

**WIRELESS**

**COMMUNICATIONS**

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**WIRELESS**

**COMMUNICATIONS** Second Edition

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Preface and Acknowledgements to the Second Edition

Since the first edition of this book appeared in 2005, wireless communications research and tech nology continued its inexorable progress. This fact, together with the positive response to the first edition, motivated a second edition that would cover the topics that have emerged in the last years. Thus, the present edition aims to bring the book again in line with the breadth of topics relevant to state-of-the-art wireless communications engineering.

There are more than 150 pages of new material, covering

• cognitive radio (new Chapter 21);

• cooperative communications, relays, and ad hoc networks (new Chapter 22); • video coding (new Chapter 23);

• 3GPP Long-Term Evolution (new Chapter 27);

• WiMAX (new Chapter 28).

There are furthermore significant extensions and additions on the following:

• MIMO (in Chapter 20), in particular a new section on multi-user MIMO (Section 20.3). • IEEE 802.11n (high-throughput WiFi) in Section 29.3.

• Coding (bit-interleaved coded modulation) in Section 14.5.

• Introduction to information theory in Sections 14.1, 14.9, and Appendix 17. • Channel models: updates of standardized channel models in Appendix 7. • A number of minor modifications and reformulations, partly based on feedback from instructors and readers of the book.

These extensions are important for students (as well as researchers) to learn “up-to-date” skills, Most of the additional material might be best suited for a graduate course on advanced wireless concepts and techniques. However, the material on LTE (or WiMAX) is also well suited as an example for standardized systems in a more elementary course (replacing, e.g., discussions of GSM or WCDMA systems).

As for the first edition, presentation slides and a solutions manual are available *for instructors that adopt the textbook for their course*. This material can also be obtained from the publisher or from a new website, wides.usc.edu/teaching/textbook. This site will also contain important resources for all readers of the book, including an “errata list,” updates, additional references, and similar material.

The writing of the new material was a major endeavor, and was greatly helped by the sup port of Sandy Sawchuk, Chair of the Department of Electrical Engineering at the University of Southern California. Particular thanks to Anthony Vetro, who wrote the new chapter on videocoding (Chapter 23). I am also grateful to the experts that kindly agreed to review the new material, namely

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Preface to the First Edition

When, in 1994, I wrote the very first draft of this book in the form of lecture notes for a wireless course, the preface started by justifying the need for giving such a course at all. I explained at length why it is important that communications engineers understand wireless systems, especially digital cellular systems. Now, more than 10 years later, such a justification seems slightly quaint and out dated. Wireless industry has become the fastest growing sector of the telecommunications industry, and there is hardly anybody in the world who is not a user of some form of wireless technology. From the ubiquitous cellphones, to wireless LANs, to wireless sensors that are proliferating – we are surrounded by wireless communications devices.

One of the key challenges in studying wireless communications is the amazing breadth of topics that impacts this field. Traditionally, communications engineers have concentrated on, for example, digital modulation and coding theory, while the world of antennas and propagation studies was completely separate – “and never the twain shall meet.” However, such an approach does not work for wireless communications. We need an understanding of *all* aspects that impact the performance of systems, and make the whole system work. This book is an attempt to provide such an overview, concentrating as it does on the physical layer of wireless communications.

Another challenge is that not only practical wireless systems, but also the science on which they are based is constantly changing. It is often claimed that while wireless systems rapidly change, the scientific basis of wireless communications stays the same, and thus engineers can rely on knowledge acquired at a given time to get them through many cycles of system changes, with just minor adjustments to their skill sets. This thought is comforting – and unfortunately false. For example, 10 years ago, topics like multiple-antenna systems, OFDM, turbo codes and LDPC codes, and multiuser detection, were mostly academic curiosities, and would at best be treated in PhD level courses; today, they dominate not only mainstream research and system development, but represent vital, basic knowledge for students and practicing engineers. I hope that, by treating both new aspects as well as more “classical” topics, my book will give today’s students and researchers knowledge and tools that will prove useful for them in the future.

The book is written for advanced undergraduate and graduate students, as well as for practicing engineers and researchers. Readers are assumed to have an understanding of elementary communi cation theory, like modulation/demodulation as well as of basic aspects of electromagnetic theory, though a brief review of these fields is given at the beginning of the corresponding chapters of the book. The core material of this book tries to get students to a stage where they can read more advanced monographs, and even research papers; for all those readers who want to dig deeper, the majority of chapters include a “further reading” section that cites the most important references. The text includes both mathematical formulations, and intuitive explanations. I firmly believe that such a dual approach leads to the deepest understanding of the material. In addition to being a textbook, the text is also intended to serve as a reference tool for researchers and practitioners. For this reason, I have tried to make it easier to read isolated chapters. All acronyms are explained the first time they occur in each chapter (not just at their first occurrence in the book); a list of symbols (see p. xlvii) explains the meaning of symbols used in the equations. Also, frequent cross-references should help for this purpose.

**xxvi** Preface to the First Edition 

**Synopsis**

The book is divided into five parts. The first part, the introduction, gives a high-level overview of wireless communications. Chapter 1 first gives a taxonomy of different wireless services, and then describes the requirements for data rate, range, energy consumption, etc., that the various applica tions impose. This chapter also contains a brief history, and a discussion of the economic and social aspects of wireless communications. Chapter 2 describes the basic challenges of wireless commu nications, like multipath propagation and limited spectrum resources. Chapter 3 then discusses how noise and interference limit the capabilities of wireless systems, and how link budgets can serve as simple system-planning tools that give a first idea about the achievable range and performance.

The second part describes the various aspects of wireless propagation channels and antennas. As the propagation channel is the medium over which communication happens, understanding it is vital to understanding the remainder of the book. Chapter 4 describes the basic propagation processes: free space propagation, reflection, transmission, diffraction, diffuse scattering, and waveguiding. We find that the signal can get from the transmitter to the receiver via many different propagation paths that involve one or more of these processes, giving rise to many multipath components. It is often convenient to give a statistical description of the effects of multipath propagation. Chapter 5 gives a statistical formulation for narrowband systems, explaining both small-scale (Rayleigh) and large-scale fading. Chapter 6 then discusses formulations for wideband systems, and systems that can distinguish the directions of multipath components at the transmitter and receiver. Chapter 7 then gives specific models for propagation channels in different environments, covering path loss as well as wideband and directional models. Since all realistic channel models have to be based on (or confirmed by) measurements, Chapter 8 summarizes techniques that are used for measuring channel impulse responses. Finally, Chapter 9 briefly discusses antennas for wireless applications, especially with respect to different restrictions at base stations and mobile stations.

The third part of the book deals with the structure and theory of wireless transceivers. After a short summary of the components of a RF transceiver in Chapter 10, Chapter 11 then describes the different modulation formats that are used for wireless applications. The discussion not only includes mathematical formulations and signal space representations, but also an assessment of their advantages and disadvantages for various purposes. The performance of all these modems in flat-fading as well as frequency-selective channels is then the topic of Chapter 12. One critical observation we make here is the fact that fading leads to a drastic increase in error probability, and that increasing the transmit power is not a suitable way of improving performance. This motivates the next two Chapters, which deal with diversity and channel coding, respectively. We find that both these measures are very effective in reducing error probabilities in a fading channel. The coding chapter also includes a discussion of near-Shannon-limit-achieving codes (turbo codes and low-density parity check codes), which have gained great popularity in recent years. Since voice communication is still the most important application for cellphones and similar devices, Chapter 15 discusses the various ways of digitizing speech, and compressing information so that it can be transmitted over wireless channels in an efficient way. Chapter 16 finally discusses equalizers, which can be used to reduce the detrimental effect of frequency selectivity of wideband wireless channels. All the chapters in this part deal with a single link – i.e., the link between one transmitter and one receiver.

The fourth part then takes into account our desire to operate a number of wireless links simulta neously in a given area. This so-called *multiple-access* problem has a number of different solutions. Chapter 17 discusses frequency domain multiple access (FDMA) and time domain multiple access (TDMA), as well as packet radio, which has gained increasing importance for data transmission. This chapter also discusses the cellular principle, and the concept of frequency reuse that forms the basis not only for cellular, but also many other high-capacity wireless systems. Chapter 18 then describes spread spectrum techniques, in particular CDMA, where different users can be distinguished by different spreading sequences. This chapter also discusses multiuser detection, a

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very advanced receiver scheme that can greatly decrease the impact of multiple-access interference. Another topic of Part IV is “advanced transceiver techniques.” Chapter 19 describes OFDM (orthog onal frequency domain multiplexing), which is a modulation method that can sustain very high data rates in channels with large delay spread. Chapter 20 finally discusses multiple-antenna techniques: “smart antennas,” typically placed at the base station, are multiple-antenna elements with sophis ticated signal processing that can (among other benefits) reduce interference and thus increase the capacity of cellular systems. MIMO (multiple-input-multiple-output) systems go one step further, allowing the transmission of parallel data streams from multiple-antenna elements at the transmit ter, which are then received and demodulated by multiple-antenna elements at the receiver. These systems achieve a dramatic capacity increase even for a single link.

The last part of the book describes standardized wireless systems. Standardization is critical so that devices from different manufacturers can work together, and also systems can work seamlessly across national borders. The book describes the most successful cellular wireless standards – namely, GSM (Global System for Mobile communications), IS-95 and its advanced form CDMA 2000, as well as Wideband CDMA (also known as UMTS) in Chapters 21, 22, and 23, respectively. Furthermore, Chapter 24 describes the most important standard for wireless LANs – namely, IEEE 802.11.

A companion website (*www.wiley.com/go/molisch*) contains some material that I deemed as useful, but which would have made the printed version of the book overly bulky. In particular, the appendices to the various chapters, as well as supplementary material on the DECT (Digital Enhanced Cordless Telecommunications) system, the most important cordless phone standard, can be found there.

**Suggestions for Courses**

The book contains more material than can be presented in a single-semester course, and spans the gamut from very elementary to quite advanced topics. This gives the instructor the freedom to tailor teaching to the level and the interests of students. The book contains worked examples in the main text, and a large number of homework exercises at the end of the book. Solutions to these exercises, as well as presentation slides, are available to instructors on the companion website of this book.

A few examples for possible courses include:

Introductory course:

• Introduction (Chapters 1–3).

• Basic channel aspects (Sections 4.1–4.3, 5.1–5.4, 6.1, 6.2, 7.1–7.3):

◦ elementary signal processing (Chapters 10, 11, and Sections 12.1, 12.2.1, 12.3.1, 13.1, 13.2, 13.4, 14.1–14.3, 16.1–16.2);

◦ multiple access and system design (Chapters 17, 22 and Sections 18.2, 18.3, 21.1-21.7). • Wireless propagation:

◦ introduction (Chapter 2);

◦ basic propagation effects (Chapter 4);

◦ statistical channel description (Chapters 5 and 6);

◦ channel modeling and measurement (Chapters 7 and 8);

◦ antennas (Chapter 9).

This course can also be combined with more basic material on electromagnetic theory and antennas.

• Advanced topics in wireless communications:

◦ introduction and refresher: should be chosen by the instructor according to audience;

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◦ CDMA and multiuser detection (Sections 18.2, 18.3, 18.4);

◦ OFDM (Chapter 19);

◦ ultrawideband communications (Sections 6.6, 18.5);

◦ multiantenna systems (Sections 6.7, 7.4, 8.5, 13.5, 13.6, and Chapter 20); ◦ advanced coding (Sections 14.5, 14.6).

• Current wireless systems:

◦ TDMA-based cellular systems (Chapter 21);

◦ CDMA-based cellular systems (Chapters 22 and 23);

◦ cordless systems (supplementary material on companion website);

◦ wireless LANs (Chapter 24); and

◦ selected material from previous chapters for the underlying theory, according to the knowledge of the audience.

