Fundamentals of Mobile Data Networks

This unique text provides a comprehensive and systematic introduction to the theory and practice of mobile data networks.

Covering basic design principles as well as analytical tools for network performance evaluation, and with a focus on system-level resource management, you will learn how state-of-the-art network design can enable you flexibly and efficiently to manage and trade off various resources such as spectrum, energy, and infrastructure investments.

Topics covered range from traditional elements such as medium access, cell deployment, capacity, handover, and interference management, to more recent cutting-edge topics such as heterogeneous networks, energy- and cost-efficient network design, and a detailed introduction to 4G Long Term Evolution (LTE).

Numerous worked examples and exercises illustrate the key theoretical concepts and help you put your knowledge into practice, making this an essential resource whether you are a student, researcher, or practicing engineer.

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Preface

The world has seen astonishing developments in wireless communications. From the early days when wireless was seen as a new and complex technology that required skilled operators to work, to a situation where wireless has become a truly pervasive technology with devices in everyone's pocket. Voice communications, including mobile telephony, have dominated the first century of wireless communications. The technical challenges have been dominated by the struggle of the engineer against nature—how to facilitate communications over long distances and how to overcome adverse radio propagation conditions. With the advent of digital communications, we have over recent decades seen marvelous advances in this area, with technologies such as error control coding, digital signal processing, advanced antenna technologies and others. Meanwhile, the number of wireless users has skyrocketed. In addition we now witness wireless Internet access becoming a dominant technology for all kinds of IT services. A necessary prerequisite for this development is that wireless access is abundant and becomes almost free. The consequence is that data rates in wireless communications have increased dramatically during the last decade. The industry predicts an exponential increase of data traffic that would correspond to a 1000-fold increase in traffic between 2010 and 2020. It has become obvious that traditional measures for increasing data rates in the wireless links, e.g. coding and signal processing, are not going to save the day since these techniques now operate close to their theoretical limits, regardless of their complexity. Instead, much of the focus of the engineering work has shifted to what can be seen as the social struggle for scarce resources. The proper management of resources such as frequency spectrum, energy consumption, and to a large extent monetary investments in infrastructure (base stations and the like) is now a key issue. The design objectives have changed from "how can we provide high quality communications in a single radio link?" to "how can we create sustainable systems that provide affordable high quality wireless communications for billions of users?" The latter question is mainly one of Radio Resource Management (RRM), which is the main theme of this book. The book approaches this problem in the following way. First we study various aspect of the classic RRM problem in wireless networks: given certain resources, a certain infrastructure of access point/base stations and a frequency spectrum, how can we maximize the capacity of the system, e.g. in terms of the number of users or the data rate per unit area. The key issue that is handled in this part is the complex mutual interference between the various network elements. In the second part, we address the problem of how, and how much, infrastructure should be deployed to meet certain user demand. As we will see there are no theoretical limits to the wireless data rate that can be provided, the problem becomes more about cost. The question becomes: "How can we meet customer expectations at the lowest cost?" where the cost for infrastructure, spectrum, energy, and so on are taken into account. Throughout the book, examples from state-of-the-art technologies such as LTE and recent WiFi standards are provided.

The book is intended as a textbook for a graduate course in wireless networks. The reader should be familiar with the fundamentals of radio communications and digital communications. Some basic queuing theory can also be useful. Wireless networks are complicated systems, which makes the design and performance analysis inherently difficult. Several approaches are taken in the book. Classical analysis involves highly simplified models but renders easily tractable results. Slightly more elaborate models are analyzed by means of numerical analysis. The book contains plenty of worked examples, figures and homework exercises in each chapter. Some of the examples and exercises require simple simulations. In addition, the slides and exercise solutions are also available for course teachers. At the end of each chapter, a small list of references is provided. We have no intention to exhaust the immense research literature and only those that are very closely related to the book material are given. All the material has been used in the courses given by the authors at KTH Royal Institute of Technology in Stockholm, Sweden.

