

TURING

图灵原版电子与电气工程系列

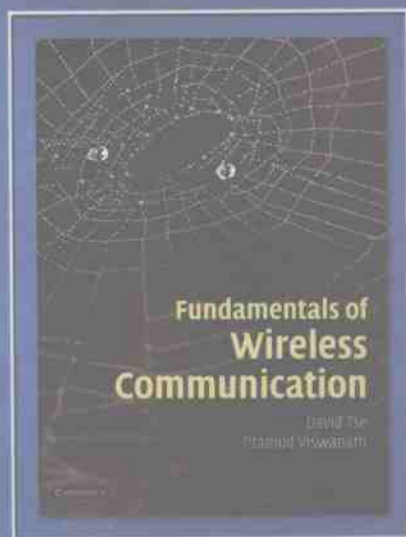
CAMBRIDGE

Fundamentals of  
Wireless Communication

# 无线通信基础

(英文版)

[美] David Tse 著  
Pramod Viswanath



人民邮电出版社  
POSTS & TELECOM PRESS

TURING

图灵原版电子与电气工程系列

Fundamentals of  
Wireless Communication

# 无线通信基础

(英文版)

[美] David Tse  
Pramod Viswanath 著

人民邮电出版社  
北京

## 图书在版编目 (CIP) 数据

无线通信基础 = Fundamentals of Wireless Communication: 英文 / (美) 谢 (Tse, D.), (美) 维斯瓦纳斯 (Viswanath, P.) 著. —北京: 人民邮电出版社, 2009. 8  
(图灵原版电子与电气工程系列)

ISBN 978-7-115-20070-9

I. 无… II. ①谢… ②维… III. 无线电通信—教材—英文 IV. TN92

中国版本图书馆CIP数据核字 (2009) 第 114107 号

## 内 容 提 要

本书介绍无线通信的基本原理, 着重强调概念及其在系统中的实现之间的相互影响, 涉及的主要问题有 MIMO 通信、空时编码、机会通信、OFDM 和 CDMA 等, 这些概念均利用无线系统的大量实例予以说明。书中还配有大量的习题和图表, 可以帮助读者进一步理解材料内容。

本书适合作为通信工程和电子信息类相关专业高年级本科生和研究生的教材, 也可供工程技术人员参考。

图灵原版电子与电气工程系列

### 无线通信基础 (英文版)

◆ 著 [美] David Tse [美] Pramod Viswanath

责任编辑 朱 巍

◆ 人民邮电出版社出版发行 北京市崇文区夕照寺街14号

邮编 100061 电子函件 315@ptpress.com.cn

网址 <http://www.ptpress.com.cn>

北京顺义振华印刷厂印刷

◆ 开本: 787 × 1092 1/16

印张: 36

字数: 690 千字

2009 年 8 月第 1 版

印数: 1 - 2 000 册

2009 年 8 月北京第 1 次印刷

著作权合同登记号 图字: 01-2009-3815 号

ISBN 978-7-115-20070-9/TN

定价: 79.00 元

读者服务热线: (010) 51095186 印装质量热线: (010) 67129223

反盗版热线: (010) 67171154

## 版 权 声 明

*Fundamentals of Wireless Communication, First Edition* (ISBN 9780521845274) by David Tse and Pramod Viswanath, first published by Cambridge University Press 2005.

All rights reserved.

This reprint edition for the People's Republic of China is published by arrangement with the Press Syndicate of the University of Cambridge, Cambridge, United Kingdom.

© Cambridge University Press & Posts & Telecom Press 2009.

This book is in copyright. No reproduction of any part may take place without the written permission of Cambridge University Press and Posts & Telecom Press.

This edition is for sale in the People's Republic of China (excluding Hong Kong SAR, Macau SAR and Taiwan Region) only.

此版本仅限在中华人民共和国境内（不包括香港、澳门特别行政区及台湾地区）销售。

# Acknowledgements

We would like first to thank the students in our research groups for the selfless help they provided. In particular, many thanks to: Sanket Dusad, Raúl Etkin and Lenny Gropop, who between them painstakingly produced most of the figures in the book; Aleksandar Jovičić, who drew quite a few figures and proofread some chapters; Ada Poon whose research shaped significantly the material in Chapter 7 and who drew several figures in that chapter as well as in Chapter 2; Saurabha Tavildar and Lizhong Zheng whose research led to Chapter 9; Tie Liu and Vinod Prabhakaran for their help in clarifying and improving the presentation of Costa precoding in Chapter 10.

