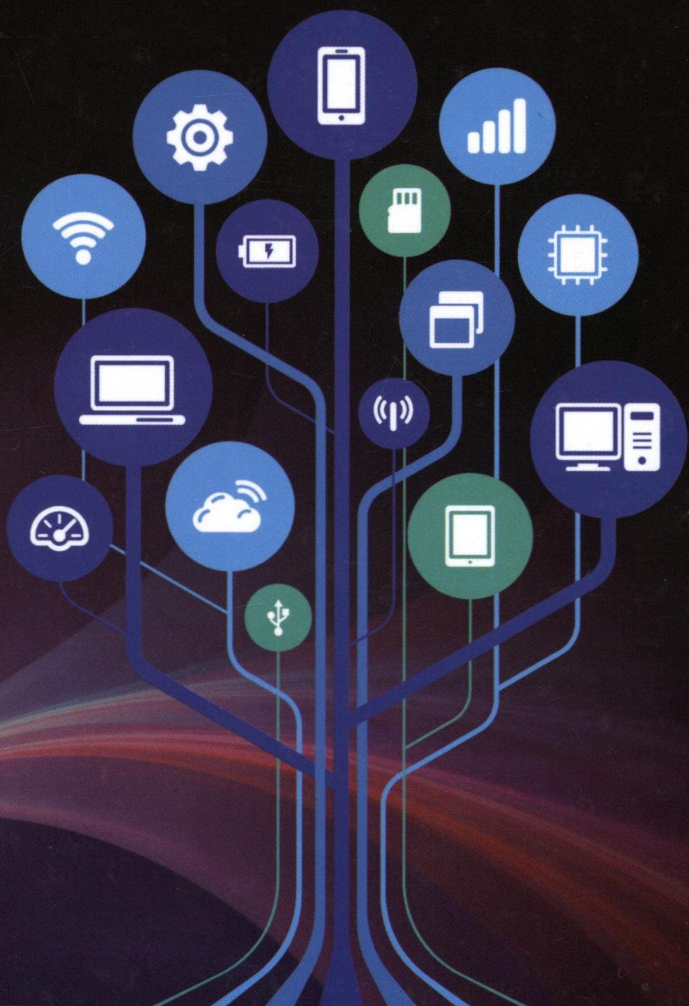
Fundamentals of MIMO Wireless Communications

Rakhesh Singh Kshetrimayum



Since the first Multiple Input Multiple Output (MIMO) approach was patented in 1994 by T. Kailath and A. J. Paulraj, MIMO has been a well-researched topic in wireless communications. Presenting state-of-the-art MIMO techniques, this book builds a clear and coherent understanding of the essential concepts of MIMO wireless communications. Dr Kshetrimayum discusses all important techniques and tools of MIMO wireless communications which include but does not limit to MIMO channel models, power allocations and channel capacity, space-time codes, MIMO detection and antenna selection. An important feature of the book is to provide practical insights into the world of modern telecommunication systems. Some recent techniques developed in MIMO wireless in the last decade including spatial modulation, MIMO based cooperative communications, Large-scale MIMO systems, massive MIMO and STBC-SM are also covered. The concepts are supported by numerous solved examples, review questions, simulation figures and exercises. This course book is intended for graduate students in electronics, electrical and computer engineering.

Rakhesh Singh Kshetrimayum is a Professor at the Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati. He is Life Fellow of IETE, Antenna Test and Measurement Society (ATMS) and a senior member of IEEE, USA. His research areas include printed monopole antennas, passive microwave devices and wireless communications.

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Dedicated to
my beloved wife G. D. Kshetrimayum

Preface

This book aims to give its readers an opportunity to build a strong foundation in the subject of MIMO wireless communications. It is an ideal book for students pursuing senior undergraduate and junior postgraduate courses in MIMO wireless communications. The necessary background details of wireless communications have been put in Appendix A–G.

Chapter 1 gives a brief introduction to multiple-input multiple-output (MIMO) (pronounced 'My-Moe') systems. The receiver diversity techniques in single-input multiple-output (SIMO) systems are briefly discussed. Following that, MIMO transmit diversity scheme viz., Open Loop, Closed Loop and Blind MIMO systems are also talked about. Rate and diversity gain is defined and a discussion about the diversity multiplexing trade-offs is also provided.

