Theory and Design of Digital Communication Systems

Providing the underlying principles of digital communication and the design techniques of real-world systems, this textbook prepares senior undergraduate and graduate students for the engineering practices required in industry. Covering the core concepts, including link analysis, modulation, demodulation, spread spectrum, equalization, channel fading effects, and channel coding, it provides step-by-step mathematical derivations to aid understanding of background material. In addition to describing the basic theory, the principles of system and subsystem design are introduced, enabling students to visualize the intricate connections between subsystems and understand how each aspect of the design supports the overall goal of achieving reliable communications. Throughout the book, theories are linked to practical applications with over 250 real-world examples, whilst 370 varied homework problems in three levels of difficulty enhance and extend the text material. With this textbook, students can understand how digital communication systems operate in the real world, learn how to design subsystems, and evaluate end-to-end performance with ease and confidence.

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Theory and Design of Digital Communication Systems

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World peace must develop from inner peace. Peace is not the absence of violence. Peace is the manifestation of human compassion.

14th Dalai Lama of Tibet (Inscription on United States Congressional Medal)

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Preface

This book was written with two goals in mind: to provide the underlying principles of digital communication and to study design techniques integrated with real world systems. The ultimate aim of a communication system is to provide reliable transmission of information to the user(s). This fundamental foundation was established in 1948 by Claude Shannon, the founding father of information theory, and led eventually to the development of modern digital communication. Analog communication is near extinction or at the very gate of it. The full spectrum dominance of digital communication has arrived and new frontiers are being established every decade; from cellular systems to wireless LAN and MAN, the bit rates are being pushed ever higher for ubiquitous mobile applications.

Knowing the limit of digital transmission is vital to the design of future communication systems, particularly mobile wireless systems, where both spectrum and power are precious resources, and design techniques can be used to manipulate these two main resources to fit real world applications. No single technique can cover all the requirements of a modern communication system, which makes it necessary for students to understand the intricate web between subsystems, each designed to support others to achieve the common goal of reliable communication.

The book contains more than 250 examples to help students achieve a firmer understanding of the subject. The problems at the end of each chapter follow closely the order of the sections. They are designed for three levels: level one covers the straightforward application of equations; level two requires patience and deep thinking; whilst level three requires some research of the literature to assist in finding a solution. A solutions manual for the instructor accompanies the book.

The book was written for both senior undergraduate and graduate students studying communications at universities and colleges. The entire book is suitable for two-semester courses in digital communications. The first course is typically a one-semester senior course in digital communication, which may be taken by students new to studying communications (the conventional wisdom is that students should learn analog communication before learning digital communications) or after completing an introductory course in communication systems (one that is heavy in analog communication systems such as AM and FM). The second course is a one-semester course for graduate students who already have a firm background in random variables and processes. The practical material included in this book (much of it focused on commercial and military systems) will be helpful for practitioners and professionals in the digital communication field.

As in the learning of any subject, some prerequisites are required for the reading of this book. A first course in probability theory is necessary and exposures to random processes

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would be helpful. Readers should also be familiar with linear system analysis. A knowledge of analog communication is helpful but not required. For readers who do not have the patience to go through all the design techniques but would appreciate the beauty of the underlying principles, we recommend our favorite book, *Principles of Digital Communication*, authored by the legendary Robert G. Gallager.

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Symbols

A	amplitude, smallest signal amplitude in MQAM, azimuth angle
Α	matrix A
$ A ^{2}$	squared Frobenius norm of matrix A
\mathbf{A}^*	conjugate and transpose of a matrix A
A_d	number of paths of Hamming weight d that merge with the all-zero paths
A_e	effective aperture area of the receiver antenna
$A \cap B, AB$	intersection of set A and set B, A and B
$A \cup B, A + B$	union of set A and set B, A or B
a	Gaussian filter parameter
$a(h_R)$	correction factor in Hata model
a_f	frequency sensitivity
a_k	Fourier series coefficients
В	bandwidth
B_d	information weight (number of information bit errors) of all paths of
	Hamming weight d
$B_{d_{free}}$	information weight (number of information bit errors) of all paths of
	Euclidean distance <i>d</i> _{free} of TCM
С	channel capacity in coded bits/input symbol, correlation
С	channel capacity in coded bits/second
C_o	outage capacity
$c(\pmb{D}_K)$	correlation metric in MLSD
C_N	correlation metric in CPM
$C_X(t_1,t_2)$	autocovariance of the random process $x(t)$
C(z)	transfer function of causal ZF-LE, z-transform of the sequence $c(k)$
$Cov(N_jN_k)$	covariance of two noise samples
С	code word, PN sequence
c_i	a coded bit, a differentially coded bit
c(t)	PN function of N chips
$\boldsymbol{c}(t)$	complex PN function
$c_I(t)$	PN function of I-channel
$c_Q(t)$	PN function of Q-channel
$c(\boldsymbol{x} \boldsymbol{H_i})$	metric for CPM demodulation
D_i	<i>i</i> th symbol in the symbol stream

