WIRELESS COMMUNICATION SYSTEMS

From RF Subsystems to 4G Enabling Technologies

KE-LIN DU & M. N. S. SWAMY

CAMBRIDGE

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Concordia University, Canada

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Wireless Communication Systems

This practically-oriented, all-inclusive guide covers all the major enabling techniques for current and next-generation cellular communications and wireless networking systems. Technologies covered include CDMA, OFDM, UWB, turbo and LDPC coding, smart antennas, wireless ad hoc and sensor networks, MIMO, and cognitive radios, providing readers with everything they need to master wireless systems design in a single volume.

Uniquely, a detailed introduction to the properties, design, and selection of RF subsystems and antennas is provided, giving readers a clear overview of the whole wireless system. It is also the first textbook to include a complete introduction to speech coders and video coders used in wireless systems.

Richly illustrated with over 400 figures, and with a unique emphasis on practical and state-of-the-art techniques in system design, rather than on the mathematical foundations, this book is ideal for graduate students and researchers in wireless communications, as well as for wireless and telecom engineers.

Ke-Lin Du is currently a researcher in the Center for Signal Processing and Communications at Concordia University, Canada. Prior to joining Concordia University in 2001, he held positions with Huawei Technologies, the China Academy of Telecommunication Technology, and the Chinese University of Hong Kong. He visited the Hong Kong University of Science and Technology in 2008. His current research interests include signal processing, wireless communications, RF systems, and neural networks. He is a Senior Member of the IEEE.

M. N. S. Swamy is currently a Director of the Center for Signal Processing and Communications in the Department of Electrical and Computer Engineering, Concordia University, where he was Dean of the Faculty of Engineering and Computer Science from 1977 to 1993. He has published extensively in the areas of circuits, systems, and signal processing, co-authoring four books. Professor Swamy is a Fellow of the IEEE, IET (UK), and EIC (Canada), and has received many IEEE-CAS awards, including the Guillemin-Cauer award in 1986, as well as the Education Award and the Golden Jubilee Medal, both in 2000.

To My Son Cynric
K.-L. Du

and

To My Parents
M. N. S. Swamy

Preface

In the last three decades, the explosive growth of mobile and wireless communications has radically changed the life of people. Wireless services have migrated from the conventional voice-centric services to data-centric services. The circuit-switched communication network is now being replaced by the all-IP packet-switched network. Mobile communications have also evolved from the first-generation (1G) analog systems to the third-generation (3G) systems now being deployed, and the fourth-generation (4G) systems are now under development and are expected to be available by 2010. The evolution of wireless networking has also taken place rapidly during this period, from low-speed wireless local-area networks (LANs) to broadband wireless LANs, wireless metropolitan-area networks (MANs), wireless wide-area networks (WANs), and wireless personal-area networks (PANs). Also, broadband wireless data service has been expanded into broadcasting service, leading to satellite TV broadcasting and wireless regional-area networks (RANs) for digital TV. The data rate has also evolved from the 10 kbits/s voice communications to approximately 1 Gbit/s in the 4G wireless network. In addition, the 4G wireless network will provide ubiquitous communications.

Scope and Purpose

A complete wireless system involves many different areas. However, most existing textbooks on wireless communications focus only on the fundamental principles of wireless communications, while many other areas associated with a whole wireless system, such as digital signal processing, antenna design, microwave and radio frequency (RF) subsystem design, speech coding, video coding, and channel coding, are left to other books.

This book provides a broad, also in certain depth, technical view of wireless communications, covering various aspects of radio systems. Various enabling technologies for modern wireless communications are also included. Unlike the existing books in the field, this book is organized from a wireless system designer's viewpoint. We give wide coverage to the techniques that are most relevant to the design of wireless communication and networking systems. We focus ourselves on the lower layers of wireless systems, since the upper layers such as network layers and transport layers are topics of general data communication systems. Due to limited space, we do not provide lengthy mathematical details, but rather emphasize the practical aspects.