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Abbreviations

2G Second Generation

3G Third Generation

3GPP Third Generation Partnership Project 3GPP2 Third Generation Partnership Project 2 3SQM Single Sided Speech Quality Measure A/D Analog to Digital

AB Access Burst

AC Access Category

AC Administration Center

AC Alternate Current

ACCH Associated Control CHannel ACELP Algebraic Code Excited Linear Prediction ACF AutoCorrelation Function

ACI Adjacent Channel Interference ACK ACKnowledgment

ACLR Adjacent Channel Leakage Ratio ACM Address Complete Message

AD Access Domain

ADC Analog to Digital Converter ADDTS ADD Traffic Stream

ADF Average Duration of Fades

ADPCM Adaptive Differential Pulse Code Modulation ADPM Adaptive Differential Pulse Modulation ADPS Angular Delay Power Spectrum ADSL Asymmetric Digital Subscriber Line AF Amplify-and-Forward

AGC Automatic Gain Control

AGCH Access Grant CHannel

AICH Acquisition Indication CHannel AIFS Arbitration Inter Frame Spacing ALOHA random access packet radio system AMPS Advanced Mobile Phone System AMR Adaptive Multi Rate

AN Access Network

ANSI American National Standards Institute AODV Ad hoc On-Demand Distance Vector AP Access Point

APS Angular Power Spectrum

ARFCN Absolute Radio Frequency Channel Number

**xxxii** Abbreviations 

ARIB Association of Radio Industries and Businesses (Japan) ARQ Automatic Repeat reQuest

ASIC Application Specific Integrated Circuit

ASK Amplitude Shift Keying

ATDPICH Auxiliary forward Transmit Diversity PIlot CHannel ATIS Alliance for Telecommunications Industry Solutions ATM Asynchronous Transfer Mode

ATSC-M/H Advanced Television Systems Committee – Mobile/Handheld AUC AUthentication Center

AV Audio and Video

AVC Advanced Video Coding

AWGN Additive White Gaussian Noise

BAM Binary Amplitude Modulation

BAN Body Area Network

BCC Base station Color Code

BCCH Broadcast Control CHannel

BCF Base Control Function

BCH Bose–Chaudhuri–Hocquenghem (code)

BCH Broadcast CHannel

BCJR Initials of the authors of Bahl et al. [1974]

BEC Backward Error Correction

BER Bit Error Rate

BFI Bad Frame Indicator

BFSK Binary Frequency Shift Keying

BICM Bit Interleaved Coded Modulation

BLAST Bell labs LAyered Space Time

Bm Traffic channel for full-rate voice coder

BN Bit Number

BNHO Barring all outgoing calls except those to Home PLMN BPF BandPass Filter

BPPM Binary Pulse Position Modulation

BPSK Binary Phase Shift Keying

BS Base Station

BSC Base Station Controller

BSI Base Station Interface

BSIC Base Station Identity Code

BSS Base Station Subsystem

BSS Basic Service Set

BSSAP Base Station Application Part

BTS Base Transceiver Station

BU Bad Urban

BW Bandwidth

CA Cell Allocation

CAF Compute and Forward

CAP Controlled Access Period

CAZAC Constant Amplitude Zero AutoCorrelation

CB Citizens’ Band

CBCH Cell Broadcast CHannel

CC Country Code

CCBS Completion of Calls to Busy Subscribers

Abbreviations **xxxiii **

CCCH Common Control CHannel

CCF Cross Correlation Function

CCI Co Channel Interference

CCITT Commite’ Consultatif International de Telegraphique et Telephonique CCK Complementary Code Keying

CCPCH Common Control Physical CHannel

CCPE Control Channel Protocol Entity

CCSA China Communications Standards Association

CCTrCH Coded Composite Traffic CHannel

cdf cumulative distribution function

CDG CDMA Development Group

CDMA Code Division Multiple Access

CELP Code Excited Linear Prediction

CEPT European Conference of Postal and Telecommunications Administrations CF Compress-and-Forward

CF-Poll Contention-Free Poll

CFB Contention Free Burst

CFP Contention Free Period

CI Cell Identify

C/I Carrier-to-Interference ratio

CM Connection Management

CMA Constant Modulus Algorithm

CMOS Complementary Metal Oxide Semiconductor

CN Core Network

CND Core Network Domain

CNG Comfort Noise Generation

CONP Connect Number Identification Presentation

COST European COoperation in the field of Scientific and Technical research CP Contention Period

CP Cyclic Prefix

CPC Cognitive Plot Channels

CPCH Common Packet CHannel

CPFSK Continuous Phase Frequency Shift Keying

CPICH Common PIlot CHannel

CRC Cyclic Redundancy Check

CRC Cyclic Redundancy Code

CS-ACELP Conjugate Structure-Algebraic Code Excited Linear Prediction CSD Cyclic Shift Diversity

CSI Channel State Information

CSIR Channel State Information at the Receiver

CSIT Channel State Information at the Transmitter

CSMA Carrier Sense Multiple Access

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance CTS Clear To Send

CTT Cellular Text Telephony

CUG Closed User Group

CW Contention Window

D-BLAST Diagonal BLAST

DAA Detect and Avoid

DAB Digital Audio Broadcasting

**xxxiv** Abbreviations 

DAC Digital to Analog Converter

DAF Diversity-Amplify-and-Forward

DAM Diagnostic Acceptability Measure

dB Decibel

DB Dummy Burst

DBPSK Differential Binary Phase Shift Keying

DC Direct Current

DCCH Dedicated Control CHannel

DCF Distributed Coordination Function

DCH Dedicated (transport) CHannel

DCM Directional Channel Model

DCS1800 Digital Cellular System at the 1800-MHz band

DCT Discrete Cosine Transform

DDF Diversity-Decode-and-Forward

DDIR Double Directional Impulse Response

DDDPS Double Directional Delay Power Spectrum

DECT Digital Enhanced Cordless Telecommunications (ETSI) DF Decode-and-Forward

DFE Decision Feedback Equalizer

DFT Discrete Fourier Transform

DIFS Distributed Inter Frame Space

DL Downlink

DLL Data Link Layer

DLP Direct Link Protocol

DM Delta Modulation

DMC Discrete Memoryless Channel

DMT Discrete Multi Tone

DNS Domain Name Server

DOA Direction Of Arrival

DOD Direction Of Departure

DPCCH Dedicated Physical Control CHannel

DPDCH Dedicated Physical Data CHannel

DPSK Differential Phase Shift Keying

DQPSK Differential Quadrature-Phase Shift Keying

DRM Discontinuous Reception Mechanisms

DRT Diagnostic Rhyme Test

DRX Discontinuous Reception

DS Direct Sequence

DS-CDMA Direct Sequence–Code Division Multiple Access DS-SS Direct Sequence–Spread Spectrum

DSA Dynamic Spectrum Access

DSCH Downlink Shared Channel

DSDF Destination-Sequenced Distance Vector

DSI Digital Speech Interpolation

DSL Digital Subscriber Line

DSMA Data Sense Multiple Access

DSP Digital Signal Processor

DSR Distributed Speech Recognition

DSR Dynamic Source Routing

DTAP Direct Transfer Application Part

Abbreviations **xxxv **

DTE Data Terminal Equipment

DtFT Discrete-time Fourier Transform

DTMF Dual Tone Multi Frequency (signalling)

DTX Discontinuous Transmission

DUT Device Under Test

DVB Digital Video Broadcasting

DVB-H Digital Video Broadcasting – Handheld

DxF Diversity xF

EC European Commission

ECL Emitter Coupled Logic

EDCA Enhanced Distributed Channel Access

EDCSD Enhanced Data rate Circuit Switched Data

EDGE Enhanced Data rates for GSM Evolution

EDPRS Enhanced Data rate GPRS

EFR Enhanced Full Rate

EGC Equal Gain Combining

EIA Electronic Industries Alliance (U.S.A.)

EIFS Extended Inter Frame Space

EIR Equipment Identity Register

EIRP Equivalent Isotropically Radiated Power

ELP Equivalent Low Pass

EMS Enhanced Messaging Service

EN European Norm

ERLE Echo Return Loss Enhancement

ESN Electronic Serial Number

ESPRIT Estimation of Signal Parameters by Rotational Invariance Techniques ETS European Telecommunication Standard

ETSI European Telecommunications Standards Institute ETX Expected Number of Transmissions

EV-DO EVolution-Data Optimized

EVD Eigen Value Decomposition

EVM Error Vector Magnitude

EVRC Enhanced Variable Rate Coder

F-APICH Forward dedicated Auxiliary PIlot CHannel

F-BCCH Forward Broadcast Control CHannel

F-CACH Forward Common Assignment CHannel

F-CCCH Forward Common Control CHannel

F-CPCCH Forward Common Power Control CHannel

F-DCCH Forward Dedicated Control CHannel

F-PDCCH Forward Packet Data Control CHannel

F-PDCH Forward Packet Data CHannel

F-QPCH Forward Quick Paging CHannel

F-SCH Forward Supplemental CHannel

F-SYNC Forward SYNChronization channel

F-TDPICH Forward Transmit Diversity PIlot CHannel

F0 Fundamental frequency

FAC Final Assembly Code

FACCH Fast Associated Control CHannel

FACCH/F Full-rate FACCH

FACCH/H Half-rate FACCH

**xxxvi** Abbreviations 

FACH Forward Access CHannel

FB Frequency correction Burst

FBI Feed Back Information

FCC Federal Communications Commission

FCCH Frequency Correction CHannel

FCH Fundamental CHannel

FCH Frame Control Header

FCS Frame Check Sequence

FDD Frequency Domain Duplexing

FDMA Frequency Division Multiple Access

FDTD Finite Difference Time Domain

FEC Forward Error Correction

FEM Finite Element Method

FFT Fast Fourier Transform

FH Frequency Hopping

FHMA Frequency Hopping Multiple Access

FIR Finite Impulse Response

FM Frequency Modulation

FN Frame Number

FOMA Japanese version of the UMTS standard

FQI Frame Quality Indicator

FR Full Rate

FS Federal Standard

FSK Frequency Shift Keying

FT Fourier Transform

FTF Fast Transversal Filter

FWA Fixed Wireless Access

GF Galois Field

GGSN Gateway GPRS Support Node

GMSC Gateway Mobile Services Switching Center

GMSK Gaussian Minimum Shift Keying

GPRS General Packet Radio Service

GPS Global Positioning System

GSC Generalized Selection Combining

GSCM Geometry-based Stochastic Channel Model

GSM Global System for Mobile communications

GSM PLMN GSM Public Land Mobile Network

GSM 1800 Global System for Mobile communications at the 1800-MHz band GTP GPRS Tunneling Protocol

H-BLAST Horizontal BLAST

H-S/MRC Hybrid Selection/Maximum Ratio Combining

HC Hybrid Coordinator

HCCA HCF (Hybrid Coordination Function) Controlled Channel Access HCF Hybrid Coordination Function

HDLC High Level Data Link Control

HF High Frequency

HIPERLAN HIgh PERformance Local Area Network

HLR Home Location Register

HMSC Home Mobile-services Switching Center

HNM Harmonic + Noise Modeling

Abbreviations **xxxvii **

hostid host address

HO HandOver

HPA High Power Amplifier

HR Half Rate

HR/DS or HR/DSSS High Rate Direct Sequence PHY

HRTF Head Related Transfer Function

HSCSD High Speed Circuit Switched Data

HSDPA High Speed Downlink Packet Access

HSN Hop Sequence Number

HSPA High-Speed Packet Access

HT High Throughput

HT Hilly Terrain

HTTP Hyper Text Transfer Protocol

IAF InterSymbol Interference Amplify-and-Forward

IAM Initial Address Message

ICB Incoming Calls Barred

ICI Inter Carrier Interference

ID Identification

ID Identifier

IDFT Inverse Discrete Fourier Transform

Ie Equipment impairment factor

IE Information Element

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

IF Intermediate Frequency

IFFT Inverse Fast Fourier Transformation

IFS Inter Frame Space

iid independent identically distributed

IIR Infinite Impulse Response

ILBC Internet Low Bit-rate Codec

IMBE Improved Multi Band Excitation

IMEI International Mobile station Equipment Identity

IMSI International Mobile Subscriber Identity

IMT International Mobile Telecommunications

IMT-2000 International Mobile Telecommunications 2000

INMARSAT INternational MARitime SATellite System

IO Interacting Object

I/O Input/Output

IP Internet Protocol

IPO Initial Public Offering

IQ In-Phase – Quadrature Phase

IR Impulse Radio

IRIDIUM Project

IRS Intermediate Reference System

IS-95 Interim Standard 95 (the first CDMA system adopted by the American TIA)

ISDN Integrated Services Digital Network

ISI InterSymbol Interference

ISM Industrial, Scientific, and Medical

**xxxviii** Abbreviations 

ISO International Standards Organization

ISPP Interleaved Single Pulse Permutation

ITU International Telecommunications Union

IWF Inter Working Function

IWU Inter Working Unit

IxF Interference xF

JD-TCDMA Joint Detection–Time/Code Division Multiple Access JDC Japanese Digital Cellular

JPEG Joint Photographic Expert Group

JVT Joint Video Team

Kc Cipher Key

Ki Key used to calculate SRES

Kl Location Key

Ks Session Key

KLT Karhunen Loeve Transform `

LA Location Area

LAC Location Area Code

LAI Location Area Identity

LAN Local Area Network

LAP-Dm Link Access Protocol on Dm Channel

LAR Logarithmic Area Ratio

LBG Linde–Buzo–Gray algorithm

LCR Level Crossing Rate

LD-CELP Low Delay–Code Excited Linear Prediction

LDPC Low Density Parity Check

LEO Low Earth Orbit

LFSR Linear Feedback Shift Register

LLC Logical Link Control

LLR Log Likelihood Ratio

LMMSE Linear Minimum Mean Square Error

LMS Least Mean Square

LNA Low Noise Amplifier

LO Local Oscillator

LPF LowPass Filter

LOS Line Of Sight

LP Linear Prediction

LP Linear Predictor

LP Linear Program

LPC Linear Predictive Coding

LPC Linear Predictive voCoder

LR Location Register

LS Least Squares

LSF Line Spectral Frequency

LSP Line Spectrum Pair

LTE Long-Term Evolution

LTI Linear Time Invariant

LTP Long Term Prediction

LTP Long Term Predictor

LTV Linear Time Variant

M-QAM M-ary Quadrature Amplitude Modulation

Abbreviations **xxxix **

MA Mobile Allocation

MA Multiple Access

MAC Medium Access Control

MACN Mobile Allocation Channel Number

MAF Mobile Additional Function

MAF Multi-hop Amplify-and-Forward

MAHO Mobile Assisted Hand Over

MAI Multiple Access Interference

MAIO Mobile Allocation Index Offset

MAN Metropolitan Area Network

MAP Maximum A Posteriori

MAP Mobile Application Part

MB Macroblock

MBE Multi Band Excitation

MBOA Multi Band OFDM Alliance

MC-CDMA Multi Carrier Code Division Multiple Access

MCC Mobile Country Code

MCS Modulation and Coding Scheme

MDC Multiple Description Coding

MDF Multi-hop Decode-and-Forward

MDHO Macro Diversity HandOver

ME Maintenance Entity

ME Mobile Equipment

MEA Multiple Element Antenna

MEF Maintenance Entity Function

MEG Mean Effective Gain

MELP Mixed Excitation Linear Prediction

MFEP Matched Front End Processor

MIC Mobile Interface Controller

MIME Multipurpose Internet Mail Extensions

MIMO Multiple Input Multiple Output system

MIPS Million Instructions Per Second

ML Maximum Likelihood

MLSE Maximum Likelihood Sequence Estimators (or Estimation) MMS Multimedia Messaging Service

