Claude Oestges and Bruno Clerckx

MIMO WIRELESS COMMUNICATIONS

From Real-World Propagation to Space–Time Code Design

MIMO Wireless Communications

From real-world propagation to space–time code design

Claude Oestges and Bruno Clerckx

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Academic Press is an imprint of Elsevier

AP

Academic Press is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford, OX2 8DP
84 Theobald's Road, London WC1X 8RR, UK
30 Corporate Drive, Burlington, MA 01803
525 B Street, Suite 1900, San Diego, California 92101-4495, USA

First edition 2007

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN 13: 9-78-0-12-372535-6
ISBN 10: 0-12-372535-6

For information on all Academic Press publications visit our web site at books.elsevier.com

Typeset by Charon Tec Ltd, Chennai, India, www.charontec.com

Printed and bound in Great Britain

07 08 09 10 11 10 9 8 7 6 5 4 3 2 1

MIMO WIRELESS COMMUNICATIONS

Reviewers' Comments

Finally, a book devoted to MIMO from a new perspective that bridges traditional borders between propagation, channel modeling, signal processing, and space-time coding. Covering the latest European and American research results, the book gives a comprehensive treatment of general MIMO topics and provides surprising insights into advanced features, such as polarization, the finite-SNR behavior of space-time coding schemes in correlated channels, as well as correlation situations leading to higher mutual information than the i.i.d. Rayleigh channel. This is a book of high reference value combining intuitive and conceptual explanations with detailed, stringent derivations of basic facts of MIMO.

Ernst Bonek
Emeritus Professor
Technische Universität Wien, Austria, former Chairman of Working Groups on Propagation and Antennas in COST 259 and COST273

Claude Oestges and Bruno Clerckx have put together a survey of real-world MIMO propagation channel models and the performance of space-time coding and pre-coding schemes in such channels. This book offers important insights into how space-time coding can be tailored for real-world MIMO channels. The discussion of MIMO propagation models is also intuitive and well developed.

The book is both valuable and timely for wireless engineers since MIMO is now entering all the emerging broadband standards such as WiFi, WiMAX and 3GPPLTE.

Professor Arogyaswami J. Paulraj
Stanford University, CA

Preface

When we started thinking about writing this book, we had been working together for more than five years on the borderline between propagation and signal processing. Therefore, it is not surprising that this book deals with propagation models and design tools for MIMO wireless communications. Yet, this book should constitute more than a simple combination of these two domains. It hopefully conveys our integrated understanding of MIMO, which results from endless controversial discussions on various multi-antenna related issues, as well as various interactions with numerous colleagues. Obviously, this area of technology is so large that it was beyond our aim to cover all aspects in details. Rather, our goal has been to provide researchers, R&D engineers and graduate students with a comprehensive coverage of radio propagation models and space–time coding techniques.

Much has been written about MIMO. Still, the present issue is to 'make the thing work' in real-word wireless channels and under realistic power constraints. Indeed, both the antenna size and the transmit power are limited, which imposes some limitations on system design. As an example, space–time coding designs relying on idealistic propagation models may lose many of their advantages in more realistic radio channels. Therefore, a true challenge consists of proposing design methodologies that take MIMO propagation into account. Often, propagation models are considered by many as the simple combination of various 'cooking recipes', typically path-loss laws and tap-delay lines. Similarly, it is sometimes thought that a wireless transmission scheme does not need to care about the physics of the radio channel, but only about its impact on the received signals. In other words, propagation models would mostly be useful for *a posteriori* testing and modifying specific designs. Whereas this is certainly an important aspect of propagation models, which is well covered by IEEE standards, it may not be the only one, especially when dealing with multi-antenna wireless systems. Not only can radio propagation provide answers to some crucial questions of MIMO related problems, but it is also of outstanding importance for designing efficient transmission schemes. As a consequence, our approach builds on a deep study of MIMO propagation aspects, naturally including, but not limited to, classical simulation models. It shall enable designers to develop robust space–time coding schemes based on solid theoretical developments allied to a strong propagation-motivated intuition.

This book combines a description of the most recent space–time coding techniques with complete coverage of MIMO propagation models. Under both information theory and error probability perspectives, we emphasize how real-world propagation affects the capacity and error performance of MIMO transmission schemes. We then describe innovative and practical designs of robust space–time codes. We also cover, in detail, precoding schemes, antenna selection techniques and multi-carrier transmissions. We have attempted to build the book content as a logical flow, pointing out important theoretical results and providing various examples. Although we have tried to supply detailed and clearly indicated proofs for most results, the reader is sometimes guided to references for greater detail.

Now that this project has come to an end, there are several people who deserve our warmest thanks. We are first deeply grateful to Professor Arogyaswami J. Paulraj at Stanford University for introducing both of us to the challenging area of MIMO communications. Professor Ernst Bonek at TU Wien also deserves our gratitude for initiating this project, as well as for his long-lasting support and careful reading of the manuscript. We also acknowledge the help of many at UCL during these last years, especially Professor Danielle Vanhoenacker-Janvier and Professor Luc Vandendorpe. We thank all the past and present members of the Microwave Laboratory and the Digital Communication Group for their friendly encouragement. We also acknowledge the help of Tim Pitts, Kate Dennis, Helen Eaton and Jackie Holding at Elsevier for their kind and efficient handling of this publication project.