Several researchers read drafts of the book carefully and provided us with very useful comments on various chapters of the book: thanks to Stark Draper, Atilla Eryilmaz, Irem Koprulu, Dana Porrat and Pascal Vontobel. This book has also benefited immensely from critical comments from students who have taken our wireless communication courses at Berkeley and Urbana-Champaign. In particular, sincere thanks to Amir Salman Avestimehr, Alex Dimakis, Krishnan Eswaran, Jana van Greunen, Nils Hoven, Shridhar Mubaraq Mishra, Jonathan Tsao, Aaron Wagner, Hua Wang, Xinzhou Wu and Xue Yang.

Earlier drafts of this book have been used in teaching courses at several universities: Cornell, ETHZ, MIT, Northwestern and University of Colorado at Boulder. We would like to thank the instructors for their feedback: Helmut Bölcskei, Anna Scaglione, Mahesh Varanasi, Gregory Wornell and Lizhong Zheng. We would like to thank Ateet Kapur, Christian Peel and Ulrich Schuster from Helmut's group for their very useful feedback. Thanks are also due to Mitchell Trott for explaining to us how the ArrayComm systems work.

This book contains the results of many researchers, but it owes an intellectual debt to two individuals in particular. Bob Gallager's research and teaching style have greatly inspired our writing of this book. He has taught us that good theory, by providing a unified and conceptually simple understanding of a morass of results, should *shrink* rather than *grow* the knowledge tree. This book is an attempt to implement this dictum. Our many discussions with Rajiv Laroia have significantly influenced our view of the system aspects of wireless communication. Several of his ideas have found their way into the "system view" discussions in the book.

Finally we would like to thank the National Science Foundation, whose continual support of our research led to this book.

# Preface

## Why we wrote this book

The writing of this book was prompted by two main developments in wireless communication in the past decade. First is the huge surge of research activities in physical-layer wireless communication theory. While this has been a subject of study since the sixties, recent developments such as opportunistic and multiple input multiple output (MIMO) communication techniques have brought completely new perspectives on how to communicate over wireless channels. Second is the rapid evolution of wireless systems, particularly cellular networks, which embody communication concepts of increasing sophistication. This evolution started with second-generation digital standards, particularly the IS-95 Code Division Multiple Access standard, continuing to more recent third-generation systems focusing on data applications. This book aims to present modern wireless communication concepts in a coherent and unified manner and to illustrate the concepts in the broader context of the wireless systems on which they have been applied.

## Structure of the book

This book is a web of interlocking concepts. The concepts can be structured roughly into three levels:

1. channel characteristics and modeling;
2. communication concepts and techniques;
3. application of these concepts in a system context.

A wireless communication engineer should have an understanding of the concepts at all three levels as well as the tight interplay between the levels. We emphasize this interplay in the book by interlacing the chapters across these levels rather than presenting the topics sequentially from one level to the next.

- Chapter 2: basic properties of multipath wireless channels and their modeling (level 1).
- Chapter 3: point-to-point communication techniques that increase reliability by exploiting time, frequency and spatial diversity (2).
- Chapter 4: cellular system design via a case study of three systems, focusing on multiple access and interference management issues (3).
- Chapter 5: point-to-point communication revisited from a more fundamental capacity point of view, culminating in the modern concept of opportunistic communication (2).
- Chapter 6: multiuser capacity and opportunistic communication, and its application in a third-generation wireless data system (3).

- Chapter 7: MIMO channel modeling (1).
- Chapter 8: MIMO capacity and architectures (2).
- Chapter 9: diversity–multiplexing tradeoff and space-time code design (2).
- Chapter 10: MIMO in multiuser channels and cellular systems (3).

## How to use this book

This book is written as a textbook for a first-year graduate course in wireless communication. The expected background is solid undergraduate/beginning graduate courses in signals and systems, probability and digital communication. This background is supplemented by the two appendices in the book. Appendix A summarizes some basic facts in vector detection and estimation in Gaussian noise which are used repeatedly throughout the book. Appendix B covers the underlying information theory behind the channel capacity results used in this book. Even though information theory has played a significant role in many of the recent developments in wireless communication, in the main text we only introduce capacity results in a heuristic manner and use them mainly to motivate communication concepts and techniques. No background in information theory is assumed. The appendix is intended for the reader who wants to have a more in-depth and unified understanding of the capacity results.

At Berkeley and Urbana-Champaign, we have used earlier versions of this book to teach one-semester (15 weeks) wireless communication courses. We have been able to cover most of the materials in Chapters 1 through 8 and parts of 9 and 10. Depending on the background of the students and the time available, one can envision several other ways to structure a course around this book. Examples:

- A senior level advanced undergraduate course in wireless communication: Chapters 2, 3, 4.
- An advanced graduate course for students with background in wireless channels and systems: Chapters 3, 5, 6, 7, 8, 9, 10.
- A short (quarter) course focusing on MIMO and space-time coding: Chapters 3, 5, 7, 8, 9.