The book is divided into twenty-two chapters, including introduction, overwiew of wireless communications and networking, wireless channel and radio propagation, cellular systems and multiple access, diversity, channel equalization, modulation and detection, spread-spectrum communications, orthogonal frequency division multiplexing (OFDM),

antennas, RF and microwave subsystems, A/D and D/A conversions, digital signal processing, information theory, ultra wideband (UWB) communications, speech/audio coding, image/video coding, channel coding, smart antennas, multiple input multiple output (MIMO) systems, cognitive radios, and wireless ad hoc/sensor networks. Each chapter contains some examples and problems.

Intended Audience

This book is primarily intended as a textbook for advanced undergraduate and graduate students specializing in wireless communications and telecommunication systems. It is also a good reference book for practicing engineers. The reader is supposed to have a background in electrical engineering and to be familiar with the theory of signals and systems, probabilities and stochastic processes, basic circuits, basic digital communications, linear algebra, and advanced calculus. These courses are offered in most electrical engineering undergraduate programs. The contents are useful for mobile cellular communications, satellite communication, and wireless networking.

The material in this book can be taught in two semesters. The first semester may cover Chapters 1 to 13, which deal with the principles of wireless communications, and the analog and digital designs. The second semester could cover the remaining chapters, including information theory and coding, and some advanced and emerging technologies. If only one semester is available for this course, we suggest teaching Chapters 1 to 13, 15, and selected sections from Chapters 18 to 22. Since each chapter is rather comprehensive on the topics treated and is relatively self-contained, the reader can select to read only those chapters that are of interest. MATLAB codes for the examples in the book are downloadable from the book website.

Acknowledgments

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Feedback

A book of this length is certain to have some errors and omissions. While we have made significant attempts to a comprehensive description of major techniques related to modern wireless communications, there are many new emerging techniques, some of which may not have been included. Feedback is welcome via email at kldu@ieee.org or swamy@ece.concordia.ca, and we promise to reply to all the messages.

Concordia University
Montreal, Canada

Abbreviations

1xEV-DO	1x Evolution, Data Optimized
1xEV-DV	1x Evolution, Data and Voice
*n*G	*n*th generation
3DES	Triple DES
3GPP	Third-Generation Partnership Project
3GPP2	Third-Generation Partnership Project 2
4GFSK	quaternary GFSK
AAC	Advanced Audio Coding
ACAB	adaptive CAB
ACELP	algebraic codebook excited linear prediction
ACF	autocorrelation function
ACI	adjacent channel interference
ACLR	adjacent channel leakage ratio
ACPR	adjacent channel power ratio
ACS	adaptive cross-SCORE
ACTS	Advanced Communication Technology Satellite
A/D	analog-to-digital
ADC	A/D converter
ADPCM	adaptive differential PCM
AES	Advanced Encryption Standard
AF	amplify-and-forward
AFC	automatic frequency control
AGC	automatic gain control
AM	amplitude modulation
AMC	adaptive modulation and coding
AMI	alternative mark inversion
AMPS	Advanced Mobile Phone Services
AMR	adaptive multi-rate
AMR-WB	adaptive multi-rate wideband
ANSI	American National Standards Institute
APS	adaptive phase-SCORE
ARQ	automatic repeat request
ASIC	application-specific integrated circuit
ASK	amplitude shift keying
AVC	Advanced Video Coding
AWGN	additive white Guaasian noise
balun	balanced-to-unbalanced transformer
BAN	body area network
BCH	Bose-Chaudhuri-Hocquenghem
BCJR	Bahl-Cocke-Jelinek-Raviv
BER	bit error probability
BER	bit error rate
BFSK	binary FSK
BICM	bit-interleaved coded modulation
BJT	bipolar junction transistor
BLAST	Bell Labs Layered Space-Time
BPSK	binary phase shift keying
BRAN	Broadband Radio Access Network
BS	base station
BSC	binary symmetric channel
BS-CDMA	block-spreading CDMA
CAB	cyclic adaptive beamforming
CABAC	context-based adaptive binary arithmetic coding