Last but not least, we wish to heartily thank a number of anonymous and not so anonymous reviewers for their careful reading and most useful advices: Bertrand Devillers, Dr Mischa Dohler, Dr Maxime Guillaud, Professor Are Hjørungnes, Marios Kountouris, and Harold Sneessens.

Claude Oestges
Bruno Clerckx

List of Abbreviations

2D, 3D	two or three dimensional
3G, 4G	third or fourth generation
3GPP	third generation partnership project
AWGN	additive white Gaussian noise
BBC	BER balancing criterion
BER	bit error rate
BPSK	binary phase-shift key
BS	base station
CCI	co-channel interference
CDD	cyclic delay-diversity
CDF	cumulative distribution function
CDI(T)	channel distribution information (at the transmitter)
CDMA	code division multiple access
CIR	channel impulse response
CP	cyclic prefix
CSI(T)	channel state information (at the transmitter)
D-BLAST	diagonal Bell Labs layered space–time
DFT	discrete Fourier transform
DoA	direction-of-arrival
DoD	direction-of-departure
DPS	direction power spectrum
EGC	equal gain combining
EVD	eigenvalue decomposition
FDD	frequency division duplexing
FEC	forward error correction
FER	frame error rate
GDD	generalized delay-diversity
HS/MRC	hybrid selection/maximal ratio combining
IDFT	inverse discrete Fourier transform
iff	if and only if
i.i.d.	independent and identically distributed
ISI	inter symbol interference
LAST	lattice space–time
LDC	linear dispersion code
LDPC	Low Density Parity Check
LOS	line of sight
LP	Lindskog-Paulraj
LSR	local scattering ratio

MC	multi-carrier
MFB	matched filter bound
MGF	moment generating function
MIMO	multiple-input multiple-output
MISO	multiple-input single-output
ML	maximum likelihood
MLSE	maximum-likelihood sequence estimation
MMSE	minimum mean square error
MRC	maximum ratio combining
MT	mobile terminal
OFDM	orthogonal frequency division multiplexing
OSIC	ordered successive interference canceller
O-SFBC	orthogonal space-frequency block code
O-STBC	orthogonal space–time block code
PAM	Pulse Amplitude modulation
PDF	probability density function
PDS	power-delay spectrum
PEP	pairwise error probability
PSK	phase shift keying
QAM	quadrature amplitude modulation
QoS	quality of service
QO-STBC	quasi-orthogonal space–time block code
QPSK	quadrature phase shift keying
RF	radio frequency
RMS	root mean square
Rx	receiver
SC	single-carrier
SER	symbol error rate
SIC	successive interference canceler
SIMO	single-input multiple-output
SINR	signal-to-interference-and-noise ratio
SISO	single-input single-output
SM	spatial multiplexing
SNR	signal-to-noise ratio
ST	space–time
STBC	space–time block code
STTC	space–time trellis code
SU	subscriber unit
SUI	Stanford University Interim
SVD	singular value decomposition
SVER	symbol vector error rate
TAST	threaded algebraic space–time
TCM	trellis coded modulation

TDD	time division duplexing
TIMO	two-input multiple-output
Tx	transmitter
ULA	Uniform linear arrays
UMTS	universal mobile telecommunication system
UTD	Uniform Theory of Diffraction
V-BLAST	vertical Bell Labs layered space–time
WLAN	wireless local area networks
WLL	wireless local loop
WMAN	wireless metropolitan area networks
WSSUH	wide-sense stationary uncorrelated scattering homogeneous
XPD	cross-polar discrimination
ZF	zero-forcing

List of Symbols

$\triangleq$	variable definition
$\mathcal{E}$	expectation operator
$\otimes$	Kronecker product
$\odot$	Hadamard (element-wise) product
$\star$	convolution product
$\doteq$	exponential equality, $f(x) \doteq x^n \Leftrightarrow \lim_{x\to\infty} \frac{\log_2(f(x))}{\log_2(x)} = b$
$\mathbb{R}$	real field
$\mathbb{Z}$	integer field
$\mathbb{C}$	complex field
ρ	signal-to-noise ratio
a, α	scalar
$\mathbf{a}$	column or row vector
$\mathbf{A}$	matrix
$\mathbf{A}(m,n)$	element in m^{th} row and n^{th} column of matrix $\mathbf{A}$
$\mathbf{A}(m,:)$	m^{th} row of matrix $\mathbf{A}$
$\mathbf{A}(:,n)$	n^{th} column of matrix $\mathbf{A}$
$\mathbf{A}^T$	transpose
$\mathbf{A}^*$	conjugate
$\mathbf{A}^H$	conjugate transpose (Hermitian)
$\mathbf{A}^\dagger$	pseudo-inverse
$\mathbf{A} \succcurlyeq 0$	means that $\mathbf{A}$ is positive semidefinite
$\det(\mathbf{A})$	determinant of $\mathbf{A}$
$\mathrm{Tr}\{\mathbf{A}\}$	trace of $\mathbf{A}$
$\Re[\mathbf{A}]$	real part of $\mathbf{A}$
$\Im[\mathbf{A}]$	imaginary part of $\mathbf{A}$
$\|a\|$	absolute value of scalar a
$\|\mathbf{A}\|_F$	Frobenius norm of $\mathbf{A}$
$\|\mathbf{A}\|$	element-wise absolute value of matrix $\mathbf{A}$
$\|\mathbf{a}\|$	norm of $\mathbf{a}$
$\mathrm{vec}(\mathbf{A})$	stacks $\mathbf{A}$ into $mn \times 1$ vector columnwise
$\mathrm{diag}\{a_1, a_2, \ldots, a_n\}$	$n \times n$ diagonal matrix with $(m,m)^{th}$ element $= a_m$
$r(\mathbf{A})$	rank of the matrix $\mathbf{A}$
$\sigma_k(\mathbf{A})$	k^{th} singular value of matrix $\mathbf{A}$
$\lambda_k(\mathbf{A})$	k^{th} eigenvalue of matrix $\mathbf{A}$ (if Hermitian) or of matrix $\mathbf{AA}^H$ (if non Hermitian)
$\mathbf{0}_{m\times n}$	$m \times n$ matrix of zeros
$\mathbf{1}_{m\times n}$	$m \times n$ matrix of ones