The more than 230 exercises form an integral part of the book. Working on at least some of them is essential in understanding the material. Most of them elaborate on concepts discussed in the main text. The exercises range from relatively straightforward derivations of results in the main text, to “back-of-envelope” calculations for actual wireless systems, to “get-your-hands-dirty” MATLAB types, and to reading exercises that point to current research literature. The small bibliographical notes at the end of each chapter provide pointers to literature that is very closely related to the material discussed in the book; we do not aim to exhaust the immense research literature related to the material covered here.

# Notation

## Some specific sets

- $\mathcal{R}$  Real numbers
- $\mathcal{C}$  Complex numbers
- $\mathcal{S}$  A subset of the users in the uplink of a cell

## Scalars

- $m$  Non-negative integer representing discrete-time
- $L$  Number of diversity branches
- $\ell$  Scalar, indexing the diversity branches
- $K$  Number of users
- $N$  Block length
- $N_c$  Number of tones in an OFDM system
- $T_c$  Coherence time
- $T_d$  Delay spread
- $W$  Bandwidth
- $n_t$  Number of transmit antennas
- $n_r$  Number of receive antennas
- $n_{\min}$  Minimum of number of transmit and receive antennas
- $h[m]$  Scalar channel, complex valued, at time  $m$
- $h^*$  Complex conjugate of the complex valued scalar  $h$
- $x[m]$  Channel input, complex valued, at time  $m$
- $y[m]$  Channel output, complex valued, at time  $m$
- $\mathcal{N}(\mu, \sigma^2)$  Real Gaussian random variable with mean  $\mu$  and variance  $\sigma^2$
- $\mathcal{CN}(0, \sigma^2)$  Circularly symmetric complex Gaussian random variable: the real and imaginary parts are i.i.d.  $\mathcal{N}(0, \sigma^2/2)$
- $N_0$  Power spectral density of white Gaussian noise
- $\{w[m]\}$  Additive Gaussian noise process, i.i.d.  $\mathcal{CN}(0, N_0)$  with time  $m$
- $z[m]$  Additive colored Gaussian noise, at time  $m$
- $P$  Average power constraint measured in joules/symbol
- $\bar{P}$  Average power constraint measured in watts
- SNR Signal-to-noise ratio
- SINR Signal-to-interference-plus-noise ratio



$\mathcal{E}_b$  Energy per received bit  
 $P_e$  Error probability

### Capacities

$C_{\text{awgn}}$  Capacity of the additive white Gaussian noise channel  
 $C_\epsilon$   $\epsilon$ -Outage capacity of the slow fading channel  
 $C_{\text{sum}}$  Sum capacity of the uplink or the downlink  
 $C_{\text{sym}}$  Symmetric capacity of the uplink or the downlink  
 $C_\epsilon^{\text{sym}}$   $\epsilon$ -Outage symmetric capacity of the slow fading uplink channel  
 $P_{\text{out}}$  Outage probability of a scalar fading channel  
 $P_{\text{out}}^{\text{Ala}}$  Outage probability when employing the Alamouti scheme  
 $P_{\text{out}}^{\text{rep}}$  Outage probability with the repetition scheme  
 $P_{\text{out}}^{\text{ul}}$  Outage probability of the uplink  
 $P_{\text{out}}^{\text{mimo}}$  Outage probability of the MIMO fading channel  
 $P_{\text{out}}^{\text{ul-mimo}}$  Outage probability of the uplink with multiple antennas at the base-station

### Vectors and matrices

$\mathbf{h}$  Vector, complex valued, channel  
 $\mathbf{x}$  Vector channel input  
 $\mathbf{y}$  Vector channel output  
 $\mathcal{CN}(0, \mathbf{K})$  Circularly symmetric Gaussian random vector with mean zero and covariance matrix  $\mathbf{K}$   
 $\mathbf{w}$  Additive Gaussian noise vector  $\mathcal{CN}(0, N_0\mathbf{I})$   
 $\mathbf{h}^*$  Complex conjugate-transpose of  $\mathbf{h}$   
 $\mathbf{d}$  Data vector  
 $\bar{\mathbf{d}}$  Discrete Fourier transform of  $\mathbf{d}$   
 $\mathbf{H}$  Matrix, complex valued, channel  
 $\mathbf{K}_x$  Covariance matrix of the random complex vector  $\mathbf{x}$   
 $\mathbf{H}^*$  Complex conjugate-transpose of  $\mathbf{H}$   
 $\mathbf{H}'$  Transpose of matrix  $\mathbf{H}$   
 $\mathbf{Q}, \mathbf{U}, \mathbf{V}$  Unitary matrices  
 $\mathbf{I}_n$  Identity  $n \times n$  matrix  
 $\Lambda, \Psi$  Diagonal matrices  
 $\text{diag}\{p_1, \dots, p_n\}$  Diagonal matrix with the diagonal entries equal to  $p_1, \dots, p_n$   
 $\mathbf{C}$  Circulant matrix  
 $\mathbf{D}$  Normalized codeword difference matrix