MMSE Minimum Mean Square Error

MNC Mobile Network Code

MNRU Modulated Noise Reference Unit

MOS Mean Opinion Score

MoU Memorandum of Understanding

MP3 Motion Picture Experts Group-1 layer 3

MPC Multi Path Component

MPDU MAC Protocol Data Unit

MPEG Motion Picture Experts Group

MPR Multi-Point Relay

MPSK M-ary Phase Shift Keying

MRC Maximum Ratio Combining

MS Mobile Station

MS ISDN Mobile Station ISDN Number

MSC Mobile Switching Center

**xl** Abbreviations 

MSCU Mobile Station Control Unit

MSDU MAC Service Data Unit

MSE Mean Square Error

MSIN Mobile Subscriber Identification Number

MSISDN Mobile Station ISDN Number

MSK Minimum Shift Keying

MSL Main Signaling Link

MSRN Mobile Station Roaming Number

MSS Mobile Satellite Service

MT Mobile Terminal

MT Mobile Termination

MTP Message Transfer Part

MUMS Multi User Mobile Station

MUSIC Multiple Signal Classification

MUX Multiplexing

MVC Multiview Video Coding

MVM Minimum Variance Method

MxF Multi-hop xF

NAV Network Allocation Vector

NB Narrow Band

NB Normal Burst

NBIN A parameter in the hopping sequence

NCELL Neighboring (adjacent) Cell

NDC National Destination Code

NDxF Nonorthogonal Diversity xF

netid network address

NF Network Function

NLOS Non Line Of Sight

NLP Non Linear Processor

NM Network Management

NMC Network Management Centre

NMSI National Mobile Station Identification number

NMT Nordic Mobile Telephone

Node-B Base station

NRZ Non Return to Zero

NSAP Network Service Access Point

NSS Network and Switching Subsystem

NT Network Termination

NTT Nippon Telephone and Telegraph

O&M Operations & Maintenance

OACSU Off Air Call Set Up

OCB Outgoing Calls Barred

ODC Ornithine DeCarboxylase

OEM Original Equipment Manufacturer

OFDM Orthogonal Frequency Division Multiplexing

OFDMA Orthogonal Frequency Division Multiple Access

OLSR Optimized Link State Routing

OMC Operations & Maintenance Center

OOK On Off Keying

OPT Operator Perturbation Technique

Abbreviations **xli **

OQAM Offset Quadrature Amplitude Modulation

OQPSK Offset Quadrature Phase Shift Keying

OS Operating Systems

OSI Operator System Interface

OSS Operation Support System

OTD Orthogonal Transmit Diversity

OVSF Orthogonal Variable Spreading Factor

P/S Parallel to Serial (conversion)

PABX Private Automatic Branch eXchange

PACCH Packet Associated Control CHannel

PACS Personal Access Communications System

PAD Packet Assembly/Disassembly facility

PAGCH Packet Access Grant CHannel

PAM Pulse Amplitude Modulation

PAN Personal Area Network

PAPR Peak-to-Average Power Ratio

PAR Peak-to-Average Ratio

PARCOR PARtial CORrelation

PBCCH Packet Broadcast Control CHannel

PC Point Coordinator

PCCCH Packet Common Control CHannel

PCF Point Coordination Function

PCG Power Control Group

PCH Paging CHannel

PCM Pulse Code Modulated

PCPCH Physical Common Packet CHannel

PCS Personal Communication System

PDA Personal Digital Assistant

PDC Pacific Digital Cellular (Japanese system)

PDCH Packet Data CHannel

pdf probability density function

PDN Public Data Network

PDP Power Delay Profile

PDSCH Physical Downlink Shared CHannel

PDTCH Packet Data Traffic CHannel

PDU Packet Data Unit

PESQ Perceptual Evaluation of Speech Quality

PHS Personal Handyphone System

PHY PHYsical layer

PIC Parallel Interference Cancellation

PICH Page Indication Channel

PIFA Planar Inverted F Antenna

PIFS Priority Inter Frame Space

PIN Personal Identification Number

PLCP Physical Layer Convergence Procedure

PLL Physical Link Layer

PLMN Public Land Mobile Network

PN Pseudo Noise

PNCH Packet Notification CHannel

POP Peak to Off Peak

**xlii** Abbreviations 

POTS Plain Old Telephone Service

PPCH Packet Paging CHannel

PPDU Physical Layer Protocol Data Unit

PPM Pulse Position Modulation

PRACH Packet Random Access CHannel

PRACH Physical Random Access CHannel

PRake Partial Rake

PRB Physical Resource Block

PRMA Packet Reservation Multiple Access

PSD Power Spectral Density

PSDU Physical Layer Service Data Unit

PSK Phase Shift Keying

PSMM Pilot Strength Measurement Message

PSPDN Packet Switched Public Data Network

PSQM Perceptual Speech Quality Measurement

PSTN Public Switched Telephone Network

PTCCH-D Packet Timing advance Control CHannel-Downlink PTCCH-U Packet Timing advance Control CHannel-Uplink PTM Point To Multipoint

PTM-M Point To Multipoint Multicast

PTM-SC Point To Multipoint Service Center

PTO Public Telecommunications Operators

PUSC Partial Use of Subcarriers

PUK Personal Unblocking Key

PWI Prototype Waveform Interpolation

PWT Personal Wireless Telephony

QAM Quadrature Amplitude Modulation

QAP QoS Access Point

QCELP Qualcomm Code Excited Linear Prediction

QFGV Quadratic Form Gaussian Variable

QOF Quasi Orthogonal Function

QoS Quality of Service

QPSK Quadrature-Phase Shift Keying

QSTA QoS STAtion

R-ACH Reverse Access CHannel

R-ACKCH Reverse ACKnowledgement CHannel

R-CCCH Reverse Common Control CHannel

R-CQICH Reverse Channel Quality Indicator CHannel

R-DCCH Reverse Dedicated Control CHannel

R-EACH Reverse Enhanced Access CHannel

R-FCH Reverse Fundamental CHannel

R-PICH Reverse PIlot CHannel

R-SCH Reverse Supplemental CHannel

RA Random Mode Request information field

RA Routing Area

RA Rural Area

RA Random Access

RAB Random Access Burst

RACH Random Access CHannel

RAN Radio Access Network

Abbreviations **xliii **

RC Raised Cosine

RCDLA Radiation Coupled Dual L Antenna

RE Resource Element

RF Radio Frequency

RFC Radio Frequency Channel

RFC Request For Comments

RFL Radio Frequency subLayer

RFN Reduced TDMA Frame Number

RLC Radio Link Control

RLP Radio Link Protocol

RLS Recursive Least Squares

RNC Radio Network Controller

RNS Radio Network Subsystem

RNTABLE Table of 128 integers in the hopping sequence

RPAR Relay PAth Routing

RPE Regular Pulse Excitation (Voice Codec)

RPE-LTP Regular Pulse Excited with Long Term Prediction RS Reed–Solomon (code)

RS Reference Signal

RS Relay Station

RSC Recursive Systematic Convolutional

RSC Radio Spectrum Committee

RSSI Received Signal Strength Indication

RTSP Real Time Streaming Protocol

RTP Real-time Transport Protocol

rv random variable

RVLC Reversible Variable Length Code

RX Receiver

RXLEV Received Signal Level

RXQUAL Received Signal Quality

S-CCPCH Secondary Common Control Physical CHannel

SABM Set Asynchronous Balanced Mode

SACCH Slow Associated Control CHannel

SAGE Space Alternating Generalized Expectation – maximization SAP Service Access Point

SAPI Service Access Point Identifier

SAPI Service Access Points Indicator

SAR Specific Absorption Rate

SB Synchronization Burst

SC-CDMA Single-Carrier CDMA

SC-FDMA Single-Carrier FDMA

SCCP Signalling Connection Control Part

SCH Synchronisation CHannel

SCN Sub Channel Number

SCxF Split-Combine xF

SDCCH Standalone Dedicated Control CHannel

SDCCH/4 Standalone Dedicated Control CHannel/4

SDCCH/8 Standalone Dedicated Control CHannel/8

SDMA Space Division Multiple Access

SEGSNR SEGmental Signal-to-Noise Ratio

**xliv** Abbreviations 

SEP Symbol Error Probability

SER Symbol Error Rate

SFBC Space Frequency Block Coding

SFIR Spatial Filtering for Interference Reduction

SFN System Frame Number

SGSN Serving GPRS Support Node

SIC Successive Interference Cancellation

SID SIlence Descriptor

SIFS Short Infer Frame Space

SIM Subscriber Identity Module

SINR Signal-to-Interference-and-Noise Ratio

SIR Signal-to-Interference Ratio

SISO Soft Input Soft Output

SISO Single Input Single Output

SLNR Signal-to-Leakage and Noise Ratio

SM Spatial Multiplexing

SMS Short Message Service

SMTP Short Message Transfer Protocol

SN Serial Number

SNDCP Subnetwork Dependent Convergence Protocol

SNR Signal-to-Noise Ratio

SOLT Short Open Loss Termination

SON Self Organizing Network

SP Shortest Path

S/P Serial to Parallel (conversion)

SQNR Signal-to-Quantization Noise Ratio

SR Spatial Reference

SRake Selective Rake

SRMA Split-channel Reservation Multiple Access

SSA Small Scale Averaged

SSF Small-Scale Fading

ST Space – Time

STA STAtion

STBC Space Time Block Code

STC Sinusoidal Transform Coder

STDCC Swept Time Delay Cross Correlator

STP Short Term Prediction

STP Short Term Predictor

STS Space Time Spreading

STTC Space Time Trellis Code

SV Saleh–Valenzuela model

SVD Singular Value Decomposition

TA Terminal Adapter

TAC Type Approval Code

TAF Terminal Adapter Function

TBF Temporary Block Flow

TC Traffic Category

TC Topology Control

TCH Traffic CHannel

TCH/F Full-rate Traffic CHannels

Abbreviations **xlv **

TCH/H Half-rate Traffic CHannels

TCM Trellis Coded Modulation

TCP Transmission Control Protocol

TD-SCDMA Time Division-Synchronous Code Division Multiple Access TDD Time Domain Duplexing

TDMA Time Division Multiple Access

TE Temporal Reference

TE Terminal Equipment

TE Transmitted Reference

TE Transversal Electric

TETRA TErrestrial Trunked RAdio

TFCI Transmit Format Combination Indicator

TFI Transport Format Indicator

TH-IR Time Hopping Impulse Radio

TIA Telecommunications Industry Association (U.S.)

TM Transversal Magnetic

TMSI Temporary Mobile Subscriber Identity

TPC Transmit Power Control

TR Technical Report (ETSI)

TR Temporal reference

TR Transmitted reference

TS Technical Specification

TS Time Slot

TSPEC Traffic SPECifications

TTA Telecommunications Technology Association of Korea TTC Telecommunications Technology Committee

TTS Text To Speech synthesis

TU Typical Urban

TX Transmitter

TXOP Transmission OPportunity

U-NII Unlicensed National Information Infrastructure

UARFCN UTRA Absolute Radio Frequency Channel Number UCPCH Uplink Common Packet CHannel

UDP User Datagram Protocol

UE User Equipment

UE-ID User Equipment in-band IDentification

UED User Equipment Domain

UL Uplink

ULA Uniform Linear Array

UMTS Universal Mobile Telecommunications System

UP User Priority

US Uncorrelated Scatterer

USB Universal Serial Bus

USF Uplink Status Flag

USIM User Service Identity Module

UTRA UMTS Terrestrial Radio Access

UTRAN UMTS Terrestrial Radio Access Network

UWB Ultra Wide Bandwidth

UWC Universal Wireless Communications

VAD Voice Activity Detection/Detector

**xlvi** Abbreviations 

VCDA Virtual Cell Deployment Area

VCEG Video Coding Expert Group

VCO Voltage Controlled Oscillator

VLC Variable Length Coding

VLR Visitor Location Register

VoIP Voice over Internet Protocol

VRB Virtual Resource Block

VQ Vector Quantization/Quantizer

VSELP Vector Sum Excited Linear Prediction

WAP Wireless Application Protocol

WB Wide Band

WCDMA Wideband Code Division Multiple Access

WF Whitening Filter

WG Working Group

WH Walsh-Hadamard

WI Waveform Interpolation

WiFi Wireless Fidelity

WLAN Wireless Local Area Network

WLL Wireless Local Loop

WM Wireless Medium

WSS Wide Sense Stationary

WSSUS Wide Sense Stationary Uncorrelated Scatterer

ZF Zero-Forcing

Symbols

This list gives a brief overview of the use of variables in the text. Due to the large number of quantities occurring, the same letter might be used in different chapters for different quantities. For this reason, this will need checking as chapter numbers have changed in which the variable is primarily used, though they can occur in other chapters as well. Those variables that are used only locally, and explained directly at their occurrence, are not mentioned here.