CAVLC	context-based adaptive variable-length code
CCF	cross-correlation function
CCI	co-channel interference
CCK	complementary code keying
CCSDS	Consultative Committee for Space Data Systems
cdf	cumulative distribution function
CDMA	code division multiple access
CDPD	Cellular Digital Packet Data
CELP	code-excited linear prediction
CF	compress-and-forward
CFO	carrier frequency offset
CIC	cascaded integrator comb
CIF	common intermediate format
CIR	carrier-to-interference ratio
CLS	constrained least-squares
CNR	carrier-to-noise ratio
CORBA	common object request broker architecture
CORDIC	Coordinate Rotation Digital Computer
CP-CDMA	cyclic prefix assisted CDMA
CPFSK	continuous phase FSK
CPM	continuous phase modulation
CQF	conjugate quadrature filters
CRC	cyclic redundancy check
CRLB	Cramer-Rao lower bound
CRSC	circular recursive systematic convolutional
CS-ACELP	Conjugate Structure ACELP
CSI	channel state information
CSMA	carrier sense multiple access
CSMA/CA	CSMA with collision avoidance
CSMA/CD	CSMA with collision detection
CT2	Second Generation Cordless Telephone
CVSDM	continuous variable slope DM
D/A	digital-to-analog
DAB	Digital Audio Broadcasting
DAC	D/A converter
D-BLAST	diagonal BLAST
DBPSK	differential BPSK
DCT	discrete cosine transform
DDCR	decision-directed carrier recovery
DDS	direct digital synthesis
DEBPSK	differentially encoded BPSK
DECT	Digital Enhanced Cordless Telephone
DEMPSK	differentially encoded MPSK
DEQPSK	differentially encoded QPSK
DES	Data Encryption Standard
DF	decode-and-forward
DFE	decision-feedback equalization
DFT	Discrete Fourier transform
DiffServ	differential services
DM	delta modulation
DMB	Digital Multimedia Broadcasting
DMPSK	differential MPSK
DNL	differential nonlinearity
DoA	direction-of-arrival
DoD	Department of Defense; also direction-of-departure
DPCM	differential PCM
DPSK	differential phase-shift keying
DQPSK	differential quarternary phase shift keying
DR	dielectric resonator
DS	direct sequence
DSB	double sideband
DSB-LC	DSB-large carrier
DSB-SC	DSB-small carrier
DSL, xDSL	digital subscriber line
DS-CDMA	direct-sequence CDMA
DSCQS	double stimulus continuous quality scale

DSMA	digital sense multiple access
DSP	digital signal processor
DSSS	direct-sequence spread spectrum
DST	discrete sine transform
DSTTD	double-STTD
DTFT	discrete-time Fourier transform
DVB-H	DVB-Handheld
DVB-RCL	Digital Video Broadcasting–Return Channel for LMDS
DVB-RCS	DVB-Return Channel via Satellite
DVB-S	Digital Video Broadcasting Satellite
DVB-S2	DVB-Satellite Second Generation
DVB-T	Terrestrial DVB
DVB-T2	Terrestrial DVB Second Generation
DWT	discrete wavelet transform
DySPAN	Dynamic Spectrum Access Networks
EBCOT	Embedded block coding with optimized truncation
ECMA	European Computer Manufacturers Association
EDGE	Enhanced Data for GSM Evolution
EFR	enhanced full rate
EGC	equal gain combining
EIA	Electronics Industry Association
EM	electromagnetic
ENOB	effective number of bits
EPC	Electronic Product Code
ESPAR	electronically steerable parasitic array radiator
ESPRIT	Estimation of Signal Parameters via Rotational Invariance Techniques
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UTRA
E-UTRAN	Evolved UTRA Network
EVRC	enhanced variable rate codec
EVRC-WB	EVRC-Wideband
EXIT	extrinsic information transfer
EZW	embedded zero-tree wavelet
FBSS	fast base station switching
FCC	Federal Communications Commission
FDD	frequency division duplexing
FDE	frequency-domain equalization
FDMA	frequency division multiple access
FDTD	finite difference time domain
FEC	forward error correction
FEM	finite element method
FET	field-effect transistor
FFT	fast Fourier transform
FH	frequency hopping
FH-CDMA	frequency-hopping CDMA
FHSS	frequency-hopping spread spectrum
FIR	finite impulse response
FM	frequency modultion
FPGA	field programmable gate array
FR	full-rate
FSK	frequency shift keying
FWT	fast wavelet transform
GaAs	gallium arsenide
GEO	geostationary earth orbit
GFSK	Gaussian FSK
GMC	generalized multi-carrier
GMSK	Gaussian minimum shift keying
GOB	group of blocks
GOP	group of pictures
GoS	grade of service
GPRS	General Packet Radio Service