### Operations

$\mathbb{E}[x]$  Mean of the random variable  $x$   
 $\mathbb{P}\{A\}$  Probability of an event  $A$   
 $\text{Tr}[\mathbf{K}]$  Trace of the square matrix  $\mathbf{K}$   
 $\text{sinc}(t)$  Defined to be the ratio of  $\sin(\pi t)$  to  $\pi t$   
 $Q(a) = \int_a^\infty (1/\sqrt{2\pi}) \exp^{-x^2/2} dx$   
 $\mathcal{L}(\cdot, \cdot)$  Lagrangian function

# Contents

<b>1</b>	<b>Introduction</b>	1
1.1	Book objective	1
1.2	Wireless systems	2
1.3	Book outline	5
<b>2</b>	<b>The wireless channel</b>	10
2.1	Physical modeling for wireless channels	10
2.1.1	Free space, fixed transmit and receive antennas	12
2.1.2	Free space, moving antenna	13
2.1.3	Reflecting wall, fixed antenna	14
2.1.4	Reflecting wall, moving antenna	16
2.1.5	Reflection from a ground plane	17
2.1.6	Power decay with distance and shadowing	18
2.1.7	Moving antenna, multiple reflectors	19
2.2	Input/output model of the wireless channel	20
2.2.1	The wireless channel as a linear time-varying system	20
2.2.2	Baseband equivalent model	22
2.2.3	A discrete-time baseband model	25
	<i>Discussion 2.1</i> Degrees of freedom	28
2.2.4	Additive white noise	29
2.3	Time and frequency coherence	30
2.3.1	Doppler spread and coherence time	30
2.3.2	Delay spread and coherence bandwidth	31
2.4	Statistical channel models	34
2.4.1	Modeling philosophy	34
2.4.2	Rayleigh and Rician fading	36
2.4.3	Tap gain auto-correlation function	37
	<i>Example 2.1</i> Clarke's model	38
	<i>Chapter 2</i> The main plot	40
2.5	Bibliographical notes	42
2.6	Exercises	42
<b>3</b>	<b>Point-to-point communication: detection, diversity, and channel uncertainty</b>	49
3.1	Detection in a Rayleigh fading channel	50
3.1.1	Non-coherent detection	50
3.1.2	Coherent detection	52
3.1.3	From BPSK to QPSK: exploiting the degrees of freedom	56
3.1.4	Diversity	59
3.2	Time diversity	60
3.2.1	Repetition coding	60
3.2.2	Beyond repetition coding	64
	<i>Summary 3.1</i> Time diversity code design criterion	68
	<i>Example 3.1</i> Time diversity in GSM	69
3.3	Antenna diversity	71
3.3.1	Receive diversity	71
3.3.2	Transmit diversity: space-time codes	73
3.3.3	MIMO: a $2 \times 2$ example	77
	<i>Summary 3.2</i> $2 \times 2$ MIMO schemes	82
3.4	Frequency diversity	83
3.4.1	Basic concept	83
3.4.2	Single-carrier with ISI equalization	84
3.4.3	Direct-sequence spread-spectrum	91
3.4.4	Orthogonal frequency division multiplexing	95
	<i>Summary 3.3</i> Communication over frequency-selective channels	101
3.5	Impact of channel uncertainty	102
3.5.1	Non-coherent detection for DS spread-spectrum	103
3.5.2	Channel estimation	105
3.5.3	Other diversity scenarios	107
	<i>Chapter 3</i> The main plot	109
3.6	Bibliographical notes	110
3.7	Exercises	111