Fading distributions, the precursors to MIMO channel models, are treated in chapter 2. Fading distributions could be divided into two kinds: (a) classical fading distributions and (b) generalized fading distributions. In classical fading distributions, the probability density function (pdf), the cumulative distribution function (cdf) and the moment generating function (mgf) of Gaussian, Rayleigh, Rice, Chi-squared and Nakagami-m fading distributions are provided. Among the many generalized fading distributions, k-μ, α-μ and η-μ fading distributions are investigated and in particular, classical fading distributions are also discussed.

Chapter 3 is devoted to the analytical MIMO channel models. Analytical MIMO channel models can be divided into four types: (a) independent and identically distributed (uncorrelated) MIMO channel model, (b) Kronecker (separately correlated) MIMO fading channel model, (c) fully correlated MIMO channel model, and (d) keyhole (rank deficit) MIMO channel model. Parallel decomposition of MIMO channel is discussed at the end of the chapter.

The capacity of a MIMO channel for uniform and adaptive power allocation scheme is treated in chapter 4. Uniform power allocation is employed when the channel state information (CSI) is available at the receiver but not at the transmitter (open loop MIMO system). Adaptive power allocation based on Waterfilling algorithm can be used when CSI is available at the receiver as well as at the transmitter (closed loop MIMO system). Near optimal power allocation for high and low SNR cases is described in the last section of the chapter.

In chapter 5, the capacity of simplified MIMO channels viz., (a) SISO channels, (b) SIMO channels, (c) MISO channels, (d) unity MIMO channel, and (e) identity MIMO channel, is investigated. The ergodic capacity and outage probability for some of the above fading channels are also found out.

The ergodic capacity and outage probability for i.i.d. fading MIMO channels are described in chapter 6. Then, the effect of antenna correlation on the MIMO channel capacity is observed. Finally, it is shown that if we have keyhole propagation for a highly scattered environment, the capacity is very low.

In chapter 7, a discussion on why we need space-time codes is presented at the very first. Then, the three code design criteria, viz., rank, determinant and trace, is provided. A study on the first and the most powerful space-time codes, also known as Alamouti space-time codes, is carried out. The performance comparison of Alamouti space-time code with maximal ratio combining (MRC) is described. The coding gain, diversity gain and code rate of Alamouti space-time code are presented. A very important concept in performance analysis of wireless communication over fading channel is that in order to find the average probability of error, we need to find the average conditional probability of error (CEP) over the received SNR. A channel is in outage whenever we transmit a message at a higher rate than the channel capacity. In the last section of the chapter, the outage probability and average probability of error for single input single output (SISO) system over fading channels, and an extension of this analysis for Alamouti space-time codes, are provided.

An extension of Alamouti space-time code for N_T number of transmitting antennas, also known as orthogonal space-time block codes (OSTBC), is introduced. But OSTBC does not provide any coding gain. There is another type of space-time code, termed as space-time trellis code (STTC), which provides both coding and diversity gains. An exploration of both of these space-time codes is carried out in chapter 8. The symbol error rate (SER) of OSTBC over spatially correlated Rayleigh fading, as well as the i.i.d. Rayleigh fading of MIMO channels is calculated. Pairwise error probability (PEP) calculation of space-time codes over correlated as well as i.i.d. Rayleigh fading is also carried out. A brief introduction to space-time Turbo codes is presented. Some sections are devoted to differential OSTBC and algebraic space-time codes, which include Perfect space time codes and Golden codes.

In MIMO detection, one needs to detect signals jointly, since many signals are transmitted from the transmitter to the receiver. Among the available detection techniques, maximum likelihood (ML) detection is the most optimal technique, but its complexity grows exponentially with the number of antennas. There are other sub-optimal techniques like Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) which are less complex. Chapter 9 is devoted to such techniques. A comparison of the noise amplification in ZF and MMSE is presented and then, the performance of these techniques in terms of probability of error and outage probability is evaluated. Sphere decoding is also discussed in this chapter.

Chapter 10 contains Diagonal-Bell Laboratories Layered Space-Time (D-BLAST) and Vertical BLAST (V-BLAST), which are spatial multiplexed MIMO systems which give high spectral efficiencies. BLAST detection scheme is basically based on the following three steps: interference nulling, ordering to select the sub-stream with the largest signal-to-noise ratio (SNR) or other criteria, and successive interference cancellation.