$\mathbf{I}_m$	$m \times m$ identity matrix
$\lceil x \rceil$	$\lceil x \rceil = \begin{cases} 1 \text{ if } x > 0 \\ 0 \text{ if } x = 0 \end{cases}$
mod x	modulo x operation
$\delta\,[x]$	Dirac delta (unit impulse) function
$\sharp\tau$	cardinality of the set τ
$\psi(n)$	digamma function, $\psi(n) = \sum_{k=1}^{n-1} \frac{1}{k} - \gamma$, $\gamma \approx 0.57721566$ is Euler's constant
$\mathcal{Q}(x)$	$\mathcal{Q}$-function, $\mathcal{Q}\,(x) = 1/\sqrt{2\pi} \int_x^\infty e^{-t^2/2} dt$
$E_p(x)$	exponential integral of order p, $E_p(x) = \int_1^\infty e^{-xu}\, u^{-p}\, du$, $\Re[x] > 0$
$\Gamma(x, y)$	incomplete gamma function, $\Gamma(x, y) = \int_y^\infty u^{x-1}\, e^{-u}\, du$, $\Re[x] > 0$
$\Gamma(x)$	gamma function, $\Gamma(x) = \Gamma(x, 0) = \int_0^\infty u^{x-1}\, e^{-u}\, du$, $\Re[x] > 0$
$\binom{n}{p}$	binomial coefficient, $\binom{n}{p} = \frac{n!}{p!(n-p)!}$
$p_x(x)$	probability density function of random variable x
$p_{x_1,\ldots,x_n}(x_1, \ldots, x_n)$	joint probability density function of random variables $x_1, \ldots, x_n$
$\mathcal{M}_x(\tau)$	moment generating function of random variable x, $\mathcal{M}_x(\tau) = \mathcal{E}\{e^{\tau x}\}$

About the Authors

Claude Oestges received the MS degree and the PhD degree in Applied Science from the Université catholique de Louvain (UCL, Louvain-la-Neuve, Belgium), in 1996 and 2000, respectively. From 1996 to 2000, he was an Assistant Lecturer in the Microwave Laboratory UCL. In 2001, he joined (for one year) the Smart Antennas Research Group (Information Systems Laboratory) of Stanford University (California, USA) as a post-doctoral scholar. Since October 2005, Claude Oestges has been a Research Associate of the Belgian National Science Foundation (FRS – Fonds de la Recherche Scientifique) and a part-time Associate Professor at UCL. His research interests cover wireless and satellite communications, with a specific focus on the propagation channel and its impact on system performance. Claude Oestges is the author or co-author of more than 60 papers in IEEE/IEE journals and conference proceedings. He was a member of the IEEE 802.11 Standardization Working Group on '*Multiple antenna channel modeling*'. He received the IEE Marconi Premium Award in 2001 and the IEEE Vehicular Technology Society 2004 Neal Shepherd Award.

Bruno Clerckx received the MS degree and the PhD degree in Applied Science from the Université catholique de Louvain (UCL, Louvain-la-Neuve, Belgium), in 2000 and 2005, respectively. From September 2000 to August 2006, he was with the Microwave Laboratory UCL, as a Research Assistant and a PhD student funded by the Belgian National Science Foundation for Industrial Research (until September 2005) and as a Post-Doctoral Scholar (until August 2006). He held several visiting research positions at the Smart Antennas Research Group (Information Systems Laboratory), Stanford University (CA, USA), and at the Mobile Communication Department of Eurecom Institute (Sophia-Antipolis, France). Bruno Clerckx is currently with the Communication & Network Laboratory of Samsung Advanced Institute of Technology (SAIT) in Korea. He is the author or co-author of more than 25 research papers and communications. He received the IEEE Symposium on Communications and Vehicular Technology Best Student Paper Award in 2002.

Contents