Lowercase symbols:

*ap*, *am* auxiliary variables 4 *a*1 amplitudes of the MPCs 5, 6, 7, 8 *a(hm)* auxiliary function 7 **a***(φ)* steering vector 8

*an,m* amplitudes of components from direction *n*,

13

delay *m*

*bm m*th bit 11, 12, 13, 14, 16, 17

*cdf* cumulative distribution function 5

*ci,k* amplitudes of resolvable MPCs; tap weights

7

for tapped delay lines

*c*0 speed of light 5, 13, 19 *cm* complex transmit symbols 11, 12, 13, 16 *d* distance BS–MS 4 *d* distance in signal space diagram 12, 13 *d*R Rayleigh distance 4 *d*break distance BS–breakpoint 4 *d*layer thickness of layer 4 *d*direct direct pathlength 4 *d*refl length of reflected path 4 *d*p distance to previous screen 4 *d*n distance to subsequent screen 4 *d*0 distance to reference point 5 *d*a distance between antenna elements 8, 13 *d*w distance between turns of helix antenna 8

*dkm* euclidean distance between signal points

11

with index *k* and *m*

*d(*→*x ,*→*y )* distance of codewords 14 *dH* Hamming distance 14 *d*cov coverage distance 3 *d*div diversity order 20 *e* basis of natural logarithm

**xlviii** Symbols 

*e*(*t*) impulse response of equalizer 16 *f* frequency 5 *f* ( ) function

*f*c carrier frequency 5, 7, 8 *f*rep repetition frequency 8 *f*slip frequency slip 8 *f*inst instantaneous frequency 12 *fk* impulse response of discrete-time channel 16 *fn* carrier frequencies in OFDM 19 *f*D modulation frequency in FSK 11 **g** network encoding vector 22 *g*( ) function

*g*(*t*) basis pulse 11, 12, 19 *g*R*(t)* rectangular basis pulse 11 *g*˜*(t)* phase pulse 11

*gm* discrete impulse response of channel plus

16

feedforward filter

*g*N Nyquist raised cosine pulse 11 *g*NR root Nyquist raised cosine pulse 11 *h(t, τ )* channel impulse response 2, 6, 7, 8, 12, 13, 18, 19, 20

*h*TX height of TX 4 *h*RX height of RX 4 *h*s height of screen 4 *h*b height of BS 7 *h*m height of MS 7

*h*r*,*d complex channel gain from relay to

22

destination

*h*roof height of rooftop 7 *h*meas*(ti, τ )* measured impulse response 8

*h*s*,*d complex channel gain from source to

22

destination

*h*s*,*r complex channel gain from source to relay 22 *h*w height of helix antenna 9 *h(t, τ, φ)* directionally resolved impulse response 7 *h*mod modulation index of CPFSK signal 11 **h**d vector of desired impulse responses 13, 20 *i* index counter

*j* index, imaginary unit 4 *k, k*0 wavenumber 4, 13 *k* index counter 8, 11, 13, 19, 20, 22, 28

*k*scale scaling factor for STDCC 8 *k*B Boltzmann constant 3 *l* index counter 8, 19, 20 *m* Nakagami *m*-factor 5, 13 *m* counter 11, 12, 13, 14, 16, 17

*m* index for parity check bits 14 *n* propagation exponent 4, 7

Symbols **xlix **

*n*1 refraction index for medium 4 *n*(*t*) noise signal 8, 12, 13, 14, 16, 18

*n*LP*(t)* low-pass noise 12 *n*BP*(t)* bandpass noise 12 *n* index counter 11 *nm* sampled noise values 16, 19

*nn* sampled noise values 14, 21 **n** vector of noise samples 20 *n*˜*m* sample values of colored noise

*p* transition probability 14 *pdf* probability density function 5 *p*(*t*) modulated pulse 8 *p*(*t*) pulse sequence 11 *qm* impulse response of channel + equalizer 16 **r** position vector 4 *r* absolute value of fieldstrength 5 *r* spectral efficiency 14 *r*LP*(t)* low-pass representation of received signal 12 **r** received signal vector 12 *r*(*t*) received signal 14, 15, 16 *s* subcarrier channel index 28 *s*(*t*) sounding signal 8 *s*1*(t)* auxiliary signal 8 *s*LP*,*BP*(t)* low-pass (bandpass) signal 11 **s**LP*,*BP signal vector in low-pass (bandpass) 11 **s**synd syndrome vector 14 **s** vector of signals at antenna array 8, 20, 27, 28 **s** transmit signal vector 14 *t* absolute time 2, 11, 12, 13, 16, 17

**t** precoding vector 20 *t*0 start time 6 *t*s sampling time 12 *u* auxiliary variable 11 *um* sequence of sample values at equalizer input 16 **u** vector of information symbols 14

v velocity 5 **v** singlar vector 20 *wl* antenna weights 8, 13, 20 *x x*-coordinate 4 *x* general variable 5 *x* transmit signal 22 *x*(*t*) input signal 6 **x** code vector 14 **x** sequence of transmit signals 14 *y y*-coordinate 4 *y* decision variable 21 *y* received signal 22 **y** sequence of receive signals 14

**l** Symbols 

*y*(*t*) output signal 6 *z z*-coordinate

Uppercase symbols:

**A** steering matrix 8 **A** antenna mapping matrix 27 *A*RX antenna area of receiver 4 *A(d*TX*, d*RX*)* amplitude factors for diffraction 4 *ADF* average duration of fades

*A* amplitude of dominant component 7 *A* state in the trellis diagram 14 *B(νf )* Doppler-variant transfer function 6 *B*coh coherence bandwidth 6 *B* bandwidth 11 *BER* bit error probability 12 *B*n noise bandwidth 12 *B*r receiver bandwidth 12 *B* state in the trellis diagram 14 *B*G bandwidth of Gaussian filter 11 *C* capacity 14, 17, 20 **C** covariance matrix

*C*crest crest factor 8 *C* proportionality constant

*C* state in the trellis diagram 14 *D* diffraction coefficient 5 *D*W diameter of helix antenna 8 *D* quadratic form 12 *D* maximum distortion 16 *D* state in the trellis diagram 14 *D* unit delay 27 *Dleav* interleaver separation 14 *D* antenna directivity

*E* electric fieldstrength 4 *E*diff fieldstrength of diffracted field 4 *E*inc fieldstrength of incident field 4 *E*{} expectation 4, 13, 14, 18

*E*1, *E*2 fieldstrength of multipath components 5 *E*0 normalization fieldstrength 13 *E*S Symbol energy 11, 12, 13 *E*B bit energy 11, 12, 13 *E*C chip energy 18 *Es,k* energy of *k*th signal 11, 18 *E*(*f* ) transfer function of equalizer 16 *F (ν*F*)* Fresnel integral 4 *F*˜ modified Fresnel integral 4 *F* local mean of fieldstrength 5

*F*(*z*) factorization of the transfer function of the

16

equivalent time discrete channel

*F* noise figure 3 *G*RX antenna gain of receive antenna 3, 4

Symbols **li **

*G*TX antenna gain transmit antenna 4 *G(D)* code polynomial 27 *G(γ ), G(ϕ, θ)* antenna pattern 5 *G(ν, ν*1*, ν*2*)* Gaussian function 7 *G*max maximum gain

*G*R spectrum of rectangular pulse 11 *G*N spectrum of Nyquist pulse 11 *G*NR spectrum of root Nyquist pulse 11 **G** generator matrix 14 *G*code code gain 14 **G**G matrix with iid Gaussian entries 20 *G* gain of an amplifier stage 3

*H* transfer function of the channel 5, 6, 19, 20 *H (X)* entropy 14 *HD(X)* entropy of binary symmetric channel 14 *HR(f )* transfer function of receive filter 12, 18 **H** parity check matrix 14 **H**had Hadamard matrix 18, 19 *I* (*t*) in-phase component 5 *I (t )* link control action 22 *I (x, y)* mutual information 14 *I*0 modified Bessel function 5, 12 |*J* | Jacobi determinant 5 *J*0 Bessel function 7 *Kr* Rice factor 5 *K(t, τ )* kernel function 6 *K* number of resolvable directions 8 *KI* system margin 3 *K* number of bits in a symbol 11

*K* number of information symbols in a

14

codeword

2*K* + 1 number of equalizer taps 16 *K* scaling constant for STDCC 8 *K* number of users 20 *K* number of relays 22 *L* number of clusters 7 *L*msd multiscreenloss

*L*rts diffraction loss 7 *Lori* street orientation loss 7 *L*a antenna dimension 4 *Li* attenuation at the *i*th screen

*L*c correlation length 4

*L* duration of the impulse response of the

16

equivalent time discrete channel *f*

*L* number of cells in convolutional encoder 14 *L* number of data streams 20 *L*˜ dimension of space-time code 20 *L*Tr truncation depth 14

*L*symb number of symbols where two possible

14

sequences differ

**lii** Symbols 

*L*f losses in feeder 3 *L* number of RF chains in HS-MRC

*M(φ, θ)* array factor 8 *M* number of elements in the alphabet 11 *M*(*s*) moment-generating function 12, 13 *N* number of screens 4 *N* number of MPCs 5, 7, 8 *N* size of the set of expansion functions 12 *N* total number of symbols in the code 14

*N* number of mod-2 adders in the

14

convolutional encoder

*N*0 noise power-spectral density 12 *N*(*f* ) noise spectrum 6, 12 *N*symb number of information bits/symbols in TCM 14

*N*˜ number of bits for convolutional encoder in

14

TCM

*N* number of users in MA 17 *N*reg length of shift register 14 *N*r number of receive antennas 8, 13, 20 *N*subchannel number of subchannels 28 *N*t number of transmit antennas 13, 20 *N*s number of significant scatterers 20 *NBS* number of BS antennas 20 *NMS* number of MS antennas 20 *N*R level crossing rate 5 *P*TX transmit power 4 *P*RX receive power 4 *P*m average power 5 *Ph,S,B* cross-power spectral densities 6 *P*h*(τ )* PDP 6 *P (t, τ )* instantaneous PDP 7 *P*n noise power

*P*pair pairwise error probability 12 *P*inst instantaneous received power 12 *P*max maximum TX power 20 *P*f false alarm probability 21 *P*md missed detection probability 21 *P*s transmit power of source 22 *P*r transmit power of relay 22 Pr probability

Prout outage probability

*PL* pathloss 4, 5 *P*s signal power 3, 11 *Q*(*x*) Q-function 12, 13 *Q* antenna quality 9 *Q* codebook size 20 *Q* queue backlog 22 *Q* quantization function 23 *Q*(*t*) quadrature component 5 *Q*T interference quotient 6

Symbols **liii **

*QM* Marcum’s Q-function 12

*Q*(*z*) transfer function of equivalent channel and

16

equalizer

*R* radius of circle 5 *R* cell size 17 *R* transmission rate 14 *R*th threshold transmission rate 22 **R**TX transmit correlation matrix 6, 7, 20 **R**RX receive correlation matrix 6, 7, 20 *Rxx* autocorrelation function of *x* 11 **R***xx* correlation matrix of *x* 8 *R*rad radiation resistance 8 *R*S symbol rate 11 *R*B bit rate 11 *R*c code rate 14 *R*e rank of error matrix 17 *Rh* impulse response correlation function 6 **R**ni noise and interference correlation matrix 20 *R*˜*yy (t, t*′*)* autocovariance signal of received signal 7 *SIR* signal-to-interference ratio 5 *S*(*f* ) power spectrum 5, 6, 12 *S(t )* topology state 22 *S(ν, τ )* spreading function 6 *Sτ* delay spread 6 *S*D*(ν, τ )* Doppler spectrum 7 *S*LP*,*BP*(f )* power spectrum of LP (BP) signal 11 *SER* symbol error probability 12 *S*N noise power-spectral density

*Sφ* angular spread 6, 7, 13 *T*B bit duration

*T* transmission factor 4 *T*m mean delay 6 *T*m*(t)* instantaneous mean delay 6 *T*rep repetition time of pulse signal 8 *TB* time bandwidth product 8 *Tslip* slip period 8 **T** auxiliary matrix 8 **T** transmit beamforming matrix 20

*T* duration (general) 11 *T*per periodicity 11 *T*s sampling time

*T*S symbol duration 11 *T*p packet duration 17 *T*cp duration of cyclic prefix 19 *T*C chip duration 18 *T*e temperature of environment 3

*T*d delay of pulse in PPM 11 *T*coh coherence time 6 *T*g group delay 12 **U** unitary matrix 8, 20

**liv** Symbols 

*W* correlation spectrum 4 *Wa* delay window 6 *W* system bandwidth

**W** unitary matrix 19 *X* complex Gaussian random variable 12 *X*(*x*) code polynomial 14 *Y* complex Gaussian random variable 12 *Z* complex Gaussian random variable 12 *Z* virtual queue backlog 22

Lowercase Greek:

*α* dielectric length 4 *α* complex channel gain 12 *α* rolloff factor 11 *α* steering vector 8 *β* decay time constant 7 *β* amplification at relay 22 *γ* SNR

*γ* mean SNR

*γ*MRC SNR at output of maximum ratio combiner 13 *γ*EGC SNR at output of equal gain combiner 13 *γ* angle for Doppler shift 5 *γS ES/N*0 12 *γB EB/N*0 12, 13, 16, 17 *δ* complex dielectric constant 4 *δik* Kronecker delta 13, 16, 19 *δ(τ )* Dirac function 12, 13, 16, 18 ∈ dielectric constant 4 ∈r relative dielectric constant 4 ∈eff effective relative dielectric constant 4 *εm* error signal 16 *ε* error vector of a code symbol 14 *ϕ* orientation of a street 7 *ϕ* phase of an MPC 5 *ϕ*˜ deterministic phaseshift 7 *ϕm(t)* base functions for expansion 11 *φ* azimuth angle of arrival 6, 7 *η(t ) g*(*t*) \* *h*(*t*) 16 *κ* auxiliary variable 13 *λ, λ*0 wavelength

*λ*p packet transmission rate 17 *λi i*th eigenvalue

*µ* metric 12 *µ* stepwidth of LMS 16 *µ(t)* transmission matrix 22 *ν* Doppler shift 6

*ν*max maximum Doppler shift 7 *ν*m mean Doppler shift 5 *ν*F Fresnel parameter 5 *ω* angular frequency 4