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xxi	List of symbols		
	_		
	d	distance	
	d	data sequence	
	dB	decibel	
	d_{free}	free distance of a convolutional code	
	d free	Euclidean free distance of TCM	
	$d_i, d(i)$	normalized bit or symbol amplitude, $d_i \in \{-1, +1\}, d_i \in \{0, 1\}$	
	$\{d_i\}, \{d(i)\}$	data sequence	
	d_{min}	minimum Hamming distance, minimum Euclidean distance	
	d(u,v)	Hamming distance between two code words	
	$d(\mathbf{x}, \mathbf{s}_i)$	Euclidean distance between two vectors	
	Ε	energy (with or without a subscript), smallest symbol energy in MQAM or	
		MASK, electric-field wave, elevation angle	
	E_b	bit energy	
	\mathcal{E}_b	diversity bit energy	
	E(d,t)	free space E -field at distance d from transmitter and time t	
	E_h	hop energy	
	EIRP	effective isotropic radiated power	
	E_0	free space <i>E</i> -field at distance d_0 from transmitter	
	E_s	symbol energy	
	\mathcal{E}_s	diversity symbol energy	
	$\mathbf{E}(X)$	expected value (mean value) of X	
	$\mathbf{E}(X^2)$	mean-square value of X^2	
	e	2.718	
	e	error word	
	e(k)	error sequence of MSE-LE	
	e(t)	error process	
	F	noise figure	
	$F\{x(t)\}$	Fourier transform of $x(t)$	
	F(z)	minimum-phase transfer function, transfer function of a synthetic channel,	
		<i>z</i> -transform of the sequence $f(k)$	
	$F^*(1/z^*)$	maximum-phase function	
	$F^{-1}\{X(f)\}$	inverse Fourier transform of <i>X</i> (<i>f</i>)	
	${}_{2}F_{1}$	Gauss hypergeometric function	
	$F_{ h ^2}^{(-1)}(p_o)SNR$	outage signal-to-noise ratio	
	$F_X^{(n)}(x)$	distribution function of X	
	$F_{XY}(x,y)$	joint distribution function of X and Y	
	$f_{ h }(x)$	density function of the channel tap magnitude $ h $	
	$f_{XY}(x,y)$	joint density function of X and Y	
	$f_{X Y}(x y)$	conditional density function of X given Y	
	f	frequency, Doppler shift	

xxii	_	List of symbols
	fc	carrier frequency
	fp.	Doppler spread
	fi fi	instantaneous carrier frequency of FH
	fr i	instantaneous local carrier frequency of a frequency synthesizer
	f _m	maximum Doppler shift
	f _s	sampling frequency
	$f_X(x)$	density function of X
	$f_{\boldsymbol{X}}(\boldsymbol{x})$	density function of vector X
	G	amplifier gain, gain of a two-port network
	G	generator matrix, space-time block code matrix
	G	TCM asymptotic coding gain
	G_{DC}	gain of a downconverter
	G_{LNA}	gain of a low-noise amplifier
	G_R	receiver antenna gain
	G_R/T_s	antenna gain-to-noise temperature ratio of the earth station
	G_S/T_{sat}	antenna gain-to-noise temperature ratio of the satellite
	G_T	transmitter antenna gain
	g	parity
	g(t)	pulse
	$g_n(t)$	orthonormal pulse shapes in OFDM
	g(x)	code generator polynomial
	Н	Hadamard matrix (with or without a subscript), parity check matrix,
		channel tap matrix
	Н	source entropy in bits/second
	H_i	hypothesis
	H(f)	transfer function or frequency response
	$H_{FE}(f)$	transfer function of the front-end filter of the receiver
	H(f)	magnitude response (amplitude response)
	$H_T(f)$	transfer function of transmit filter
	$H_R(f)$	transfer function of receive filter
	H(k)	<i>N</i> -point DFT of the sequence $h(n)$
	H(X)	entropy of the discrete random variable (discrete source) X
	h	Planck constant, digital modulation index, complex channel tap
	h	row vector of a Hadamard matrix
	ĥ	MMSE of the vector h
	$h_i, h(i)$	<i>i</i> th channel tap
	h(i)	complex channel tap
	$h_L(t)$	complex envelope of the impulse response $h(t)$
	h(n)	sequence used in OFDM
	h_R	receive antenna height