<b>4 Cellular systems: multiple access and interference management</b>	120
<b>4.1 Introduction</b>	120
<b>4.2 Narrowband cellular systems</b>	123
4.2.1 Narrowband allocations: GSM system	124
4.2.2 Impact on network and system design	126
4.2.3 Impact on frequency reuse	127
<i>Summary 4.1</i> Narrowband systems	128
<b>4.3 Wideband systems: CDMA</b>	128
4.3.1 CDMA uplink	131
4.3.2 CDMA downlink	145
4.3.3 System issues	147
<i>Summary 4.2</i> CDMA	147
<b>4.4 Wideband systems: OFDM</b>	148
4.4.1 Allocation design principles	148
4.4.2 Hopping pattern	150
4.4.3 Signal characteristics and receiver design	152
4.4.4 Sectorization	153
<i>Example 4.1</i> Flash-OFDM	153
<i>Chapter 4</i> The main plot	154
<b>4.5 Bibliographical notes</b>	155
<b>4.6 Exercises</b>	155
<b>5 Capacity of wireless channels</b>	166
<b>5.1 AWGN channel capacity</b>	167
5.1.1 Repetition coding	167
5.1.2 Packing spheres	168
<i>Discussion 5.1</i> Capacity-achieving AWGN channel codes	170
<i>Summary 5.1</i> Reliable rate of communication and capacity	171
<b>5.2 Resources of the AWGN channel</b>	172
5.2.1 Continuous-time AWGN channel	172
5.2.2 Power and bandwidth	173
<i>Example 5.2</i> Bandwidth reuse in cellular systems	175
<b>5.3 Linear time-invariant Gaussian channels</b>	179
5.3.1 Single input multiple output (SIMO) channel	179
5.3.2 Multiple input single output (MISO) channel	179
5.3.3 Frequency-selective channel	181
<b>5.4 Capacity of fading channels</b>	186
5.4.1 Slow fading channel	187
5.4.2 Receive diversity	189
5.4.3 Transmit diversity	191
<i>Summary 5.2</i> Transmit and receive diversity	195
5.4.4 Time and frequency diversity	195
<i>Summary 5.3</i> Outage for parallel channels	199
5.4.5 Fast fading channel	199
5.4.6 Transmitter side information	203
<i>Example 5.3</i> Rate adaptation in IS-856	209
5.4.7 Frequency-selective fading channels	213
5.4.8 Summary: a shift in point of view	213
<i>Chapter 5</i> The main plot	214
<b>5.5 Bibliographical notes</b>	217
<b>5.6 Exercises</b>	217
<b>6 Multiuser capacity and opportunistic communication</b>	228
<b>6.1 Uplink AWGN channel</b>	229
6.1.1 Capacity via successive interference cancellation	229
6.1.2 Comparison with conventional CDMA	232
6.1.3 Comparison with orthogonal multiple access	232
6.1.4 General $K$ -user uplink capacity	234
<b>6.2 Downlink AWGN channel</b>	235
6.2.1 Symmetric case: two capacity-achieving schemes	236
6.2.2 General case: superposition coding achieves capacity	238
<i>Summary 6.1</i> Uplink and downlink AWGN capacity	240
<i>Discussion 6.1</i> SIC: implementation issues	241
<b>6.3 Uplink fading channel</b>	243
6.3.1 Slow fading channel	243

6.3.2	Fast fading channel	245
6.3.3	Full channel side information	247
	<i>Summary 6.2 Uplink fading channel</i>	250
<b>6.4</b>	<b>Downlink fading channel</b>	250
6.4.1	Channel side information at receiver only	250
6.4.2	Full channel side information	251
<b>6.5</b>	<b>Frequency-selective fading channels</b>	252
<b>6.6</b>	<b>Multiuser diversity</b>	253
6.6.1	Multiuser diversity gain	253
6.6.2	Multiuser versus classical diversity	256
<b>6.7</b>	<b>Multiuser diversity: system aspects</b>	256
6.7.1	Fair scheduling and multiuser diversity	258
6.7.2	Channel prediction and feedback	262
6.7.3	Opportunistic beamforming using dumb antennas	263
6.7.4	Multiuser diversity in multicell systems	270
6.7.5	A system view	272
	<i>Chapter 6 The main plot</i>	275
<b>6.8</b>	<b>Bibliographical notes</b>	277
<b>6.9</b>	<b>Exercises</b>	278
<b>7</b>	<b>MIMO I: spatial multiplexing and channel modeling</b>	290
<b>7.1</b>	<b>Multiplexing capability of deterministic MIMO channels</b>	291
7.1.1	Capacity via singular value decomposition	291
7.1.2	Rank and condition number	294
<b>7.2</b>	<b>Physical modeling of MIMO channels</b>	295
7.2.1	Line-of-sight SIMO channel	296
7.2.2	Line-of-sight MISO channel	298
7.2.3	Antenna arrays with only a line-of-sight path	299
7.2.4	Geographically separated antennas	300
7.2.5	Line-of-sight plus one reflected path	306
	<i>Summary 7.1 Multiplexing capability of MIMO channels</i>	309
<b>7.3</b>	<b>Modeling of MIMO fading channels</b>	309
7.3.1	Basic approach	309
7.3.2	MIMO multipath channel	311
7.3.3	Angular domain representation of signals	311
7.3.4	Angular domain representation of MIMO channels	315
7.3.5	Statistical modeling in the angular domain	317
7.3.6	Degrees of freedom and diversity	318
	<i>Example 7.1 Degrees of freedom in clustered response models</i>	319
7.3.7	Dependency on antenna spacing	323
7.3.8	i.i.d. Rayleigh fading model	327
	<i>Chapter 7 The main plot</i>	328
<b>7.4</b>	<b>Bibliographical notes</b>	329
<b>7.5</b>	<b>Exercises</b>	330
<b>8</b>	<b>MIMO II: capacity and multiplexing architectures</b>	332
<b>8.1</b>	<b>The V-BLAST architecture</b>	333
<b>8.2</b>	<b>Fast fading MIMO channel</b>	335
8.2.1	Capacity with CSI at receiver	336
8.2.2	Performance gains	338
8.2.3	Full CSI	346
	<i>Summary 8.1 Performance gains in a MIMO channel</i>	348
<b>8.3</b>	<b>Receiver architectures</b>	348
8.3.1	Linear decorrelator	349
8.3.2	Successive cancellation	355
8.3.3	Linear MMSE receiver	356
8.3.4	Information theoretic optimality	362
	<i>Discussion 8.1 Connections with CDMA multiuser detection and ISI equalization</i>	364
<b>8.4</b>	<b>Slow fading MIMO channel</b>	366
<b>8.5</b>	<b>D-BLAST: an outage-optimal architecture</b>	368
8.5.1	Suboptimality of V-BLAST	368
8.5.2	Coding across transmit antennas: D-BLAST	371
8.5.3	Discussion	372