Symbols **lv **

*ρ* position vector

*ρkm* correlation coefficients between signals 11 *σ*c conductivity 4 *σ*h standard deviation of height 4 *σ* standard deviation 5 *σF* standard deviation of local mean 5 *σ*G standard deviation of Gaussian pulse 11 *σ*n noise standard deviation

*σ*2S power in symbol sequence 11 *τ* delay 4, 5 *τ*Gr group delay 5, 12 *τi* delay of the *i*th MPC 7 *τ*max maximum excess delay

*χi(t)* distortion of the *i*-th pulse 13 *ζ* ACF of *η(t )* 16 *ξ* SNR loss for discrete precoding 20 *ξn(t)* noise correlation function 12 *ξ*˜*s(t)* FT of the normalized Doppler spectrum 12 *ξs(ν, τ )* scattering function 12 *ξh(t, τ )* FT of the scattering function 12

Uppercase Greek:

*4hb* = *hb* − *hroof* 7 *4xs* distance between measurement points 8 *4τ*min minimum resolvable *τ* 8 *4f*chip difference in chip frequency 8 *4ϕ* angle difference of paths 4 *4τ* runtime difference 5 *4ν* Doppler shift 5 *4* phaseshift between two antenna elements 8 *4* Lyapunov drift 22

*4C* determinant of **C** 13 *4φ* angular range 13 *5H* phase of the channel transfer function 5, 12 *5*CPFSK*(t)* phase of transmit signal for CPFSK signal 11 *6* matrix of eigenvalues

*5*TX*(t)* phase of transmit signal

*7* mean quadratic power Nakagami 5 *7* direction of departure

*7n n*th moment of Doppler spectrum 5, 13 *8(t)* queue backlog 22 *8e* angle of incidence 4 *8r* angle of reflection 4 *8t* angle of transmission 4 *8n* transmission phase of *n*th bit

*8*d diffraction angle

*φ*TX angle TX wedge 4 *φ*RX angle RX wedge 4 *φ* azimuth 7 *φ*0 nominal DOA 7, 13

**lvi** Symbols 

*φi* DOA of *i*th wave 13 *ψ* auxiliary angle 4, 13 *ψ* angle of incidence 90 − *8e* 4 *x*¯ = *E*{*x*}

*r*˙ = *dr/dt*

**U**† Hermitian transpose

**U***T* transpose

**x**∗ complex conjugate

*:* Fourier transform of *ζm*

*F* Fourier transform

*X* transmit alphabet 14

**Part I**

**Introduction**

In the first part of this book, we give an introduction to the basic applications of wireless com munications, as well as the technical problems inherent in this communication paradigm. After a brief history of wireless, Chapter 1 describes the different types of wireless services, and works out their fundamental differences. The subsequent Section 1.3 looks at the same problem from a different angle: what data rates, ranges, etc., occur in practical systems, and especially, what combination of performance measures are demanded (e.g., what data rates need to be transmitted over short distances; what data rates are required over long distances?) Chapter 2 then describes the technical challenges of communicating without wires, putting special emphasis on fading and co-channel interference. Chapter 3 describes the most elementary problem of designing a wireless system, namely to set up a link budget in either a noise-limited or an interference-limited system.

After studying this part of the book, the reader should have an overview of different types of wireless services, and understand the technical challenges involved in each of them. The solutions to those challenges are described in the later parts of this book.

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**1**

Applications and Requirements of Wireless Services

Wireless communications is one of the big engineering success stories of the last 25 years – not only from a scientific point of view, where the progress has been phenomenal but also in terms of market size and impact on society. Companies that were completely unknown 25 years ago are now household names all over the world, due to their wireless products, and in several countries the wireless industry is dominating the whole economy. Working habits, and even more generally the ways we all communicate, have been changed by the possibility of talking “anywhere, anytime.”

For a long time, wireless communications has been associated with cellular telephony, as this is the biggest market segment, and has had the highest impact on everyday lives. In recent times, wireless computer networks have also led to a significant change in working habits and mobility of workers – answering emails in a coffee shop has become an everyday occurrence. But besides these widely publicized cases, a large number of less obvious applications have been developed, and are starting to change our lives. Wireless sensor networks monitor factories, wireless links replace the cables between computers and keyboards, and wireless positioning systems monitor the location of trucks that have goods identified by wireless Radio Frequency (RF) tags. This variety of new applications causes the technical challenges for the wireless engineers to become bigger with each day. This book aims to give an overview of the solution methods for current as well as future challenges.

Quite generally, there are two paths to developing new technical solutions: engineering driven and market driven. In the first case, the engineers come up with a brilliant scientific idea – without having an immediate application in mind. As time progresses, the market finds applications enabled by this idea.1 In the other approach, the market demands a specific product and the engineers try to develop a technical solution that fulfills this demand. In this chapter, we describe these market demands. We start out with a brief history of wireless communications, in order to convey a feeling of how the science, as well as the market, has developed in the past 100 years. Then follows a description of the types of services that constitute the majority of the wireless market today. Each of these services makes specific demands in terms of data rate, range, number of users, energy consumption, mobility, and so on. We discuss all these aspects in Section 1.3. We wrap up this section with a description of the interaction between the engineering of wireless devices and the behavioral changes induced by them in society.

1 The second chapter gives a summary of the main technical challenges in wireless communications – i.e., the basis for the engineering-driven solutions. Chapters 3–23 discuss the technical details of these challenges and the scientific basis, while Chapters 24–29 expound specific systems that have been developed in recent years.

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**4** Wireless Communications 

**1.1 History**

*1.1.1 How It All Started*

When looking at the history of communications, we find that wireless communications is actually the oldest form – shouts and jungle drums did not require any wires or cables to function. Even the oldest “electromagnetic” (optical) communications are wireless: smoke signals are based on propagation of optical signals along a line-of-sight connection. However, wireless communications as we know it started only with the work of Maxwell and Hertz, who laid the basis for our under standing of the transmission of electromagnetic waves. It was not long after their groundbreaking work that Tesla demonstrated the transmission of information via these waves – in essence, the first wireless communications system. In 1898, Marconi made his well-publicized demonstration of wireless communications from a boat to the Isle of Wight in the English Channel. It is noteworthy that while Tesla was the first to succeed in this important endeavor, Marconi had the better public relations, and is widely cited as the inventor of wireless communications, receiving a Nobel prize in 1909.2

In the subsequent years, the use of radio (and later television) became widespread throughout the world. While in the “normal” language, we usually do not think of radio or TV as “wireless communications,” they certainly are, in a scientific sense, information transmission from one place to another by means of electromagnetic waves. They can even constitute “mobile communications,” as evidenced by car radios. A lot of basic research – especially concerning wireless propagation channels – was done for entertainment broadcasting. By the late 1930s, a wide network of wireless information transmission – though unidirectional – was in place.

*1.1.2 The First Systems*

At the same time, the need for bidirectional mobile communications emerged. Police departments and the military had obvious applications for such two-way communications, and were the first to use wireless systems with closed user groups. Military applications drove a lot of the research during, and shortly after, the Second World War. This was also the time when much of the theoretical foundations for communications in general were laid. Claude Shannon’s [1948] groundbreaking work *A Mathematical Theory of Communications* appeared during that time, and established the possibility of error-free transmission under restrictions for the data rate and the Signal-to-Noise Ratio (SNR). Some of the suggestions in that work, like the use of optimum power allocation in frequency-selective channels, are only now being introduced into wireless systems.

The 1940s and 1950s saw several important developments: the use of *Citizens’ Band* (CB) radios became widespread, establishing a new way of communicating between cars on the road. Communicating with these systems was useful for transferring vital traffic information and related aspects within the closed community of the drivers owning such devices, but it lacked an interface to the public telephone system, and the range was limited to some 100 km, depending on the power of the (mobile) transmitters. In 1946, the first mobile telephone system was installed in the U.S.A. (St. Louis). This system did have an interface to the *Public Switched Telephone Network* (PSTN), the landline phone system, though this interface was not automated, but rather consisted of human telephone operators. However, with a total of six speech channels for the whole city, the system soon met its limits. This motivated investigations of how the number of users could be increased, even though the allocated spectrum would remain limited. Researchers at AT&T’s Bell Labs found the answer: the cellular principle, where the geographical area is divided into cells; different cells might use the same frequencies. To this day, this principle forms the basis for the majority of wireless communications.



2 Marconi’s patents were actually overturned in the 1940s.

Applications and Requirements of Wireless Services **5 **

Despite the theoretical breakthrough, cellular telephony did not experience significant growth during the 1960s. However, there were exciting developments on a different front: in 1957, the Soviet Union launched the first satellite (*Sputnik*) and the U.S.A. soon followed. This development fostered research in the new area of satellite communications.3 Many basic questions had to be solved, including the effects of propagation through the atmosphere, the impact of solar storms, the design of solar panels and other long-lasting energy sources for the satellites, and so on. To this day, satellite communications is an important area of wireless communications (though not one that we address specifically in this book). The most widespread application lies in satellite TV transmission.

*1.1.3 Analog Cellular Systems*

The 1970s saw a revived interest in cellular communications. In scientific research, these years saw the formulation of models for path loss, Doppler spectra, fading statistics, and other quantities that determine the performance of analog telephone systems. A highlight of that work was Jakes’ book *Microwave Mobile Radio* that summed up the state of the art in this area [Jakes 1974]. The 1960s and 1970s also saw a lot of basic research that was originally intended for landline communications, but later also proved to be instrumental for wireless communications. For example, the basics of adaptive equalizers, as well as multicarrier communications, were developed during that time.

For the practical use of wireless telephony, the progress in device miniaturization made the vision of “portable” devices more realistic. Companies like Motorola and AT&T vied for leadership in this area and made vital contributions. Nippon Telephone and Telegraph (NTT) established a commercial cellphone system in Tokyo in 1979. However, it was a Swedish company that built up the first system with large coverage and automated switching: up to that point, Ericsson AB had been mostly known for telephone switches while radio communications was of limited interest to them. However, it was just that expertise in switching technology and the (for that time, daring) decision to use digital switching technology that allowed them to combine different cells in a large area into a single network, and establish the *Nordic Mobile Telephone* (NMT) system [Meurling and Jeans 1994]. Note that while the switching technology was digital, the radio transmission technology was still analog, and the systems became therefore known as *analog* systems. Subsequently, other countries developed their own analog phone standards. The system in the U.S.A., e.g., was called *Advanced Mobile Phone System* (AMPS).

An investigation of NMT also established an interesting method for estimating market size: busi ness consultants equated the possible number of mobile phone users with the number of Mercedes 600 (the top-of-the-line luxury car at that time) in Sweden. Obviously, mobile telephony could never become a mass market, could it? Similar thoughts must have occurred to the management of the inventor of cellular telephony, AT&T. Upon advice from a consulting company, they decided that mobile telephony could never attract a significant number of participants and stopped business activities in cellular communications.4

The analog systems paved the way for the wireless revolution. During the 1980s, they grew at a frenetic pace and reached market penetrations of up to 10% in Europe, though their impact was somewhat less in the U.S.A. In the beginning of the 1980s, the phones were “portable,” but definitely not handheld. In most languages, they were just called “carphones,” because the battery and transmitter were stored in the trunk of the car and were too heavy to be carried around. But at the end of the 1980s, handheld phones with good speech quality and quite acceptable battery



3 Satellite communications – specifically by geostationary satellites – had already been suggested by science fiction writer Arthur C. Clark in the 1940s.

4 These activities were restarted in the early 1990s, when the folly of the original decision became clear. AT&T then paid more than 10 billion dollars to acquire McCaw, which it renamed “AT&T Wireless.”

**6** Wireless Communications 

lifetime abounded. The quality had become so good that in some markets digital phones had difficulty establishing themselves – there just did not seem to be a need for further improvements.

*1.1.4 GSM and the Worldwide Cellular Revolution*

Even though the public did not see a need for changing from analog to digital, the network operators knew better. Analog phones have a bad spectral efficiency (we will see why in Chapter 3), and due to the rapid growth of the cellular market, operators had a high interest in making room for more customers. Also, research in communications had started its inexorable turn to digital communications, and that included digital wireless communications as well. In the late 1970s and the 1980s, research into spectrally efficient modulation formats, the impact of channel distortions, and temporal variations on digital signals, as well as multiple access schemes and much more, were explored in research labs throughout the world. It thus became clear to the cognoscenti that the real-world systems would soon follow the research.

Again, it was Europe that led the way. The *European Telecommunications Standards Institute* (ETSI) group started the development of a digital cellular standard that would become mandatory throughout Europe and was later adopted in most parts of the world: *Global System for Mobile communications* (GSM). The system was developed throughout the 1980s; deployment started in the early 1990s and user acceptance was swift. Due to additional features, better speech quality, and the possibility for secure communications, GSM-based services overtook analog services typically within 2 years of their introduction. In the U.S.A., the change to digital systems was somewhat slower, but by the end of the 1990s, this country also was overwhelmingly digital.

Digital phones turned cellular communications, which was already on the road to success, into a blockbuster. By the year 2000, market penetration in Western Europe and Japan had exceeded 50%, and though the U.S.A. showed a somewhat delayed development, growth rates were spectacular as well.

The development of wireless systems also made clear the necessity of standards. Devices can only communicate if they are compatible, and each receiver can “understand” each transmitter – i.e., if they follow the same standard. But how should these standards be set? Different countries developed different approaches. The approach in the U.S.A. is “hands-off”: allow a wide variety of standards and let the market establish the winner (or several winners). When frequencies for digital cellular communications were auctioned off in the 1990s, the buyers of the spectrum licences could choose the system standard they would use. For this reason, three different standards are now being used in the U.S.A. A similar approach was used by Japan, where two different systems fought for the market of Second Generation (2G) cellular systems. In both Japan and the U.S.A., the networks based on different standards work in the *same* geographical regions, allowing consumers to choose between different technical standards.