xxiii		List of symbols
	h_T	transmit antenna height
	h(t)	impulse response
	h(X)	differential entropy of a continuous random variable X
	h(X Y)	conditional differential entropy of a continuous random variable X
	h(X)	differential entropy of a continuous n -dimensional random vector X
	h(x)	monic binary irreducible primitive polynomial, PN code polynomial
	Ι	interference power, photodiode current
	I_m	interchannel interference
	Ι	MUI variable
	I(X)	self-information of the discrete random variable (discrete source) X
	$I(u_i, v_j)$	pair-wise mutual information
	I(U, V)	mutual information
	$I_0(ullet)$	modified Bessel function of the first kind of zero order
	$I_n(ullet)$	modified Bessel function of the first kind of <i>n</i> th order
	J	jamming variable
	$J_0, J_0(ullet)$	jamming spectral density, Bessel function of zero order
	Κ	number of simultaneous users in CDMA, Kelvin
	K	covariance matrix
	k	integer, Boltzmann constant, number of information bits in a block code,
		number of inputs of a convolutional encoder
	k_0	free space wave number
	k/n	code rate
	L_C	path loss
	L	diversity order, loss of a two-port network
	L(f)	transfer function of an equalizer
	L_r	receive antenna diversity
	L_s	number of symbol times for m transmitted symbols in transmit diversity
	L_{TL}	loss of a transmission line
	L_t	transmit antenna diversity
	L_{dB}	mean value in decibels of the log-normal density variable
	$L(\lambda, P_1,, P_n)$	Lagrangian
	l	length of a code word
	l	average length of a code word
	ln	natural logarithm
	$\ln \Lambda(X y)$	conditional ln-likelihood ratio
	log	base-10 logarithm
	\log_2	base-2 logarithm
	M	number of distinct M-ary symbols
	$\mathbf{M}(\mathbf{r} \mid \mathbf{c})$	path metric in Viterbi algorithm or log-likelihood function
	т	mean value of a random variable, Nakagami-m parameter

xxiv		List of symbols
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	$m_A(X^{-1})$	arithmetic mean of $1/X(f)$
	$m_G(X)$	geometric mean of X(f)
	m_n	metric for OFDM timing synchronization
	m(t)	message signal
	$\mathbf{m}_{ii}^{(l)}$	message sent by the bit node <i>i</i> to check node <i>j</i> at the <i>l</i> th iteration
	$\mathbf{\hat{m}}_{ii}^{(l)}$	message sent by the check node <i>j</i> to bit node <i>i</i> at the <i>l</i> th iteration
	m_l^2	sum of the squares of the means
	$m_X(t)$	mean value of the random process $x(t)$
	N	noise variable, available noise power, number of OFDM subcarriers,
		period of a PN sequence
	N	noise vector, complex noise
	${\mathcal N}$	noise variable at detector input
	Ν	noise variable
	N	complex noise variable, complex noise vector
	N(f)	power spectral density of the equivalent lowpass noise $n(t)$
	N_D	number of branches in a frequency bin determinator
	N_H	number of hop bins
	N_i	system noise power
	N_n	average number of nearest neighbors of a signal vector
	$N(0,\sigma^2)$	Gaussian random variable with zero mean and variance σ^2
	$N(0,\sigma^2)$	Gaussian vector with iid components of zero mean and variance σ^2
	N_k	noise sample
	$N_{0}/2$	power spectral density of noise
	${\cal N}_V$	average number of level crossings
	п	code word length, path loss exponent
	n_I, N_I	in-phase noise variables
	n_Q, N_Q	quadrature noise variables
	(n,k)	block code of k information bits and code word length n
	n(t)	noise
	$n_L(t)$	complex envelope of bandpass noise
	$n_0(t)$	output noise of a matched filter
	Р	power
	$P_{c,h}$	probability of correctly identifying the frequency bin
	P(d)	pair-wise error probability ($\Pr(\boldsymbol{c} \rightarrow \boldsymbol{c}')$)
	P_e	error probability (bit, symbol, code word)
	P(f)	energy spectrum, Fourier transform of pulse shape $p(t)$
	P_j	power of a jamming signal
	P_p	peak power
	$\Pr(A)$	probability of A
	$\Pr(A,B)$	joint probability of A and B

