

Introduction to MIMO Communications

This accessible, self-contained guide contains everything you need to get up to speed on the theory and implementation of MIMO techniques.

In-depth coverage of topics such as RF propagation, space-time coding, spatial multiplexing, OFDM in MIMO for broadband applications, the theoretical MIMO capacity formula, and channel estimation, will give you a deep understanding of how the results are obtained, while detailed descriptions of how MIMO is implemented in commercial WiFi and LTE networks will help you apply the theory to practical wireless systems.

Key concepts in matrix mathematics and information theory are introduced and developed as you need them, and key results are derived step by step, with no details omitted. Including numerous worked examples, and end-of-chapter exercises to reinforce and solidify your understanding, this is the perfect introduction to MIMO for anyone new to the field.

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“This is a well-organized comprehensive treatise on MIMO principles, methods, and applications. While many concepts are introduced in intuitively pleasing ways; the integration of detailed step-by-step mathematical developments of MIMO principles, propagation models, channel characterizations, and applications of MIMO in commercial systems adds tremendous depth and understanding to the concepts. After studying this text, if readers have interests in topics not covered, they will very likely be able to understand or author for themselves advanced MIMO literature on such topics.”

David Nicholson, Communications consultant

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Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment,
a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781107042834

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First published 2014

A catalogue record for this publication is available from the British Library

ISBN 978-1-107-04283-4 Hardback

Additional resources for this publication at www.cambridge.org/hampton

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Preface

This book is an outgrowth of a graduate course I have taught for the past four years on MIMO Wireless Communications in the Engineering for Professionals (EP) Program within the Whiting School of Engineering at The Johns Hopkins University. When I began to develop the course in the spring of 2006, I initially thought I would simply choose a textbook from the collection of numerous books that had been written on MIMO communications at that time. As I began studying these books, however, I found that, although they were each excellent in various ways, none of them was as accessible to the average practicing communications engineer or early level electrical engineering graduate student as I had hoped. Many of these books were written by experts in the field, researchers who had made seminal contributions in the area of MIMO communications, but the prerequisites needed to follow and understand the details in their presentations were often above the level of expertise of those being introduced to MIMO for the first time.

This book is my attempt to remedy this problem. In developing the course and in writing this book, I have tried to make the concepts and techniques associated with MIMO communications accessible to an average communications engineer with an undergraduate degree in electrical engineering. I assume that readers are familiar with digital communication techniques and that they have had a formal course (or its equivalent) in digital signal processing; however, I do not assume readers are familiar with information theory or are proficient in advanced matrix mathematics, areas of expertise that are normally assumed in the MIMO literature and in many of the books that have been published on this topic. When knowledge in these areas is required to understand MIMO concepts, I have attempted to include the necessary information on those topics in the book so that it is not necessary to consult external resources. In this sense, the book has been designed to be as self-contained as possible.

As its name suggests, this book is intended to provide an introduction to the field of MIMO communications, and is, therefore, by design not encyclopedic. My goal has been to provide readers new to MIMO communications with an understanding of the basic concepts and methods, thereby laying a foundation for further study and providing them with the ability to understand the vast literature on this subject.

Although my goal has been to make the concepts of MIMO understandable to the average communications engineer, I have tried to remain rigorous at the same time. One of my initial frustrations when I began searching for a textbook was that there were often large steps or gaps in derivations that were not explained, so I have attempted to fill in

the details of as many gaps as possible in my book, in some cases relegating the details to appendices to avoid interrupting the flow of the text.

A third feature of this book that I hope will be useful to readers is that it contains descriptions of how MIMO concepts are implemented in practical systems. MIMO techniques have now become as commonplace in wireless communications systems as modulation and error correction coding, so there is no shortage of examples of systems that use MIMO methods. In this book, I focus on WiFi (IEEE 802.11n) and LTE and explain how these two popular wireless standards implement MIMO concepts in practice.

Chapter 1 provides an overview of MIMO communication concepts and includes a section on key matrix properties and identities that are used throughout the book. This initial chapter explains the different types of MIMO schemes, defines fundamental concepts such as spatial diversity and spatial multiplexing, and presents measured performance results that demonstrate the performance benefits of MIMO.