GPS	Global Positioning System
GSC	Golay Sequential Code
GSM	Global System for Mobile Communications
HAPS	high-altitude aeronautical platform system
HARQ	hybrid-ARQ
H-BLAST	Horizontal encoding BLAST
HBT	heterojunction bipolar transistor
HDTV	high definition television
HEMT	high electron mobility transistor
HFET	heterostructure FET
HiperACCESS	High-Performance Access
HiperLAN	High Performance Radio LAN
HiperMAN	High Performance Metropolitan Area Network
HiSWAN	High Speed Wireless Access Network
HILN	harmonic and individual lines plus noise
HLR	home location register
HR	half-rate
HSCSD	High Speed Circuit Switched Data
HSDPA	High-Speed Downlink Packet Access
H-S/MRC	hybrid selection/maximum ratio combining
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
HTS	high-temperature superconductor
I	in-phase
IC	integrated circuit
ICI	intercarrier interference
IDCT	inverse DCT
IDMA	interleave division multiple access
IDWT	inverse DWT
IEC	International Electrotechnical Commission
IETF	Internet Engineering Task Force
IF	intermediate frequency
IIP3	input IP3
IIR	infinite impulse response
IMD	intermodulation distortion
IMDCT	inverse MDCT
IMI	intermodulation interference
IMPATT	impact avalanche and transit time
IMT-2000	International Mobile Telecommunications 2000
IntServ	integrated services
INL	integral nonlinearity
IP	Internet Protocol
IP3	third-order intercept point
IPv4/v6	Internet Protocol version 4/version 6
IS	Interim Standard
ISI	intersymbol interference
ISM	industrial, scientific, medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-R	ITU's Radiocommunication Sector
ITU-T	ITU's Telecomunication Standarization Sector
JPEG	Joint Photographic Experts Group
JTRS	Joint Tactical Radio System

LAN	local area network
LBG	Linde-Buzo-Gray
LCC	lost call clearing
LCH	lost call hold
LCMV	linearly constrained minimum variance
LCR	level crossing rate
LD-CELP	low-delay CELP
LDPC	low density parity code
LEACH	low-energy adaptive clustering hierarchy
LEO	low earth orbit
LHCP	left-hand circular polarization
LINC	linear amplification using nonlinear components
LLC	logical link control
LLR	log-likelihood ratio
LMDS	Local Multipoint Distribution Service
LMS	least mean squares
LNA	low-noise amplifier
LO	local oscillator
LOS	line-of-sight
LOT	lapped orthogonal transform
LPC	linear predictive coding
LS	least squares
LSB	least significant bit
LS-DRMTA	least squares despread respread multitarget array
LSF	line spectral frequency
LSP	linear spectral pair
LTCC	low-temperature cofired ceramic
LTE	Long-Term Evolution
LTI	linear time-invariant
LTP	long-term prediction
LUT	look-up table
MAC	medium access control; also multiply-accumulate
MAD	mean absolute difference
MAHO	mobile-assisted handoff
MAI	multiple-access interference
MAN	metropolitan-area network
MANET	mobile ad hoc networking
MAP	maximum a posteriori
MASK	M-ary amplitude-shift keying
MB-OFDM	multiband OFDM-based
MCA	maximally constrained autocorrelation
MC-CDMA	multi-carrier CDMA
MC-DS-CDMA	multi-carrier DS-CDMA
MCM	multicarrier modulation
MCU	microcontroller unit
MDCT	modified DCT
MDF	magnitude difference function
MDHO	macro diversity handoff
MDS	minimum detectable signal
MELP	mixed excitation linear prediction
MEMS	micro-electromechanical system
MESFET	metal-semiconductor field effect transistor
MFSK	M-ary FSK
MIC	microwave integrated circuit
MIM	metal-insulator-metal
MIMO	multiple input multiple output
MIMO-SC	MIMO single carrier
MIMO-SS	MIMO spread spectrum
MIPS	million instructions per second
MISO	multiple-input single-output
ML	maximum-likelihood
MLSE	maximum-likelihood sequence estimation
MLSR	maximal length shift register
MLT	modulated lapped transform
MMDS	Multichannel Multipoint Distribution Service
MMIC	monolithic microwave integrated circuit
MMSE	minimum mean squared error