XXV	_	List of symbols
	$\Pr(A B)$	conditional probability of A given B
	$\Pr(\mathbf{c} \to \mathbf{c'})$	pair-wise error probability
	$\Pr(\boldsymbol{c} \mid \boldsymbol{r})$	a posteriori probability
	$\Pr(\mathbf{r} \mid \mathbf{c})$	likelihood of the transmitted code vector c
	P_T	transmit power
	P(z)	linear predictor in MSE-DFE
	р	crossover probability of a BSC, probability of a binary symbol
	p_{out}	outage probability
	$p_{UV}(u_i, v_j)$	joint distribution of u_i, v_j
	$p(v_j u_i)$	transition probability of a discrete channel
	$p_X(x_i)$	distribution of the discrete random variable X , $i = 1, 2,, n$
	p(t)	pulse shape
	Q(a,b)	Marcum <i>Q</i> -function
	Q(x)	Gaussian integral Q -function of argument x
	Q(z)	transfer function of the composite channel in suboptimum MSE-LE
	q	optimum number of jamming tones
	R	resistance, Rayleigh random variable, source rate in symbols/second
	R_b	bit rate
	R_c	chip rate
	R	responsivity
	R_e	Earth's radius (6378 km)
	$R_h(au, t')$	multipath autocorrelation profile
	$R_{h_i}(t')$	<i>i</i> th path autocorrelation
	R(i-j)	autocorrelation of the data sequence $\{d_i\}$
	R_s	symbol rate
	R(t)	envelope of a bandpass process
	$oldsymbol{\mathcal{R}}_V$	level crossing rate
	R_w	Walsh chip rate
	$R_x(au)$	autocorrelation of WSS random process $x(t)$
	$R_X(t_1,t_2)$	autocorrelation of the random process $x(t)$
	r	value assumed by a random variable R, code rate, spectral efficiency
	r	received word
	r^2	signal-to-intertone interference ratio
	r _e	extinction ratio
	S	input variable of a Gaussian channel
	S	input vector of a Gaussian channel
	S	sample space
	S(f)	power spectral density (with or without a subscript)
	$S_h(au, oldsymbol{f}^{\prime})$	multipath Doppler profile
	$S_{h_i}(f')$	<i>i</i> th path Doppler power spectrum

xxvi		List of symbols
	S	syndrome vector, orthogonal covering symbol
	sgn(x)	signum function
	sign[x]	sign of x
	s(t)	digital signal
	$\{s_i(t)\}$	set of M digital signals, $i = 1, 2,, M$
	$\{s_i\}$	set of M signal vectors in the signal space, $i = 1, 2,, M$
	$ s_i $	norm of signal vector s_i
	Sik	coefficients of the Gram–Schmidt orthogonal expansion, $I-Q$ values of a
		two-dimensional signal vector
	$s_L(n)$	time samples of an OFDM signal
	$s_L(t)$	complex envelope a bandpass signal $s(t)$
	$s_0(t)$	output signal of a matched filter
	S_p	pilot symbol
	Т	time interval, period, sampling period
	Т	phase error rotation matrix
	T_A	antenna noise temperature
	T_b	bit time
	T_c	chip time, channel coherence time
	T_d	time delay, multipath delay spread
	T_{DC}	effective noise temperature of a downconverter
	T_{DM}	effective noise temperature of a demodulator
	T_e	effective noise temperature
	T_h	hop time
	T_{LNA}	effective noise temperature of a low-noise amplifier
	T_n	physical temperature of the resistor
	T_0	reference temperature, time interval, period
	T_p	pulse width
	$Tr(\mathbf{A})$	trace of matrix A
	T_s	symbol time, system noise temperature
	t	time, error-correcting capability of a block code
	U_{\perp}	set of M input symbols of a discrete channel
	$\bigcup_{i=1}^{M} A_i$	union of A_i set
	u(t)	unit step function
	и	message vector
	V	voltage, set of Q output symbols of a discrete channel
	Var(X)	variance of X
	V_{rms}	root mean-square voltage
	V_T	threshold voltage
	v	radial velocity
	v(t)	voltage signal