The situation was different in Europe. When digital communications were introduced, usually only one operator *per country* (typically, the incumbent public telephone operators) existed. If each of these operators would adopt a different standard, the result would be high market fragmentation (i.e., a small market for each standard), without the benefit of competition between operators. Furthermore, roaming from country to country, which for obvious geographical regions is much more frequent in Europe than in the U.S.A. or Japan, would be impossible. It was thus logical to establish a single common standard for all of Europe. This decision proved to be beneficial for wireless communications in general, as it provided the economy of scales that decreased cost and thus increased the popularity of the new services.

Applications and Requirements of Wireless Services **7 **

*1.1.5 New Wireless Systems and the Burst of the Bubble*

Though cellular communications defined the picture of wireless communications in the general population, a whole range of new services was introduced in the 1990s. Cordless telephones started to replace the “normal” telephones in many homes. The first versions of these phones used analog technology; however, also for this application, digital technology proved to be superior. Among other aspects, the possibility of listening in to analog conversations, and the possibility for neighbors to “highjack” an analog cordless Base Station (BS) and make calls at other people’s expense, led to a shift to digital communications. While cordless phones never achieved the spectacular market size of cellphones, they constitute a solid market.

Another market that seemed to have great promise in the 1990s was *fixed wireless access* and *Wireless Local Loop* (WLL) – in other words, replacing the copper lines to the homes of the users by wireless links, but without the specific benefit of mobility. A number of technical solutions were developed, but all of them ultimately failed. The reasons were as much economical and political as they were technical. The original motivation for WLL was to give access to customers for alternative providers of phone services, bypassing the copper lines that belonged to the incumbents. However, regulators throughout the world ruled in the mid-1990s that the incumbents *have* to lease their lines to the alternative providers, often at favorable prices. This eliminated much of the economic basis for WLL. Similarly, fixed wireless access was touted as the scheme to provide broadband data access at competitive prices. However, the price war between Digital Subscriber Line (DSL) technology and cable TV has greatly dimmed the economic attractiveness of this approach.

The biggest treasure thus seemed to lie in a further development of cellular systems, establishing the *Third Generation* (3G) (after the analog systems and 2G systems like GSM) [Bi et al. 2001]. 2G systems were essentially pure voice transmission systems (though some simple data services, like the *Short Message Service* – SMS – were included as well). The new 3G systems were to provide data transmission at rates comparable with the ill-fated *Integrated Services Digital Network* (ISDN) (144 kbit/s), and even up to 2 Mbit/s, at speeds of up to 500 km/h. After long deliberations, two standards were established: *Third Generation Partnership Project* (3GPP) (supported by Europe, Japan, and some American companies) and 3GPP2 (supported by another faction of American companies). The new standards also required a new spectrum allocation in most of the world, and the selling of this spectrum became a bonanza for the treasuries of several countries.

The development of 3GPP, and the earlier introduction of the IS-95 CDMA (*Code Division Mul tiple Access*) system in the U.S.A., sparked a lot of research into CDMA and other spread spectrum techniques (see Chapter 18) for wireless communications; by the end of the decade, multicarrier techniques (Chapter 19) had also gained a strong footing in the research community. Multiuser detection – i.e., the fact that the effect of interference can be greatly mitigated by exploiting its structure – was another area that many researchers concentrated on, particularly in the early 1990s. Finally, the field of multiantenna systems (Chapter 20) saw an enormous growth since 1995, and for some time accounted for almost half of all published research in the area of the physical layer design of wireless communications.

The spectrum sales for 3G cellular systems and the Initial Public Offerings (IPOs) of some wire less start-up companies represented the peak of the “telecom bubble” of the 1990s. In 2000/2001, the market collapsed with a spectacular crash. Developments on many of the new wireless systems (like fixed wireless) were stopped as their proponents went bankrupt, while the deployment of other systems, including 3G cellular systems, was slowed down considerably. Most worrisome, many companies slowed or completely stopped research, and the general economic malaise led to decreased funding of academic research as well.

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*1.1.6 Wireless Revival*

Since 2003, several developments have led to a renewed interest in wireless communications. The first one is a continued growth of 2G and 2.5G cellular communications, stimulated by new markets as well as new applications. To give just one example, in 2008, China had more than 500 million cellphone users – even before the first 3G networks became operative. Worldwide, about 3.5 billion cellphones were in use in 2008, most of them based on 2G and 2.5G standards.

Furthermore, 3G networks have become widely available and popular – especially in Japan, Europe, and the U.S.A. – (in 2008, overall cellphone market penetration of cellphones in Western Europe was more than 100% and was approaching 90% in the U.S.A.). Data transmission speeds comparable to cable (5 Mbit/s) are available. This development has, in turn, spurred the proliferation of devices that not only allow voice calls but also Internet browsing and reception of streaming audio and video. One such device, called *iPhone*, received enormous attention among the general public when first introduced, but there exist actually dozens of cellphones with similar capabilities – these so-called “smartphones” account for 20% of the cellphone market in the U.S.A. As a consequence of all these developments, transmission of data to and from cellphones has become a large market.

Even while 3G networks are still being deployed, the next generation (sometimes called *4G* or *3.9G*) has been developed. Most infrastructure manufacturers are concentrating on the Long-Term Evolution (LTE) of the dominating 3G standard. An alternative standard, whose roots are based in fixed wireless access systems, is also under deployment. In addition, access to TV programming (either live TV or prerecorded episodes) from cellphones is becoming more and more popular. For 4G networks as well as TV transmission, Multiple Input Multiple Output system-Orthogonal Frequency Division Multiplexing (MIMO-OFDM) (see Chapters 19 and 20) is the modulation method of choice, which has spurred research in this area.

A second important development was the unexpected success of wireless computer networks (wireless Local Area Networks (LANs)). Devices following the Institute of Electrical and Elec tronics Engineers (IEEE) 802.11 standard (Chapter 29) have enabled computers to be used in a way that is almost as versatile and mobile as cellphones. The standardization process had already started in the mid-1990s, but it took several versions, and the impact of intense competition from manufacturers, to turn this into a mass product. Currently, wireless access points are widely avail able not only at homes and offices but also at airports, coffee shops, and similar locations. As a consequence, many people who depend on laptops and Internet connections to do their work now have more freedom to choose when and where to work.

Thirdly, wireless sensor networks offer new possibilities of monitoring and controlling factories and even homes from remote sites, and also find applications for military and surveillance purposes. The interest in sensor networks has also spurred a wave of research into ad hoc and peer-to-peer networks. Such networks do not use a dedicated infrastructure. If the distance between source and destination is too large, other nodes of the network help in forwarding the information to the final destination. Since the structure of those networks is significantly different from the traditional cellular networks, a lot of new research is required.

Summarizing, the “wireless revival” is based on three tendencies: (i) a much broader range of products, (ii) data transmission with a higher rate for already existing products, and (iii) higher user densities. These trends determine the directions of research in the field and provide a motivation for many of the more recent scientific developments.

**1.2 Types of Services**

*1.2.1 Broadcast*

The first wireless service was broadcast radio. In this application, information is transmitted to different, possibly mobile, users (see Figure 1.1). Four properties differentiate broadcast radio

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Broadcast

Transmitter

**Figure 1.1** Principle of broadcast transmission.

from, e.g., cellular telephony:

1. The information is only sent in one direction. It is only the broadcast station that sends infor mation to the radio or TV receivers; the listeners (or viewers) do not transmit any information back to the broadcast station.

2. The transmitted information is the same for all users.

3. The information is transmitted continuously.

4. In many cases, multiple transmitters send the same information. This is especially true in Europe, where national broadcast networks cover a whole country and broadcast the same program in every part of that country.5

The above properties led to a great many simplifications in the design of broadcast radio networks. The transmitter does not need to have any knowledge or consideration about the receivers. There is no requirement to provide for duplex channels (i.e., for bringing information from the receiver to the transmitter). The number of possible users of the service does not influence the transmitter structure either – irrespective of whether there are millions of users, or just a single one, the transmitter sends out the same information.

The above description has been mainly true for traditional broadcast TV and radio. Satellite TV and radio differ in the fact that often the transmissions are intended only for a subset of all possible users (pay-TV or pay-per-view customers), and therefore, encryption of the content is required in order to prevent unauthorized viewing. Note, however, that this “privacy” problem is different from regular cellphones: for pay-TV, the content should be accessible to all members of the authorized user group, (“multicast”) while for cellphones, each call should be accessible only for the single person it is intended for (“unicast”) and not to all customers of a network provider.

Despite their undisputed economic importance, broadcast networks are not at the center of interest for this book – space restrictions prevent a more detailed discussion. Still, it is useful to keep in mind that they are a specific case of wireless information transmission, and recent developments, like simulcast digital TV, interactive TV, and especially streaming TV to computers and cellphones, tend to obscure the distinction from cellular telephony even more.

*1.2.2 Paging*

Similar to broadcast, paging systems are unidirectional wireless communications systems. They are characterized by the following properties (see also Figure 1.2):



5 The situation is slightly different in the U.S.A., where a “local station” usually covers only a single metropolitan area, often with a single transmitter.

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1. The user can only receive information, but cannot transmit. Consequently, a “call” (message) can only be initiated by the call center, not by the user.

2. The information is intended for, and received by, only a single user.

3. The amount of transmitted information is very small. Originally, the received information con sisted of a single bit of information, which indicated to the user that “somebody has sent you a message.” The user then had to make a phone call (usually from a payphone) to the call center, where a human operator repeated the content of the waiting message. Later, paging systems became more sophisticated, allowing the transmission of short messages (e.g., a different phone number that should be called, or the nature of an emergency). Still, the amount of information was rather limited.

Pager

**MS**

BS

BS Call

center

BS

**Figure 1.2** Principle of a pager.

**MS**

Due to the unidirectional nature of the communications, and the small amount of information, the bandwidth required for this service is small. This in turn allows the service to operate at lower carrier frequencies – e.g., 150 MHz – where only small amounts of spectrum are available. As we will see later on, such lower carrier frequencies make it much easier to achieve good coverage of a large area with just a few transmitters.

Pagers were very popular during the 1980s and early 1990s. For some professional groups, like doctors, they were essential tools of the trade, allowing them to react to emergencies in shorter time. However, the success of cellular telephony has considerably reduced their appeal. Cellphones allow provision of all the services of a pager, plus many other features as well. The main appeal of paging systems, after the year 2000, lies in the better area coverage that they can achieve.

*1.2.3 Cellular Telephony*

Cellular telephony is the economically most important form of wireless communications. It is characterized by the following properties:

1. The information flow is bidirectional. A user can transmit and receive information at the same time.

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Due to this reason, this book often draws its examples from cellular telephony, even though the general principles are applicable to other wireless systems as well. Chapters 24–28 give a detailed description of the most popular cellular systems.

*1.2.4 Trunking Radio*

Trunking radio systems are an important variant of cellular phones, where there is no connection between the wireless system and the PSTN; therefore, it allows the communications of closed user groups. Obvious applications include police departments, fire departments, taxis, and similar services. The closed user group allows implementation of several technical innovations that are not possible (or more difficult) in normal cellular systems:

1. *Group calls*: a communication can be sent to several users simultaneously, or several users can set up a conference call between multiple users of the system.

2. *Call priorities*: a normal cellular system operates on a “first-come, first-serve” basis. Once a call is established, it cannot be interrupted.6 This is reasonable for cellphone systems, where the network operator cannot ascertain the importance or urgency of a call. However, for the trunk radio system of, e.g., a fire department, this is not an acceptable procedure. Notifications of emergencies have to go through to the affected parties, even if that means interrupting an existing, lower priority call. A trunking radio system thus has to enable the prioritization of calls and has to allow dropping a low-priority call in favor of a high-priority one.

3. *Relay networks*: the range of the network can be extended by using each *Mobile Station* (MS) as a relay station for other MSs. Thus, an MS that is out of the coverage region of the BS might send its information to another MS that is within the coverage region, and that MS will forward the message to the BS; the system can even use multiple relays to finally reach the BS. Such an approach increases the effective coverage area and the reliability of the network. However, it can only be used in a trunking radio system and not in a cellular system – normal cellular users would not want to have to spend “their” battery power on relaying messages for other users.

*1.2.5 Cordless Telephony*

Cordless telephony describes a wireless link between a handset and a BS that is directly connected to the public telephone system. The main difference from a cellphone is that the cordless telephone is associated with, and can communicate with, only a single BS (see Figure 1.4). There is thus no *mobile switching center*; rather, the BS is directly connected to the PSTN. This has several important consequences:

1. The BS does not need to have any network functionality. When a call is coming in from the PSTN, there is no need to find out the location of the MS. Similarly, there is no need to provide for handover between different BSs.

2. There is no central system. A user typically has one BS for his/her apartment or business under control, but no influence on any other BSs. For that reason, there is no need for (and no possibility for) frequency planning.

3. The fact that the cordless phone is under the control of the user also implies a different pricing structure: there are no network operators that can charge fees for connections from the MS to the BS; rather, the only occurring fees are the fees from the BS into the PSTN.



6 Except for interrupts due to technical problems, like the user moving outside the coverage region.

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Cordless phone

PSTN

BS

**Figure 1.4** Principle of a simple cordless phone.

Wireless PABX

PSTN

PABX

**Figure 1.5** Principle of a wireless private automatic branch exchange.

In many other respects, the cordless phone is similar to the cellular phone: it allows mobility *within* the cell area; the information flow is bidirectional; calls can originate from either the PSTN or the mobile user, and there have to be provisions such that calls cannot be intercepted or listened to by unauthorized users and no unauthorized calls can be made.