MoM	method of moments
MOS	mean opinion score
MOSFET	metal-oxide-semiconductor field effect transistor
MPAM	M-ary pulse amplitude modulation
MPE	multipulse excitation
MPEG	Moving Pictures Experts Group
MPLS	multiprotol label switching
MP-MLQ	multipulse maximum likelihood quantization
MPSK	M-ary PSK
MQAM	M-ary QAM
MRC	maximum ratio combining
MS	mobile station
MSC	mobile switching center
MSE	mean squared error
MSK	minimum shift keying
MT-CDMA	multi-tone CDMA
MUD	multiuser detection
MUI	multiple-user interference
MUSIC	MUltiple SIgnal Classifications
MVDR	minimum variance distortionless response
NADC	North American Digital Cellular
NCO	numerically controlled oscillator
NMT	Nordic Mobile Telephone
NRZ/-L/-M/-S	nonreturn-to-zero/-level/-mark/-space
NTT	Nippon Telephone and Telegraph
OCC	orthogonal complementary code
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OOK	on-off keying
OQPSK	offset QPSK
OSI	Open Systems Interconnect
OSIC	ordered serial (successive) interference cancellation
OSTBC	orthogonal space-time block code
OVSF	orthogonal variable spreading factor
PABX	private automatic branch exchange
PACS	Personal Access Communication System
PAE	power-added efficiency
PAL	Phase Alternation Line
PAM	pulse amplitude modulation
PAN	personal area network
PAPR	peak-to-average power ratio
PCCC	parallel concatenated convolutional code
PCM	pulse code modulation
PCS	Personal Communications Service
PDC	Personal Digital Cellular
pdf	probability distribution function
PDF	Portable Document Format
PDP	power delay profile
PEAQ	perceptual evaluation of audio quality
PESQ	perceptual evaluation of speech quality
PHS	Personal Handyphone System)
PIC	parallel interference cancellation
PLL	phase-locked loop
PM	phase modulation
PN	pseudo-noise
POCSAG	Post Office Code Standard Advisory Group
PPM	pulse position modulation
PSD	power spectral density
PSI-CELP	pitch synchronous innovation CELP
PSK	phase-shift keying
PSNR	peak signal-to-noise ratio