	<i>Chapter 8 The main plot</i> .....	373
8.6	<b>Bibliographical notes</b> .....	374
8.7	<b>Exercises</b> .....	374
<b>9</b>	<b>MIMO III: diversity–multiplexing tradeoff and universal space-time codes</b> .....	383
9.1	<b>Diversity–multiplexing tradeoff</b> .....	384
9.1.1	Formulation .....	384
9.1.2	Scalar Rayleigh channel .....	386
9.1.3	Parallel Rayleigh channel .....	390
9.1.4	MISO Rayleigh channel .....	391
9.1.5	$2 \times 2$ MIMO Rayleigh channel .....	392
9.1.6	$n_t \times n_r$ MIMO i.i.d. Rayleigh channel .....	395
9.2	<b>Universal code design for optimal diversity–multiplexing tradeoff</b> .....	398
9.2.1	QAM is approximately universal for scalar channels .....	398
	<i>Summary 9.1</i> Approximate universality .....	400
9.2.2	Universal code design for parallel channels .....	400
	<i>Summary 9.2</i> Universal codes for the parallel channel .....	406
9.2.3	Universal code design for MISO channels .....	407
	<i>Summary 9.3</i> Universal codes for the MISO channel .....	410
9.2.4	Universal code design for MIMO channels .....	411
	<i>Discussion 9.1</i> Universal codes in the downlink .....	415
	<i>Chapter 9 The main plot</i> .....	415
9.3	<b>Bibliographical notes</b> .....	416
9.4	<b>Exercises</b> .....	417
<b>10</b>	<b>MIMO IV: multiuser communication</b> .....	425
10.1	<b>Uplink with multiple receive antennas</b> .....	426
10.1.1	Space-division multiple access .....	426
10.1.2	SDMA capacity region .....	428
10.1.3	System implications .....	431
	<i>Summary 10.1</i> SDMA and orthogonal multiple access .....	432
10.1.4	Slow fading .....	433
10.1.5	Fast fading .....	436
10.1.6	Multiuser diversity revisited .....	439
	<i>Summary 10.2</i> Opportunistic communication and multiple receive antennas .....	442
10.2	<b>MIMO uplink</b> .....	442
10.2.1	SDMA with multiple transmit antennas .....	442
10.2.2	System implications .....	444
10.2.3	Fast fading .....	446
10.3	<b>Downlink with multiple transmit antennas</b> .....	448
10.3.1	Degrees of freedom in the downlink .....	448
10.3.2	Uplink–downlink duality and transmit beamforming .....	449
10.3.3	Precoding for interference known at transmitter .....	454
10.3.4	Precoding for the downlink .....	465
10.3.5	Fast fading .....	468
10.4	<b>MIMO downlink</b> .....	471
10.5	<b>Multiple antennas in cellular networks: a system view</b> .....	473
	<i>Summary 10.3</i> System implications of multiple antennas on multiple access .....	473
10.5.1	Inter-cell interference management .....	474
10.5.2	Uplink with multiple receive antennas .....	476
10.5.3	MIMO uplink .....	478
10.5.4	Downlink with multiple receive antennas .....	479
10.5.5	Downlink with multiple transmit antennas .....	479
	<i>Example 10.1</i> SDMA in ArrayComm systems .....	479
	<i>Chapter 10 The main plot</i> .....	481
10.6	<b>Bibliographical notes</b> .....	482
10.7	<b>Exercises</b> .....	483
Appendix A	Detection and estimation in additive Gaussian noise .....	496
Appendix B	Information theory from first principles .....	516
	<i>References</i> .....	546
	<i>Index</i> .....	554