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Acronyms

3GPP	3rd Generation Partnership Project
ACK	ACKnowledgment
AP	Access Point
ARQ	Automatic Repeat reQuest
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	BLock Error Rate
bps	bits per second
BPSK	Binary Phase Shift Keying
BS	Base Station
C/I	Carrier to Interference
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CoMP	Coordinated Multi-Point Transmission
CP	Cyclic Prefix
CRA	Conflict Resolution Algorithm
CRE	Cell Range Extension
CRPC	Constant Received Power Control
CSI	Channel State Information
CSG	Closed Subscriber Group
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordinated Function
DCH	Dedicated CHannel
DCPC	Distributed Constrained Power Control
DIFS	DCF Inter-frame Space
DPC	Distributed Power Control
DS-CDMA	Direct Sequence-Code Division Multiple Access
DSP	Digital Signal Processing
DSSS	Direct Sequence Spread Spectrum
EE	Energy Efficiency

FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FH-CDMA	Frequency Hop-Code Division Multiple Access
FSTD	Frequency Switched Transmit Diversity
GoS	Grade of Service
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
HARQ	Hybrid Automatic Repeat reQuest
HetNet	Heterogeneous Networks
ICIC	Inter-Cell Interference Coordination
ICT	Information and Communication Technology
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ITU	International Telecommunication Union
LTE	Long-Term Evolution
MAC	Medium Access Control
MAHO	Mobile-Assisted Handover
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
M-QAM	M-ary Quadrature Amplitude Modulation
MRC	Maximum Ratio Combining
MU-MIMO	Multiple-User MIMO
NACK	Negative ACKnowledgment
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
PDCCH	Physical Downlink Control CHannel
PDSCH	Physical Downlink Shared CHannel
PER	Packet Error Rate
PF	Proportional Fair
PG	Processing Gain
PN	Pseudonoise
PRB	Physical Resource Block
P/S	Parallel to Serial
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACH	Random Access CHannel
RAP	Radio Access Point
RAT	Radio Access Technology
RB	Resource Block

RE	Resource Element
RF	Radio Frequency
RR	Round-Robin
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTS	Request To Send
SC-FDMA	Single Carrier-Frequency Division Multiple Access
SDMA	Space Division Multiple Access
SE	Spectral Efficiency
SFBC	Space Frequecy Block Code
SIC	Successive Interference Cancelation
SINR	Signal to Interference Plus Noise Ratio
SIR	Signal to Interference Ratio
S-MAC	Sensor-Medium Access Control
SNR	Signal to Noise Ratio
S/P	Serial to Parallel
SU-MIMO	Single-User MIMO
SVD	Singular Value Decomposition
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TPC	Transmitter Power Control
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
VoIP	Voice over IP
WLAN	Wireless Local Area Network

Notations

Scalars

A	Area
C	Channel capacity
D	Delay
D_o	Cell radius
d	Distance
E	Energy
g	Link power gain
G	Number of guard samples
h	Normalized link power gain
H	Channel signal gain
I	Scheduling indicator
N_{BS}	BS density
N_0	Noise power spectral density
P	Radio power at either the sender or receiver side
P_c	Circuit power
P_l	Listening circuit power
P_s	Sleep circuit power
$\hat{P}$	Maximum power
p	Probability
Q	Number of bits
q	Probability
R	Data rate
r	Data rate
S	Throughput
T	Duration
t	Time
U	Utility
u_e	Energy efficiency
u_s	Spectral efficiency
w	Size of a contention window
W	Signal bandwidth
η	Normalized thermal noise

Γ	SINR
κ	Cross-correlations between two waveforms
θ	Gap between the channel capacity and a practical coding and modulation scheme
γ	SINR target
δ	Access attempt rate
χ	Ratio between the channel gain and the interference plus noise
γ_0	Target threshold
ν	Assignment failure rate
ω	Active terminals per area unit
λ	Arrival or dropping rate
σ	Rate of retransmission
ξ	Expectation of retransmission delay
ζ	Power amplifier efficiency
ϕ	Network coupling factor
α	Path loss exponent

Vectors and matrices

$\mathbf{G}$	Link power gain matrix
$\mathbf{H}$	Normalized link power gain matrix
$\mathbf{h}$	Channel signal gain matrix
$\mathbf{I}$	Identity matrix
$\mathbf{N}$	Noise vector
$\mathbf{P}$	Power vector
$\mathbf{R}$	Data rate vector

Others

$\mathcal{C}$	Capacity region
$E[X]$	Expectation of X
$f()$	Mapping from SINR to data rate for a link
$\mathbb{I}$	Interference function
$i[t]$	The index of the user scheduled at time t
$\rho(X)$	Dominant eigenvalue of X
X_i	X of user i
X_{ij}	X between i and j
$X[t]$	X at time t
X^*	Optimal value of X
X'	First-order derivative of X
$X(Z)$	One-to-one mapping from Z to X

$X(\mathbf{Z})$	N-to-one mapping from $\mathbf{Z}$ to X
$\mathbf{X}(\mathbf{Z})$	N-to-M mapping from $\mathbf{Z}$ to $\mathbf{X}$
$\mathbf{X}^T$	Transpose of $\mathbf{X}$
$\mathbf{X}^H$	Hermitian of $\mathbf{X}$