MIMO systems increase the capacity and minimize the error rate as compared to SISO systems. But, they have a higher fabrication cost and energy consumption due to multiple RF chains. Selection of suitable antenna minimizes this by using lesser number of RF chains and switches. The best set of antennas should be selected at the transmitter or the receiver end, so as to maximize the channel capacity or the received SNR. Transmit antenna selection over η–μ fading channels is described in chapter 11 where soft antenna selection for closely spaced antennas is also introduced. Spatial Modulation (SM) is a multiple input multiple output (MIMO) wireless communication technique that gives better spectral efficiency for a fixed bandwidth and same signal constellation size. Symbol error rate (SER) performance of an SM system in generalized η-μ fading channels for several modulation schemes is evaluated. It is also shown that spatial modulation with antenna selection has a huge advantage in the outage probability over SM MIMO systems.

STBC-SM, MIMO based cooperative communication, Large scale MIMO systems and MIMO cognitive radios are some of the latest developments in MIMO wireless communications. A discussion on hybrid STBC and SM is provided also in this chapter. In chapter 12, it is shown that there can be a significant improvement in the performance of cooperative communication if one employs MIMO techniques. After this, Large scale MIMO systems are investigated. Three scenarios are discussed viz., Single User, Multi-user and Multi-cell Large scale MIMO systems. Finally MIMO Cognitive Radios are discussed in some detail.

Finally, there is a suggestion for all the students: hone your fundamentals! Technologies change every now and then, however, the fundamentals which are the building blocks for these new technologies remain the same.

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Abbreviations

AF	Amplify and Forward
ASTBC	Algebraic Space Time Block Codes
AWGN	Additive White Gaussian Noise
BC	Broadcast Channel
BEP	Bit Error Probability
BLAST	Bell Laboratories Layered Space Time
BPSK	Binary Phase Shift Keying
BS	Base Station
CDF	Cumulative Distribution Function
CGD	Coding Gain Distance
CoMP	Coordinated Multipoint Transmission
CPE	Conditional Probability of Error
CSI	Channel State Information
CSIR	Channel State Information at the Receiver
CSIT	Channel State Information at the Transmitter
CVP	Closest Vector Problem
DAST	Diagonal Algebraic Space Time
D-BLAST	Diagonal Bell Laboratories Layered Space Time
DBPSK	Differential Binary Phase Shift Keying
DF	Decode and Forward
DMUX	Demultiplexing
EP	Error Propagation
EVM	Error Vector Magnitude
FFT	Fast Fourier Transform
GSM	Global System for Mobile Communication
HAS	Hard Antenna Selection
H-BLAST	Horizontal Bell Laboratories Layered Space Time
ICI	Inter Cell Interference
iid	Independent and Identically Distributed
I-O	Input-Output
IUI	Inter User Interference
LLL	Lenstra, Lenstra & Lovasz
LLR	Log Likelihood Ratio
LOS	Line of Sight

LR	Lattice Reduction
LS MIMO	Large Scale Multiple-input Multiple-output
LTE	Long Term Evolution
MAC	Multiple Access Channel
MGF	Moment Generating Function
MIMO	Multiple-input Multiple-output
MISO	Multiple-input Single-output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MPAM	M-ary Pulse Amplitude Modulation
M-PSK	Multiple Phase Shift Keying
MRC	Maximal Ratio Combining
MSK	Minimum Shift Keying
MU MIMO	Multi User Multiple-input Multiple-output
NLOS	Non Line of Sight
NVD	Non Vanishing Determinant
Od	Orthogonal Defect
OOPSIC	Optimal Ordered Perfect Successive Interference Cancellation
OSIC	Ordered Successive Interference Cancellation
OSTBC	Orthogonal Space Time Block Code
PEP	Pairwise Error Probability
PSIC	Perfect Successive Interference Cancellation
PSD	Power Spectral Density
PSTBC	Perfect Space Time Block Code
PUs	Primary Users
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RV	Random Variable
RZF	Regularized Zero Forcing
SAS	Soft Antenna Selection
SC	Selection Combining
SER	Symbol Error Rate
SIC	Successive Interference Cancellation
SINR	Signal-plus-interference-plus-noise Ratio
SIMO	Single-input Multiple-output
SISO	Single-input Single-output
SM	Spatial Modulation
S/P	Serial to Parallel Conversion
SNR	Signal to Noise Ratio
SRCC	Systematic Recursive Convolutional Codes
STBC	Space Time Block Code
STTC	Space Time Trellis Code
SU MIMO	Single User Multiple-input Multiple-output

SUs	Secondary Users
SVD	Singular Value Decomposition
TAS	Transmit Antenna Selection
TAST	Threaded Algebraic Space Time
V-BLAST	Vertical Bell Laboratories Layered Space Time
ZF	Zero Forcing
ZMCSCG	Zero Mean Circular Symmetric Complex Gaussian