### 1.1 Book objective

Wireless communication is one of the most vibrant areas in the communication field today. While it has been a topic of study since the 1960s, the past decade has seen a surge of research activities in the area. This is due to a confluence of several factors. First, there has been an explosive increase in demand for tetherless connectivity, driven so far mainly by cellular telephony but expected to be soon eclipsed by wireless data applications. Second, the dramatic progress in VLSI technology has enabled small-area and low-power implementation of sophisticated signal processing algorithms and coding techniques. Third, the success of second-generation (2G) digital wireless standards, in particular, the IS-95 Code Division Multiple Access (CDMA) standard, provides a concrete demonstration that good ideas from communication theory can have a significant impact in practice. The research thrust in the past decade has led to a much richer set of perspectives and tools on how to communicate over wireless channels, and the picture is still very much evolving.

There are two fundamental aspects of wireless communication that make the problem challenging and interesting. These aspects are by and large not as significant in wireline communication. First is the phenomenon of *fading*: the time variation of the channel strengths due to the small-scale effect of multipath fading, as well as larger-scale effects such as path loss via distance attenuation and shadowing by obstacles. Second, unlike in the wired world where each transmitter–receiver pair can often be thought of as an isolated point-to-point link, wireless users communicate over the air and there is significant *interference* between them. The interference can be between transmitters communicating with a common receiver (e.g., uplink of a cellular system), between signals from a single transmitter to multiple receivers (e.g., downlink of a cellular system), or between different transmitter–receiver pairs (e.g., interference between users in different cells). How to deal with fading and with interference is central to the design of wireless communication

systems and will be the central theme of this book. Although this book takes a physical-layer perspective, it will be seen that in fact the management of fading and interference has ramifications across multiple layers.

Traditionally the design of wireless systems has focused on increasing the *reliability* of the air interface; in this context, fading and interference are viewed as *nuisances* that are to be countered. Recent focus has shifted more towards increasing the *spectral efficiency*; associated with this shift is a new point of view that fading can be viewed as an *opportunity* to be exploited. The main objective of the book is to provide a unified treatment of wireless communication from both these points of view. In addition to traditional topics such as diversity and interference averaging, a substantial portion of the book will be devoted to more modern topics such as opportunistic and multiple input multiple output (MIMO) communication.

An important component of this book is the *system view* emphasis: the successful implementation of a theoretical concept or a technique requires an understanding of how it interacts with the wireless system as a whole. Unlike the derivation of a concept or a technique, this system view is less malleable to mathematical formulations and is primarily acquired through experience with designing actual wireless systems. We try to help the reader develop some of this intuition by giving numerous examples of how the concepts are applied in actual wireless systems. Five examples of wireless systems are used. The next section gives some sense of the scope of the wireless systems considered in this book.

## 1.2 Wireless systems

Wireless communication, despite the hype of the popular press, is a field that has been around for over a hundred years, starting around 1897 with Marconi's successful demonstrations of wireless telegraphy. By 1901, radio reception across the Atlantic Ocean had been established; thus, rapid progress in technology has also been around for quite a while. In the intervening hundred years, many types of wireless systems have flourished, and often later disappeared. For example, television transmission, in its early days, was broadcast by wireless radio transmitters, which are increasingly being replaced by cable transmission. Similarly, the point-to-point microwave circuits that formed the backbone of the telephone network are being replaced by optical fiber. In the first example, wireless technology became outdated when a wired distribution network was installed; in the second, a new wired technology (optical fiber) replaced the older technology. The opposite type of example is occurring today in telephony, where wireless (cellular) technology is partially replacing the use of the wired telephone network (particularly in parts of the world where the wired network is not well developed). The point of these examples is that there are many situations in which there is a choice

between wireless and wire technologies, and the choice often changes when new technologies become available.