Chapter 2 is devoted to derivation of the MIMO capacity formula, which predicts the maximum error-free data rate that can be supported by a MIMO communication system. This formula is used later in Chapter 3 to provide useful conceptual insights into how multiple antennas enable increased spectral efficiency. Although the MIMO capacity formula is derived using concepts from information theory, the chapter introduces concepts as necessary to derive the final result and does not assume the reader has a background in that subject.

Chapter 3 explores the implications of the MIMO capacity formula and uses it to compute the communications capacities of MIMO systems under various assumptions. The concepts of eigenmodes and channel rank are examined, and the spatial multiplexing technique called eigenbeamforming is derived and explained in this chapter.

Chapter 4 discusses RF propagation in general and develops the terminology and concepts used in characterizing multipath propagation in particular.

Chapter 5 presents several theoretical MIMO propagation models that have been developed based on theory and empirical results. Expressions for the channel model when both Rayleigh fading and line-of-sight propagation exist are also presented. These models are used to derive expressions for the dependence of the MIMO capacity on antenna correlation as well as on the amount of scattering in the channel.

Chapter 6 describes Alamouti coding, which is an important practical MIMO technique used to achieve transmit diversity. This chapter begins by examining the performance of ideal maximal ratio receive combining and then shows how Alamouti coding achieves diversity gain equal to a maximal ratio receive combiner.

Chapter 7 broadens the discussion begun in Chapter 6 to consider other types of coding techniques, called space-time codes, that can be used to achieve transmit spatial diversity. This chapter focuses on space-time block codes, but also introduces the reader to space-time trellis coding concepts. The chapter describes how to perform decoding, concluding with a presentation of representative performance results.

Chapter 8 addresses spatial multiplexing, which comprises the second major class of MIMO techniques. These techniques, which exploit multipath, enable MIMO systems to transmit higher data rates than can be achieved with conventional communication systems.

Chapter 9 discusses MIMO over broadband channels. Up to this point in the book, the assumption is that the bandwidth of the transmitted signal is smaller than the coherence bandwidth of the channel; however, in modern wireless communication systems this is seldom the case. In practice, broadband systems operate by employing OFDM signaling, so this chapter reviews OFDM and then shows how OFDM is used with the narrowband MIMO techniques developed earlier to support broadband service.

Chapter 10 discusses an important practical aspect of MIMO communications – the estimation of the properties of the communications channel. Since most MIMO techniques require that either the transmitter or the receiver (or both) have knowledge of the channel, channel estimation techniques are an essential aspect of any MIMO communication system. This chapter discusses the fundamental concepts used in MIMO channel estimation and describes how practical MIMO systems perform this function.

The book concludes with Chapter 11, which describes how MIMO is implemented in WiFi and LTE wireless communication systems.

I would like to conclude by acknowledging and thanking some key people that helped make this book possible. First, I want to thank the various students who have taken my course on MIMO Wireless Communications at Johns Hopkins over the past several years. Their penetrating questions have helped me improve both the course as well as this book. To the extent that this book succeeds in helping others understand MIMO concepts, I am indebted to these students.

In addition to my students in the EP program at Johns Hopkins, I would like to acknowledge Dennis Ryan at The Johns Hopkins University Applied Physics Laboratory who chairs the Janney Publication Program, which funds, on a competitive basis, sabbaticals for employees to write books and journal papers. I would like to thank Dennis and the Janney committee for granting me a sabbatical during the summer of 2012 to finish writing this book. Thanks also go to Rob Nichols for his encouragement and willingness to accommodate my absence from normal work duties during this sabbatical.

I would also like to express my gratitude to two colleagues who have provided invaluable support during the preparation of this book. Eric Yang shared his extensive knowledge of cellular wireless standards and guided me through the labyrinth of LTE and IEEE 802.11n standards documents that I used to write Chapter 11. Thanks Eric! I would also like to offer special thanks to Feng Ouyang, another colleague, who served as a sounding board for my interminable discussions on many aspects of MIMO theory during the lengthy gestation period of this book. Feng was incredibly patient and generous with his time while sharing his insights and mathematical expertise with me. Thanks Feng! This book would not have come about without Feng's and Eric's help.

Finally, I would like to thank my wife, Dorothy, for her support and patience during this project, which has consumed far too many of my weekends and nights over the past several years. I dedicate this book to her, to our two wonderful children, Jessica and Joshua, and finally, and ultimately, to God. *Soli Deo Gloria*

Jerry R. Hampton