PSTN	public switched telephone network
PWM	pulse-width modulation
Q	quadrature-phase
Q^2PSK	quadrature quadrature PSK
QAM	quadrature amplitude modulation
QCELP	Qualcomm CELP
QCIF	quarter-CIF
QMF	quadrature mirror filter
QO-STBC	quasi-orthogonal STBC
QoS	quality of service
QPSK	quaternary phase shift keying
QS-CDMA	quasi-synchronous CDMA
QSIF	quarter-SIF
RAN	regional area network
RCELP	relaxed CELP
RCPC	rate-compatible punctured convolutional
RELP	residual excited linear prediction
RF	radio frequency
RFID	radio frequency identification
RHCP	right-hand circular polarization
RLE	run-length encoding
RLS	recursive least-squares
rms	root-mean-squared
ROC	region of convergence
ROI	region of interest
RPE	regular pulse excitation
RPE-LTP	regular pulse excitation with long-term prediction
RS	Reed-Solomon
RSSI	radio signal strength indication
RTMS	Radio Telephone Mobile System
RTP	Real-time Transport Protocol
RZ	return-to-zero
SA-DCT	shape-adaptive DCT
SA-DWT	shape-adaptive DWT
SAR	successive approximation register
SAW	surface acoustic wave
SB-ADPCM	subband-split ADPCM
SC	single-carrier
SCCC	serially concatenated convolutional code
SCD	spectrum cyclic density
SCORE	Signal Communication by Orbital Relay Equipment; also self-coherence restoral
SDMA	space division multiple access
SDR	software-defined radio
SECAM	SEquential Couleur Avec Memoire
SEGSNR	segmental SNR
SEP	symbol error probability
SER	symbol error rate
SFBC	space–frequency block code
SFDR	spurious-free dynamic range
SFIR	spatial filtering for interference reduction
SF-OFDM	space-frequency coded OFDM
S/H	sample-and-hold
SIC	serial interference cancellation
SICM	symbol-interleaved coded modulation
SIF	source input format
SiGe	silicon-germanium
SIMO	single-input multiple-output
SINAD	signal-to-noise-and-distortion
SINR	signal-to-interference-plus-noise ratio
SIR	signal-to-interference ratio
SISO	soft-in/soft-out
SMV	selectable mode vocoder

SNDR	signal-to-noise-plus-distortion ratio
SNR	signal-to-noise radio
SOI	signal-of-interest
SOVA	soft output Viterbi algorithm
SPIHT	set partitioning in hierarchical trees
SPIN	Sensor Protocols for Information via Negotiation
SQNR	signal-to-quantization-noise ratio
SS7	Signaling System No. 7
SSB	single sideband
SSMA	spread spectrum multiple access
STBC	space-time block code
STDO	space-time Doppler
ST-MF	space-time matched filter
ST-MUD	space-time MUD
STF-OFDM	space-time-frequency coded OFDM
ST-OFDM	space-time coded OFDM
STP	short-term prediction
STS	space-time spreading
STTC	space-time trellis code
STTD	space-time transmit diversity
SUI	Standford University Interim
TACS	Total Access Communication System
TCM	trellis-coded modulation
TCP	Transmission Control Protocol
TDAC	time domain aliasing cancellation
T-DMB	Terrestrial-DMB
TDD	time-division duplexing
TDoA	time-difference-of-arrival
TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
TDMA	time division multiple access
TDRSS	Tracking and Data Relay Satellite System
TEC	total electron content
TEM	transverse electromagnetic
TH	time hopping
THSS	time-hopping spread spectrum
TIA	Telecommunications Industry Association
ToA	time-of-arrival
TR	transmitted reference
TXCO	temperature-controlled crystal oscillator
UDP	User Datagram Protocol
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
UPE	unequal error protection
UQ-DZ	uniform quantizer with dead zone
USB	Universal Serial Bus
UTRA	UMTS Terrestrial Radio Access
UWB	ultra wideband
UWC-136	Universal Wireless Communication 136
V-BLAST	vertical encoding BLAST
VCO	voltage-controlled oscillator
VGA	variable gain amplifier
VLR	visitor location register
VMR-WB	variable multi-rate wideband
VO	video object
VoIP	voice over IP
VOP	video object plane
VQ	vector quantization
VSELP	vector-sum excited linear prediction
VSWR	voltage standing-wave ratio
VTC	Visual Texture Coding
WAN	wide area network
WCDMA	Wideband CDMA
WiBro	Wireless Broadband

Wi-Fi	Wireless Fidelity	XPD	cross-polarization discrimination
WiMAX	Worldwide Interoperability for Microwave Access	ZCR	zero-crossing rate
WSN	wireless sensor network	ZF	zero-forcing
WSSUS	wide sense stationary, uncorrelated scattering	ZMCSCG	zero-mean circularly symmetric complex Gaussian