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Fundamentals of Wireless Communication

无线通信基础

（英文版）

[美] David Tse
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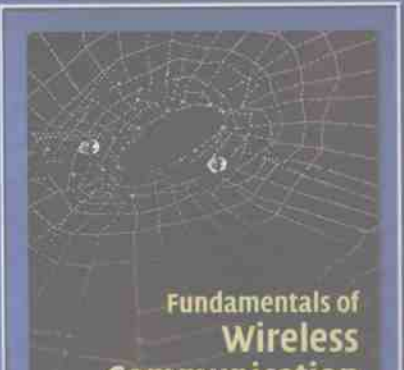

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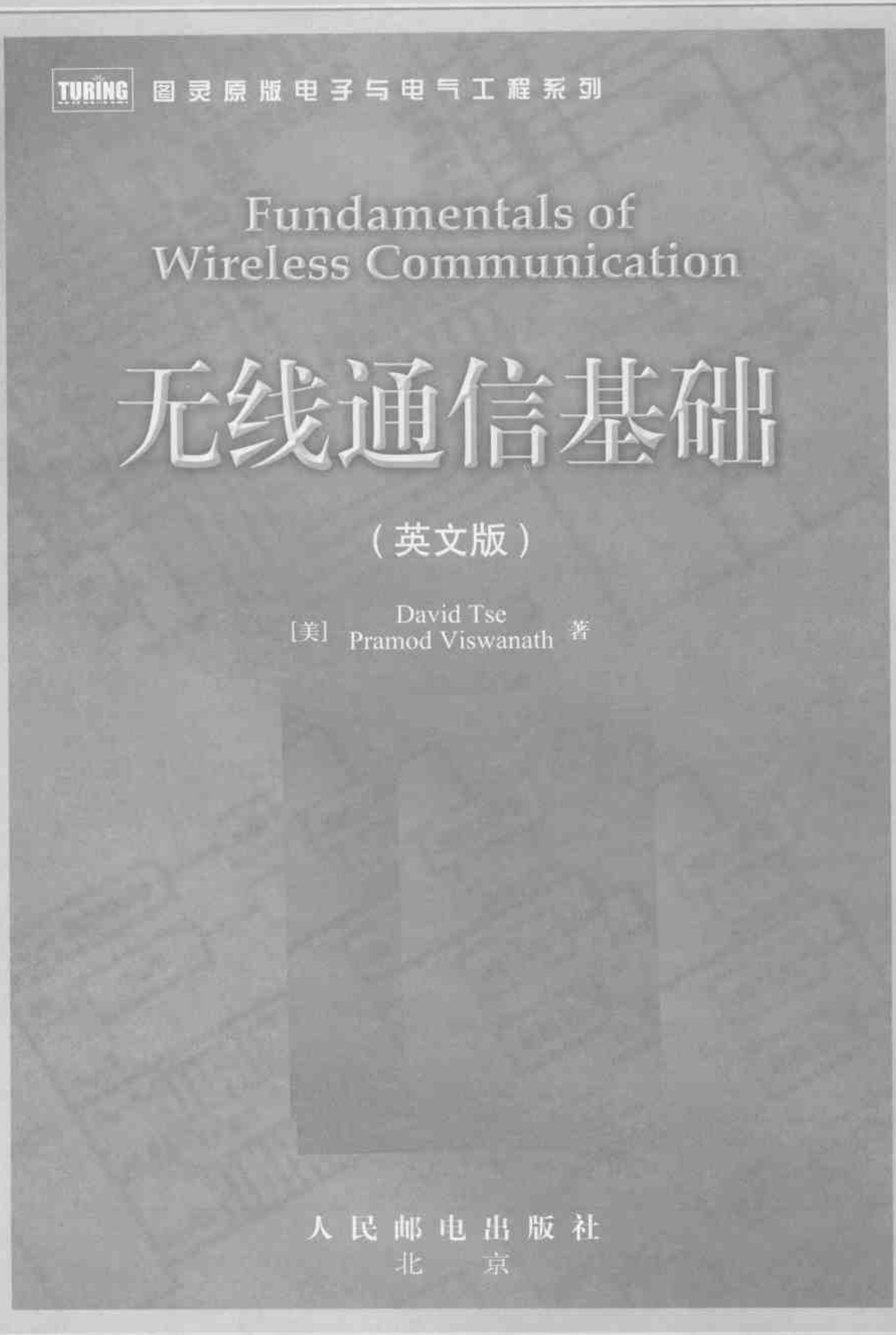

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内 容 提 要

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。

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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
ℓ	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 μ and variance σ^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

$\mathcal{E}_\mathrm{b}$	Energy per received bit
P_e	Error probability

Capacities

C_awgn	Capacity of the additive white Gaussian noise channel
C_ϵ	ϵ-Outage capacity of the slow fading channel
C_sum	Sum capacity of the uplink or the downlink
C_sym	Symmetric capacity of the uplink or the downlink
C_ϵ^sym	ϵ-Outage symmetric capacity of the slow fading uplink channel
p_out	Outage probability of a scalar fading channel
$p_\mathrm{out}^\mathrm{Ala}$	Outage probability when employing the Alamouti scheme
$p_\mathrm{out}^\mathrm{rep}$	Outage probability with the repetition scheme
$p_\mathrm{out}^\mathrm{ul}$	Outage probability of the uplink
$p_\mathrm{out}^\mathrm{mimo}$	Outage probability of the MIMO fading channel
$p_\mathrm{out}^\mathrm{ul-mimo}$	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
$\tilde{\mathbf{d}}$	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 $\mathbf{H}$
$\mathbf{H}^t$	Transpose of matrix $\mathbf{H}$
$\mathbf{Q}, \mathbf{U}, \mathbf{V}$	Unitary matrices
$\mathbf{I}_n$	Identity $n \times n$ matrix
Λ, Ψ	Diagonal matrices
$\mathrm{diag}\{p_1, \ldots, p_n\}$	Diagonal matrix with the diagonal entries equal to $p_1, \ldots, p_n$
$\mathbf{C}$	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
$\mathrm{Tr}[\mathbf{K}]$	Trace of the square matrix $\mathbf{K}$
$\mathrm{sinc}(t)$	Defined to be the ratio of $\sin(\pi t)$ to πt
$Q(a)$	$\int_a^\infty (1/\sqrt{2\pi}) \exp^{-x^2/2}\, \mathrm{d}x$
$\mathcal{L}(\cdot, \cdot)$	Lagrangian function

Contents

CHAPTER

1 Introduction

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,

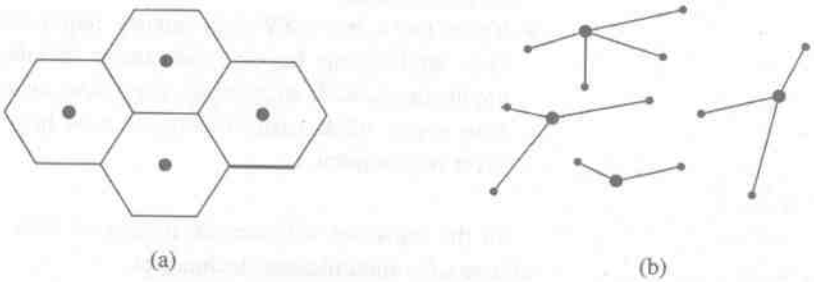

Figure 1.1 Cells and base-stations for a cellular network. (a) An oversimplified view in which each cell is hexagonal. (b) A more realistic case where base-stations are irregularly placed and cell phones choose the best base-station.

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.