Cordless systems have also evolved into wireless *Private Automatic Branch eXchanges* (PABXs) (see Figure 1.5). In its most simple form, a PABX has a single BS that can serve several handsets simultaneously – either connecting them to the PSTN or establishing a connection between them (for calls within the same company or house). In its more advanced form, the PABX contains several BSs that are connected to a central control station. Such a system has essentially the same functionality as a cellular system; it is only the size of the coverage area that distinguishes such a full functionality wireless PABX from a cellular network.

The first cordless phone systems were analog systems that just established a simple wireless link between a handset and a BS; often, they did not even provide rudimentary security (i.e., stopping unauthorized calls). Current systems are digital and provide more sophisticated functionality. In Europe, the Digital Enhanced Cordless Telecommunications (DECT) system (see the companion website at *www.wiley.com/go/molisch*) is the dominant standard; Japan has a similar system called the Personal Handyphone System (PHS) that provides both the possibility for cordless telephony and an alternative cellular system (a full functionality PABX system that covers most of Japan and provides the possibility of public access). Both systems operate in the 1,800-MHz band, using a spectrum specifically dedicated to cordless applications. In the U.S.A., digital cordless phones mainly operate in the 2.45-GHz *Industrial, Scientific, and Medical* (ISM) band, which they share with many other wireless services.

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*1.2.6 Wireless Local Area Networks*

The functionality of Wireless Local Area Networks (WLANs) is very similar to that of cordless phones – connecting a single mobile user device to a public landline system. The “mobile user device” in this case is usually a laptop computer and the public landline system is the Internet. As in the cordless phone case, the main advantage is convenience for the user, allowing mobility. Wireless LANs can even be useful for connecting fixed-location computers (desktops) to the Internet, as they save the costs for laying cables to the desired location of the computer.

A major difference between wireless LANs and cordless phones is the required data rate. While cordless phones need to transmit (digitized) speech, which requires at most 64 kbit/s, wireless LANs should be at least as fast as the Internet that they are connected to. For consumer (home) applications, this means between 700 kbit/s (the speed of DSLs in the U.S.A.) and 3–5 Mbit/s (speed of cable providers in the U.S.A. and Europe) to ≥20 Mbit/s (speed of DSLs in Japan). For companies that have faster Internet connections, the requirements are proportionately higher. In order to satisfy the need for these high data rates, a number of standards have been developed, all of which carry the identifier IEEE 802.11. The original IEEE 802.11 standard enabled transmission with 1 Mbit/s, the very popular 802.11b standard (also known under the name WiFi) allows up to 11 Mbit/s and the 802.11a standard extends that to 55 Mbit/s. Even higher rates are realized by the 802.11n standard that was introduced in 2008/2009.

WLAN devices can, in principle, connect to any BS (access point) that uses the same standard. However, the owner of the access point can restrict the access – e.g., by appropriate security settings.

*1.2.7 Personal Area Networks*

When the coverage area becomes even smaller than that of WLANs, we speak of *Personal Area Networks* (PANs). Such networks are mostly intended for simple “cable replacement” duties. For example, devices following the *Bluetooth* standard allow to connect a hands-free headset to a phone without requiring a cable; in that case, the distance between the two devices is less than a meter. In such applications, data rates are fairly low (*<*1 Mbit/s). Recently, wireless communications between components in an entertainment system (DVD player to TV), between computer and peripheral devices (printer, mouse), and similar applications have gained importance, and a number of standards for PANs have been developed by the IEEE 802.15 group. For these applications, data rates in excess of 100 Mbit/s are used.

Networks for even smaller distances are called *Body Area Networks* (BANs), which enable communications between devices located on various parts of a user’s body. Such BANs play an increasingly important role in the monitoring of patients’ health and of medical devices (e.g., pacemakers).

We note finally that PANs and BANs can either have a network structure similar to a cellular approach or they can be ad hoc networks as discussed in Section 1.2.9.

*1.2.8 Fixed Wireless Access*

Fixed wireless access systems can also be considered as a derivative of cordless phones or WLANs, essentially replacing a dedicated cable connection between the user and the public landline system. The main difference from a cordless system is that (i) there is no mobility of the user devices and (ii) the BS almost always serves multiple users. Furthermore, the distances bridged by fixed wireless access devices are much larger (between 100 m and several tens of kilometers) than those bridged by cordless telephones.

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The purpose of fixed wireless access lies in providing users with telephone and data connections without having to lay cables from a central switching office to the office or apartment the user is in. Considering the high cost of labor for the cable-laying operations, this can be an economical approach. However, it is worth keeping in mind that most buildings, especially in the urban areas of developed countries, are already supplied by some form of cable – regular telephone cable, cable TV, or even optical fiber. Rulings of the telecom regulators in various countries have stressed that incumbent operators (owners of these lines) have to allow competing companies to use these lines. As a consequence, fixed wireless access has its main market for covering rural areas, and for establishing connections in developing countries that do not have any wired infrastructure in place. In general, the business cases for fixed wireless has been disappointing (see “Burst of the Bubble” in Section 1.1.5). The IEEE 802.16 (WiMAX) standard tries to alleviate that problem by allowing some limited mobility in the system, and thus blurs the distinction from cellular telephony.

*1.2.9 Ad hoc Networks and Sensor Networks*

Up to now, we have dealt with “infrastructure-based” wireless communications, where certain components (base stations, TV transmitters, etc.) are intended by design to be in a fixed location, to exercise control over the network and interface with other networks. The size of the networks may differ (from LANs covering just one apartment to cellular networks covering whole countries), but the central principle of distinguishing between “infrastructure” and “user equipment” is common to them all. There is, however, an alternative in which there is only one type of equipment, and those devices, all of which may be mobile, organize themselves into a network according to their location and according to necessity. Such networks are called *ad hoc networks* (see Figure 1.6). There can still be “controllers” in an ad hoc network, but the choice of which device acts as master and which as slave is done opportunistically whenever a network is formed. There are also ad hoc networks without any hierarchy. While the actual transmission of the data (i.e., physical layer communication) is almost identical to that of the infrastructure-based networks, the medium access and the networking functionalities are very different.



**Figure 1.6** Principle of an ad hoc network.

The advantages of ad hoc networks lie in their low costs (because no infrastructure is required) and high flexibility. The drawbacks include reduced efficiency, smaller communication range, and restrictions on the number of devices that can be included in a network. Ad hoc networks play a major role in the recent proliferation of sensor networks, which allow communications between machines for the purpose of building control (controlling air conditioning, lighting, etc., based on sensor data), factory automation, surveillance, etc. Ad hoc networks also play a role in emer gency communications (when infrastructure was destroyed, e.g., by an earthquake) as well as military communications.

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*1.2.10 Satellite Cellular Communications*

Besides TV, which creates the biggest revenues in the satellite market, cellular communications are a second important application of satellites. Satellite cellular communications mostly have the same operating principles as land-based cellular communications. However, there are some key differences.

The distance between the “BS” (i.e., the satellite) and the MS is *much* larger: for geostationary satellites, that distance is 36,000 km; for *Low Earth Orbit* (LEO) satellites, it is several hundred kilometers. Consequently, the transmit powers need to be larger, high-gain antennas need to be used on the satellite (and in many cases also on the MS), and communications from within buildings is almost impossible.

Another important difference from the land-based cellular system lies in the cell size: due to the large distance between the satellite and the Earth, it is impossible to have cells with diameters less than 100 km even with LEO satellites; for geostationary satellites, the cell areas are even larger. This large cell size is the biggest advantage as well as the biggest drawback of the satellite systems. On the positive side, it makes it easy to have good coverage even of large, sparsely populated areas – a single cell might cover most of the Sahara region. On the other hand, the area spectral efficiency is very low, which means that (given the limited spectrum assigned to this service) only a few people can communicate at the same time.

The costs of setting up a “BS” – i.e., a satellite – are much higher than for a land-based system. Not only is the launching of a communications satellite very expensive but it is also necessary to build up an appropriate infrastructure of ground stations for linking the satellites to the PSTN.

As a consequence of all these issues, the business case for satellite communications systems is quite different: it is based on supplying a small number of users with vital communications at a much higher price. Emergency workers and journalists in disaster and war areas, ship-based communications, and workers on offshore oil drilling platforms are typical users for such systems. The INMARSAT system is the leading provider for such communications. In the late 1990s, the IRIDIUM project attempted to provide lower priced satellite communications services by means of some 60 LEO satellites, but ended in bankruptcy.

**1.3 Requirements for the Services**

A key to understanding wireless design is to realize that different applications have different require ments in terms of data rate, range, mobility, energy consumption, and so on. It is *not* necessary to design a system that can sustain gigabit per second data rates over a 100-km range when the user is moving at 500 km/h. We stress this fact because there is a tendency among engineers to design a system that “does everything but wash the dishes”; while appealing from a scientific point of view, such systems tend to have a high price and low spectral efficiency. In the following, we list the range of requirements encountered in system design and we enumerate which requirements occur in which applications.

*1.3.1 Data Rate*

Data rates for wireless services span the gamut from a few bits per second to several gigabit per second, depending on the application:

• *Sensor networks* usually require data rates from a few bits per second to about 1 kbit/s. Typically, a sensor measures some critical parameter, like temperature, speed, etc., and transmits the current value (which corresponds to just a few bits) at intervals that can range from milliseconds to several

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hours. Higher data rates are often required for the central nodes of sensor networks that collect the information from a large number of sensors and forward it for further processing. In that case, data rates of up to 10 Mbit/s can be required. These “central nodes” show more similarity to WLANs or fixed wireless access.

• *Speech communications* usually require between 5 and 64 kbit/s depending on the required quality and the amount of compression. For cellular systems, which require higher spectral efficiency, source data rates of about 10 kbit/s are standard. For cordless systems, less elaborate compression and therefore higher data rates (32 kbit/s) are used.

• *Elementary data services* require between 10 and 100 kbit/s. One category of these services uses the display of the cellphone to provide Internet-like information. Since the displays are smaller, the required data rates are often smaller than for conventional Internet applications. Another type of data service provides a wireless mobile connection to laptop computers. In this case, speeds that are at least comparable with dial-up (around 50 kbit/s) are demanded by most users, though elementary services with 10 kbit/s (exploiting the same type of communications channels foreseen for speech) are sometimes used as well. Elementary data services are mostly replaced by high-speed data services in the U.S.A., Europe, and Japan, but still play an important role in other parts of the world.

• *Communications between computer peripherals and similar devices*: for the replacement of cables that link computer peripherals, like mouse and keyboard, to the computer (or similarly for cellphones), wireless links with data rates around 1 Mbit/s are used. The functionality of these links is similar to the previously popular infrared links, but usually provides higher reliability.

• *High-speed data services*: WLANs and 3G cellular systems are used to provide fast Internet access, with speeds that range from 0.5 to 100 Mbit/s (currently under development). • *Personal Area Networks* (PANs) is a newly coined term that refers mostly to the range of a wireless network (up to 10 m), but often also has the connotation of high data rates (over 100 Mbit/s), mostly for linking the components of consumer entertainment systems (streaming video from computer or DVD player to a TV) or high-speed computer connections (wireless Universal Serial Bus (USB)).

*1.3.2 Range and Number of Users*

Another distinction among the different networks is the range and the number of users that they serve. By “range,” we mean here the distance between one transmitter and receiver. The coverage area of a system can be made almost independent of the range, by just combining a larger number of BSs into one big network.

• *Body Area Networks* (BANs) cover the communication between different devices attached to one body – e.g., from a cellphone in a hip holster to a headset attached to the ear. The range is thus on the order of 1 m. BANs are often subsumed into PANs.

• *Personal Area Networks* include networks that achieve distances of up to or about 10 m, covering the “personal space” of one user. Examples are networks linking components of computers and home entertainment systems. Due to the small range, the number of devices within a PAN is small, and all are associated with a single “owner.” Also, the number of overlapping PANs (i.e., sharing the same space or room) is small – usually less than five. That makes cell planning and multiple access much simpler.

• *WLANs*, as well as cordless telephones cover still larger ranges of up to 100 m. The number of users is usually limited to about 10. When much larger numbers occur (e.g., at conferences or meetings), the data rates for each user decrease. Similarly, cordless phones have a range of up to 300 m and the number of users connected to one BS is of the same order as for WLANs. Note,

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however, that wireless PABXs can have much larger ranges and user numbers – as mentioned before, they can be seen essentially as small private cellular systems.

• *Cellular systems* have a range that is larger than, e.g., the range of WLANs. Microcells typically cover cells with 500 m radius, while macrocells can have a radius of 10 or even 30 km. Depending on the available bandwidth and the multiple access scheme, the number of active users in a cell is usually between 5 and 50. If the system is providing high-speed data services to one user, the number of active users usually shrinks.

• *Fixed wireless access services* cover a range that is similar to that of cellphones – namely, between 100 m and several tens of kilometers. Also, the number of users is of a similar order as for cellular systems.

• *Satellite systems* provide even larger cell sizes, often covering whole countries and even con tinents. Cell size depends critically on the orbit of the satellite: geostationary satellites provide larger cell sizes (1,000-km radius) than LEOs.

Figure 1.7 gives a graphical representation of the link between data rate and range. Obviously, higher data rates are easier to achieve if the required range is smaller. One exception is fixed wireless access, which demands a high data rate at rather large distances.