xxvii		List of symbols
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	W	bandwidth, watt
	$\{w_n(t)\}$	set of Walsh functions, $n = 1, 2,, M$
	X	random variable, discrete source, output variable of a Gaussian channel or
		a matched filter
	X	random vector, output vector of a Gaussian channel
	\overline{X}	mean value (expected value) of X
	$\overline{X^2}$	mean-square value of X^2
	$X(e^{j2\pi f'})$	discrete-time Fourier transform of the sequence $x(k)$
	$ X(f)^2 $	energy spectral density of the energy signal $x(t)$
	X(f)	Fourier transform of $x(t)$, folded spectrum
	X(k)	<i>N</i> -point DFT of the sequence $x(n)$
	X^n	<i>n</i> th extension of the discrete source <i>X</i>
	$X_T(f)$	Fourier transform of $x_T(t)$, 2 <i>T</i> -truncation of $x(t)$, $-T \le t \le T$
	X(z)	<i>z</i> -transform of the sequence $x(k)$, transfer function of the composite
		channel in optimum MSE-LE
	x	value assumed by a random variable X
	x	value assumed by a random vector X
	$\lfloor x \rfloor$	integer part of x
	x(n)	discrete-time signal, sequence used in OFDM
	x(t)	continuous-time signal (with or without a subscript)
	$x_I(t)$	in-phase component of the bandpass signal $x(t)$
	$\{x_k(t)\}$	set of L orthonormal basis functions, $k = 1, 2,, L$
	$\{\mathbf{x}_k\}$	set of L orthonormal basis vectors, $k = 1, 2,, L$
	$x_L(t)$	complex envelope (equivalent lowpass signal) of the bandpass signal $x(t)$
	$x_p(t)$	periodic signal
	$x_Q(t)$	quadrature component of the bandpass signal $x(t)$
	$x_s(t)$	sampled function
	$x_T(t)$	2 <i>T</i> -truncation of $x(t)$, $-T \le t \le T$
	Y(k)	<i>N</i> -point DFT of the sequence $y(n)$
	y(n)	sequence
	y(t)	continuous-time function
	Ζ	pre-mapped vector at the input of the combiner
	Z(k)	frequency samples of an OFDM signal (the I-Q values of symbols of
		OFDM subcarriers)
	Z_0	amplifier transimpedance
	$z_k(t)$	complex envelope of the kth OFDM subcarrier
	*	linear convolution
	\otimes	circular convolution
	$()^{*}$	complex conjugate
	α	arbitrary constant

xxviii		List of symbols
	α_n	normalized signal amplitude in MQAM
	α_p	complex Doppler factor
	$ \alpha_p $	Doppler loss factor
	β	proportionality constant, roll-off factor of a raised-cosine filter
	γ	threshold
	$\gamma_{k,m}$	complex Doppler loss factor
	γ_n	MSK data stream
	Γ	ground reflection coefficient, gamma function
	ΔF	frequency offset in OFDM
	Δf	peak frequency deviation
	$\Delta \varepsilon_l$	differential Doppler phase error
	$\Delta \hat{\varepsilon}_{l-1}$	post-estimated differential Doppler phase error
	$\Delta \varepsilon_l - \Delta \hat{\varepsilon}_{l-1}$	double-differential Doppler phase error
	δ	jamming pulse duty cycle, fraction of FH bandwidth being jammed,
		fraction of a hop being jammed
	δ_{ij}	0 for $i \neq j$ and 1 for $i = j$
	$\delta(t)$	unit impulse function
	ε	phase error
	ε_l	Doppler phase error
	θ	phase
	$ heta_k$	azimuth angle of the <i>k</i> th wave
	$ heta_L$	Earth station longitude
	$ heta_\ell$	Earth station latitude
	$ heta_S$	GEO satellite longitude
	heta(t)	phase function
	λ	wavelength, Lagrange multiplier
	μ	conditional mean value
	$\Lambda(\mathbf{X} \mathbf{y})$	conditional likelihood ratio
	Π	product, fractional coverage area
	ρ	spatial correlation coefficient
	$ ho_X(oldsymbol{ au})$	normalized autocovariance of the random process $x(t)$
	σ^2	variance of noise
	σ_{dB}	standard deviation of the log-normal density variable in decibels
	σ_X^2	variance of the random variable X
	σ_s^2	power of the diffuse paths
	τ	time delay variable, average fade duration
	$ au_i(t)$	path delay
	arphi	phase state in CPM
	$arphi_k$	polar angle of the <i>k</i> th wave
	ϕ	impossible event, null set, phase in MFSK and CPM, phase shift

xxix	List of symbols		
	-		
	$\Phi_0(f)$	power spectral density of the equalizer output noise	
	$\{\phi_k(t)\}$	set of orthonormal eigenfunctions of the noise autocorrelation	
	χ	voice activity factor or data duty cycle	
	χ^2	chi-square	
	ψ	angle of mobile direction with respect to the x-axis, Doppler phase error	
	$\Psi(f)$	power spectral density of sampled noise	
	$\Psi_0(f)$	power spectral density of output noise of ZF-LE	
	$\Psi(t)$	phase of a bandpass process	
	Ω	mean-square value of the envelope of the Nakagami-m process	