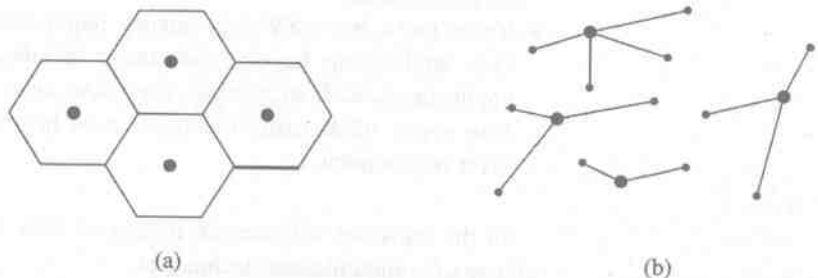
In this book, we will concentrate on cellular networks, both because they are of great current interest and also because the features of many other wireless systems can be easily understood as special cases or simple generalizations of the features of cellular networks. A cellular network consists of a large number of wireless subscribers who have cellular telephones (users), that can be used in cars, in buildings, on the street, or almost anywhere. There are also a number of fixed base-stations, arranged to provide coverage of the subscribers.

The area covered by a base-station, i.e., the area from which incoming calls reach that base-station, is called a cell. One often pictures a cell as a hexagonal region with the base-station in the middle. One then pictures a city or region as being broken up into a hexagonal lattice of cells (see Figure 1.1a). In reality, the base-stations are placed somewhat irregularly, depending on the location of places such as building tops or hill tops that have good communication coverage and that can be leased or bought (see Figure 1.1b). Similarly, mobile users connected to a base-station are chosen by good communication paths rather than geographic distance.

When a user makes a call, it is connected to the base-station to which it appears to have the best path (often but not always the closest base-station). The base-stations in a given area are then connected to a *mobile telephone switching office* (MTSO, also called a *mobile switching center* MSC) by high-speed wire connections or microwave links. The MTSO is connected to the public wired telephone network. Thus an incoming call from a mobile user is first connected to a base-station and from there to the MTSO and then to the wired network. From there the call goes to its destination, which might be an ordinary wire line telephone, or might be another mobile subscriber. Thus, we see that a cellular network is not an independent network, but rather an appendage to the wired network. The MTSO also plays a major role in coordinating which base-station will handle a call to or from a user and when to handoff a user from one base-station to another.

When another user (either wired or wireless) places a call to a given user, the reverse process takes place. First the MTSO for the called subscriber is found,

**Figure 1.1** Cells and base-stations for a cellular network. (a) An oversimplified view in which each cell is hexagonal. (b) A more realistic case where base-stations are irregularly placed and cell phones choose the best base-station.





then the closest base-station is found, and finally the call is set up through the MTSO and the base-station. The wireless link from a base-station to the mobile users is interchangeably called the *downlink* or the *forward channel*, and the link from the users to a base-station is called the *uplink* or a *reverse channel*. There are usually many users connected to a single base-station, and thus, for the downlink channel, the base-station must multiplex together the signals to the various connected users and then broadcast one waveform from which each user can extract its own signal. For the uplink channel, each user connected to a given base-station transmits its own waveform, and the base-station receives the sum of the waveforms from the various users plus noise. The base-station must then separate out the signals from each user and forward these signals to the MTSO.

Older cellular systems, such as the AMPS (advanced mobile phone service) system developed in the USA in the eighties, are analog. That is, a voice waveform is modulated on a carrier and transmitted without being transformed into a digital stream. Different users in the same cell are assigned different modulation frequencies, and adjacent cells use different sets of frequencies. Cells sufficiently far away from each other can reuse the same set of frequencies with little danger of interference.

Second-generation cellular systems are digital. One is the GSM (global system for mobile communication) system, which was standardized in Europe but now used worldwide, another is the TDMA (time-division multiple access) standard developed in the USA (IS-136), and a third is CDMA (code division multiple access) (IS-95). Since these cellular systems, and their standards, were originally developed for telephony, the current data rates and delays in cellular systems are essentially determined by voice requirements. Third-generation cellular systems are designed to handle data and/or voice. While some of the third-generation systems are essentially evolution of second-generation voice systems, others are designed from scratch to cater for the specific characteristics of data. In addition to a requirement for higher rates, data applications have two features that distinguish them from voice:

- Many data applications are extremely bursty; users may remain inactive for long periods of time but have very high demands for short periods of time. Voice applications, in contrast, have a fixed-rate demand over long periods of time.
- Voice has a relatively tight latency requirement of the order of 100 ms. Data applications have a wide range of latency requirements; real-time applications, such as gaming, may have even tighter delay requirements than voice, while many others, such as http file transfers, have a much laxer requirement.

In the book we will see the impact of these features on the appropriate choice of communication techniques.