Data rate

1Gbit/s

100Mbit/s 10Mbit/s 1Mbit/s

100kbit/s

PAN

WLAN

Cordless

Fixed

wireless

Third-generation cellphones

Second-generation

10kbit/s

phones Satellite

cellphones

phones

Range 1m 10m 100m 1km 10km 100km

**Figure 1.7** Data rate versus range for various applications.

*1.3.3 Mobility*

Wireless systems also differ in the amount of mobility that they have to allow for the users. The ability to move around while communicating is one of the main charms of wireless communication for the user. Still, within that requirement of mobility, different grades exist:

• *Fixed devices* are placed only once, and after that time communicate with their BS, or with each other, always from the same location. The main motivation for using wireless transmission techniques for such devices lies in avoiding the laying of cables. Even though the devices are not mobile, the propagation channel they transmit over can change with time: both due to people

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walking by and due to changes in the environment (rearranging of machinery, furniture, etc.). Fixed wireless access is a typical case in point. Note also that all wired communications (e.g., the PSTN) fall into this category.

• *Nomadic devices*: nomadic devices are placed at a certain location for a limited duration of time (minutes to hours) and then moved to a different location. This means that during one “drop” (placing of the device), the device is similar to a fixed device. However, from one drop to the next, the environment can change radically. Laptops are typical examples: people do not operate their laptops while walking around, but place them on a desk to work with them. Minutes or hours later, they might bring them to a different location and operate them there.

• *Low mobility*: many communications devices are operated at pedestrian speeds. Cordless phones, as well as cellphones operated by walking human users are typical examples. The effect of the low mobility is a channel that changes rather slowly, and – in a system with multiple BSs – handover from one cell to another is a rare event.

• *High mobility* usually describes speed ranges from about 30 to 150 km/h. Cellphones operated by people in moving cars are one typical example.

• *Extremely high mobility* is represented by high-speed trains and planes, which cover speeds between 300 and 1000 km/h. These speeds pose unique challenges both for the design of the physical layer (Doppler shift, see Chapter 5) and for the handover between cells.

Figure 1.8 shows the relationship between mobility and data rate.

Data rate

1Gbit/s

100 Mbit/s 10 Mbit/s 1Mbit/s

100 kbit/s

PAN

Fixed WLAN

wireless

Fourth-generation cellphones

Third-generation cellphones

Second-generation

10kbit/s

cellphones Cordless

phonesSatellite

phones PSTN

Stationary Nomadic Pedestrian Vehicular High-speed Trains Planes

**Figure 1.8** Data rate versus mobility for various applications.

Mobility

*1.3.4 Energy Consumption*

Energy consumption is a critical aspect for wireless devices. Most wireless devices use (one-way or rechargeable) batteries, as they should be free of *any* wires – both the ones used for communication and the ones providing the power supply.

• *Rechargeable batteries*: nomadic and mobile devices, like laptops, cellphones, and cordless phones, are usually operated with rechargeable batteries. Standby times as well as operating

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times are one of the determining factors for customer satisfaction. Energy consumption is deter mined on one hand by the distance over which the data have to be transmitted (remember that a minimum SNR has to be maintained), and on the other hand, by the amount of data that are to be transmitted (the SNR is proportional to the energy per bit). The energy density of batteries has increased slowly over the past 100 years, so that the main improvements in terms of operating and standby time stem from reduced energy consumption of the devices. For cellphones, talk times of more than 2 hours and standby times of more than 48 hours are minimum requirements. For laptops, power consumption is not mainly determined by the wireless transmitter, but rather by other factors like hard drive usage and processor speed. For smartphones, the energy con sumption of the processor and of the wireless connection is of the same order, and both have to be considered for maximizing battery lifetime.

• *One-way batteries*: sensor network nodes often use one-way batteries, which offer higher energy density at lower prices. Furthermore, changing the battery is often not an option; rather, the sensor including the battery and the wireless transceiver is often discarded after the battery has run out. It is obvious that in this case energy-efficient operation is even more important than for devices with rechargeable batteries.

• *Power mains*: BSs and other fixed devices can be connected to the power mains. Therefore, energy efficiency is not a major concern for them. It is thus desirable, if possible, to shift as much functionality (and thus energy consumption) from the MS to the BS.

User requirements concerning batteries are also important sales issues, especially in the market for cellular handsets:

• The weight of an MS is determined mostly (70–80%) by the battery. Weight and size of a handset are critical sales issues. It was in the mid-1980s that cellphones were commonly called “carphones,” because the MS could only be transported in the trunk of a car and was powered by the car battery. By the end of the 1980s, the weight and dimensions of the batteries had decreased to about 2 kg, so that it could be carried by the user in a backpack. By the year 2000, the battery weight had decreased to about 200 g. Part of this improvement stems from more efficient battery technology, but to a large part, it is caused by the decrease of the power consumption of the handsets.

• Also, the costs of a cellphone (raw materials) are determined to a considerable degree by the battery.

• Users require standby times of several days, as well as talk times of at least 2 hours before recharging.

These “commercial” aspects determine the maximum size (and thus energy content) of the battery, and consequently, the admissible energy consumption of the phone during standby and talk operation.

*1.3.5 Use of Spectrum*

Spectrum can be assigned on an exclusive basis, or on a shared basis. That determines to a large degree the multiple access scheme and the interference resistance that the system has to provide:

• *Spectrum dedicated to service and operator*: in this case, a certain part of the electromagnetic spectrum is assigned, on an exclusive basis, to a service provider. A prime point in case is cellular telephony, where the network operators buy or lease the spectrum on an exclusive basis (often for a very high price). Due to this arrangement, the operator has control over the spectrum and can plan the use of different parts of this spectrum in different geographical regions, in order to minimize interference.

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• *Spectrum allowing multiple operators*:

◦ *Spectrum dedicated to a service*: in this case, the spectrum can be used only for a certain service (e.g., cordless telephones in Europe and Japan), but is not assigned to a specific operator. Rather, users can set up qualified equipment without a license. Such an approach does not require (or allow) interference planning. Rather, the system must be designed in such a way that it avoids interfering with other users in the same region. Since the only interfer ence *can* come from equipment of the same type, coordination between different devices is relatively simple. Limits on transmit power (identical for all users) are a key component of this approach – without them, each user would just increase the transmit power to drown out interferers, leading essentially to an “arms race” between users.

◦ *Free spectrum*: is assigned for different services as well as for different operators. The ISM band at 2.45 GHz is the best known example – it is allowed to operate microwave ovens, WiFi LANs, and Bluetooth wireless links, among others, in this band. Also for this case, each user has to adhere to strict emission limits, in order not to interfere too much with other systems and users. However, coordination between users (in order to minimize interference) becomes almost impossible – different systems cannot exchange coordination messages with each other, and often even have problems determining the exact characteristics (bandwidth, duty cycle) of the interferers.

After 2000, two new approaches have been promulgated, but are not yet in widespread use:

• *Ultra Wide Bandwidth systems* (UWB) spread their information over a very large bandwidth, while at the same time keeping a very low-power spectral density. Therefore, the transmit band can include frequency bands that have already been assigned to other services, without creating significant interference. UWB is discussed in more detail in Chapter 17.

• *Adaptive spectral usage*: another approach relies on first determining the current spectrum usage at a certain location and then employing unused parts of the spectrum. This approach, also known as *cognitive radio*, is described in detail in Chapter 21.

*1.3.6 Direction of Transmission*

Not all wireless services need to convey information in both directions.

• *Simplex systems* send the information only in one direction – e.g., broadcast systems and pagers. • *Semi-duplex systems* can transmit information in both directions. However, only one direction is allowed at any time. Walkie-talkies, which require the user to push a button in order to talk, are a typical example. Note that one user must signify (e.g., by using the word “over”) that (s)he

has finished his/her transmission; then the other user knows that now (s)he can transmit. • *Full-duplex systems* allow simultaneous transmission in both directions – e.g., cellphones and cordless phones.

• *Asymmetric duplex systems*: for data transmission, we often find that the required data rate in one direction (usually the downlink) is higher than in the other direction. However, even in this case, full duplex capability is maintained.

*1.3.7 Service Quality*

The requirements for service quality also differ vastly for different wireless services. The first main indicator for service quality is *speech quality* for speech services and *file transfer speed* for data services. Speech quality is usually measured by the *Mean Opinion Score* (MOS). It represents the average of a large number of (subjective) human judgments (on a scale from 1 to 5) about the

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quality of received speech (see also Chapter 15). The speed of data transmission is simply measured in bit/s – obviously, a higher speed is better.

An even more important factor is the availability of a service. For cellphones and other speech services, the *service quality* is often computed as the complement of “fraction of blocked calls7 plus 10 times the fraction of dropped calls.” This formula takes into account that the dropping of an active call is more annoying to the user than the inability to make a call at all. For cellular systems in Europe and Japan, this service quality measure usually exceeds 95%; in the U.S.A., the rate is considerably lower.8

For emergency services and military applications, service quality is better measured as the com plement of “fraction of blocked calls plus fraction of dropped calls.” In emergency situations, the inability to make a call is as annoying as the situation of having a call interrupted. Also, the systems must be planned in a much more robust way, as service qualities better than 99% are required. “Ultrareliable systems,” which are required, e.g., for factory automation systems, require service quality in excess of 99.99%.

A related aspect is the *admissible delay (latency)* of the communication. For voice communica tions, the delay between the time when one person speaks and the other hears the message must not be larger than about 100 ms. For streaming video and music, delays can be larger, as buffering of the streams (up to several tens of seconds) is deemed acceptable by most users. In both voice and streaming video communications, it is important that the data transmitted first are also the ones made available to the receiving user first. For data files, the acceptable delays can be usually larger and the sequence with which the data arrive at the receiver is not critical (e.g., when downloading email from a server, it is not important whether the first or the seventh of the emails is the first to arrive). However, there are some data applications where small latency is vital – e.g., for control applications, security and safety monitoring, etc.

**1.4 Economic and Social Aspects**

*1.4.1 Economic Requirements for Building Wireless Communications Systems*

The design of wireless systems not only aims to optimize performance for specific applications but also to do that at a reasonable cost. As economic factors impact the design, scientists and engineers have to have at least a basic understanding of the constraints imposed by marketing and sales divisions. Some of the guidelines for the design of wireless *devices* are as follows:

• Move as much functionality as possible from the (more expensive) analog components to digital circuitry. The costs for digital circuits decrease much faster with time than those of analog components.

• For mass-market applications, try to integrate as many components onto one chip as possible. Most systems strive to use only two chips; one for analog RF circuitry and one for digital (baseband) processing. Further integration into a single chip (system on a chip) is desirable. Exceptions are niche market products, which typically try to use general-purpose processors, Application Specific Integrated Circuits (ASICs), or off-the-shelf components, as the number of sold units does not justify the cost of designing more highly integrated chips.

• As human labor is very expensive, any circuit that requires human intervention (e.g., tuning of RF elements) is to be avoided. Again, this aspect is more important for mass-market products.



7 Here, “blocked calls” encompasses all failed call attempts, including those that are caused by insufficient signal strength, as well as insufficient network capacity.

8 The reason for this discrepancy is partly historical and economical, and partly geographical.

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• In order to increase the efficiency of the development process and production, the same chips should be used in as many systems as possible.

When it comes to the design of wireless *systems and services*, we have to distinguish between two different categories:

• Systems where the mobility is of value of itself – e.g., in cellular telephony. Such services can charge a premium to the customer – i.e., be more expensive than equivalent, wired systems. Cellular telephony is a case in point: the per-minute price has been higher than that of landline telephony in the past, and is expected to remain so (especially when compared, e.g., with Voice over Internet Protocol (VoIP) telephone services). Despite this fact, the services might compete (and ultimately edge out) traditional wired services if the price difference is not too large. The years since 1990 have certainly seen such a trend, with many consumers (and even companies) canceling wired services and relying on cellular telephony alone.

• Services where wireless access is only intended as a cheap cable replacement, without enabling additional features – e.g., fixed wireless access. Such systems have to be especially cost-conscious, as the buildup of the infrastructure has to remain cheaper than the laying of new wired connections, or buying access to existing ones.

*1.4.2 The Market for Wireless Communications*

Cellphones are a highly dynamic market that has grown tremendously. Still, different countries show different market penetrations. Some of the factors influencing this penetration are:

• *Price of the offered services*: the price of the services is in turn influenced by the amount of competition, the willingness of the operators to accept losses in order to gain greater market penetration, and the external costs of the operators (especially, the cost of spectrum licenses). However, the price of the services is not always the decisive factor for market penetration: Scandinavia, with its relatively high prices, has the highest market penetration in the world.

• *Price of the MSs*: the MSs are usually subsidized by the operators and are either free or sold at a nominal price, if the consumer agrees to a long-term contract. Exceptions are “prepaid” services, where a user buys a certain number of minutes of service usage (in that case, the handsets are sold to the consumer at full cost); at the other end of the market spectrum, high-end devices usually require a significant co-payment by the consumer.

• *Attractiveness of the offered services*: in many markets, the price of the services offered by different network operators is almost identical. Operators try to distinguish themselves by dif ferent features, like better coverage, text and picture message service, etc. The offering of these improved features also helps to increase the market size in general, as it allows customers to find services tailored to their needs.

• *General economic situation*: obviously, a good general economic situation allows the general population to spend more money on such “non-essential” things as mobile communications services. In countries where a very large percentage of the income goes to basic necessities like food and housing, the market for cellular telephony is obviously more limited.

• *Existing telecom infrastructure*: in countries or areas with a bad existing landline-based telecom infrastructure, cellular telephony and other wireless services can be the only way of communicat ing. This would enable high market penetration. Unfortunately, these areas are usually also the ones that have the bad economic situation mentioned above (large percentage of income goes to basic necessities). This fact has hindered especially the development of fixed wireless services.9



9 To put it succinctly: “the market for this product is the people who cannot afford to pay for it.”