity check
LLR	log likelihood ratio
LOS	line of sight
LS	least squares
LSTC	layered space-time code
MAP	maximum a posteriori
MAPP	modified a posteriori probability
MIMO	multiple-input multiple-output
MISO	multiple-output single-input
ML	maximum likelihood
MLSD	maximum likelihood sequence detector

MLSTC	multilayered space-time code
MMSE	minimum mean-squared error
MMSE-IC	minimum mean-squared error with interference cancellation
M-PSK	M-ary phase shift keying
MRC	maximum ratio combining
MSOVA	modified soft output Viterbi algorithm
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PAM	pulse amplitude modulation
PCCC	parallel concatenated convolutional code
PEP	pairwise error probability
p.d.f.	probability density function
PSK	phase shift keying
QAM	quadrature amplitude modulation
RF	radio frequency
RSC	recursive systematic convolutional
SC	selection combining
SCBLAST	single code Bell Laboratories layered space-time
SCCC	serial concatenated convolutional code
SDD	soft decision decoding
SISO	soft-input soft-output
SOVA	soft-output Viterbi algorithm
SSC	switch and stay combining
STBC	space-time block code
STC	space-time code
STCM	space-time coded modulation
STTC	space-time trellis code
SVD	singular value decomposition
TC-DSTC	turbo coded differential space-time code
TC-USTC	turbo-coded unitary space-time code
TCM	trellis-coded modulation
TDMA	time-division multiple access
TSTC	threaded space-time code
TuCM	turbo-coded modulation
USTC	unitary space-time code
VA	Viterbi algorithm
VBLAST	vertical Bell Laboratories layered space-time
ZF	zero forcing
ZF-IC	zero forcing with interference cancelation

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