Abbreviations

2G	second generation
3G	third generation
A/D	analog/digital conversion
AGN	additive Gaussian noise
AMPS	advanced mobile phone system
APD	avalanche photodiode
ASK	amplitude shift keying
AWGN	additive white Gaussian noise
BCH	Bose-Chaudhuri-Hocquenghem code
BEC	binary erasure channel
BPA	belief propagation algorithm
BSC	binary symmetric channel
CDM	code division multiplexing
CDMA	code division multiple access
CDMA 2000	3G CDMA
СР	cyclic prefix
CPM	continuous phase modulation
CP-MFSK	continuous phase M-ary frequency shift keying
CRC	cyclic redundancy check
CSI	channel side information
CSIR	channel side information at the receiver
CSK	code shift keying
D/A	digital/analog conversion
DD-DF	double-differential decision-feedback algorithm
D-DF	differential decision-feedback algorithm
DEMUX	demultiplexer
DFS	decision-feedback selection
DFT	discrete Fourier transform
DMC	discrete memoryless channel
DMPSK	differential M-ary phase shift keying
DMQAM	differential quadrature amplitude modulation
DPSK	differential phase shift keying
DQPSK	differential quadrature phase shift keying

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xxxi	List of abbreviations		
	DSB-AM	double sideband-amplitude modulation	
	DS	direct sequence	
	DS-CSK	direct sequence-code shift keying	
	DS-PSK	direct sequence-phase shift keying	
	DS-SS	direct sequence spread spectrum	
	DTFT	discrete-time Fourier transform	
	EGC	equal gain combining	
	EIRP	effective isotropic radiated power	
	ESN	electronic serial number	
	ETACS	extended total access cellular system	
	FCC	Federal Communications Commission	
	FDM	frequency division multiplexing	
	FDMA	frequency division multiple access	
	FFH	fast frequency hop	
	FFT	fast Fourier transform	
	FH	frequency hop	
	FIR	finite impulse response	
	FM	frequency modulation	
	FSE	fractionally spaced equalizer	
	FSK	frequency shift keying (binary frequency shift keying)	
	fT	frequency-time product	
	GEO	geostationary orbit	
	GMSK	Gaussian minimum shift keying	
	GPS	global positioning system	
	GSM	global system for mobile communication	
	$ h ^2 SNR$	instantaneous SNR	
	ICI	intercarrier interference	
	ICI	interchannel interference	
	IDFT	inverse discrete Fourier transform	
	IEEE	Institute of Electrical and Electronics Engineers	
	IFFT	inverse fast Fourier transform	
	iid	independent and identically distributed	
	IIR	infinite impulse response	
	IPI	intrapath interference	
	IS	interim standard	
	ISI	intersymbol interference	
	ISI	intersample interference	
	JDC	Japanese digital cellular system	
	JTACS	Japanese total access communication system	
	LDPC	low-density parity-check code	

xxxii		List of abbreviations
	LFSR	linear feedback shift-register
	LLR	In-likelihood ratio
	LR	likelihood ratio
	L-REC	rectangular pulse of duration L symbols
	L-RC	raised cosine pulse shape of duration L symbols
	LSB	lower sideband
	LTI	linear time-invariant
	MAP	maximum a posteriori
	MASK	M-ary amplitude shift keying
	MFSK	M-ary frequency shift keying
	MIMO	multiple-input multiple-output
	MIN	mobile identification number
	MIP	multipath intensity profile
	MISO	multiple-input single-output
	ML	maximum likelihood
	MLSD	maximum likelihood sequence detection
	MMSE	minimum mean-square error
	MPA	message passing algorithm
	MPSK	M-ary phase shift keying
	MQAM	quadrature amplitude modulation
	MRC	maximal ratio combining
	MSC	mobile switching center
	MSE-DFE	mean-square error decision-feedback equalizer
	MSE-LE	mean-square error linear equalizer
	MSK	minimum shift keying
	MUI	multi-user interference
	MUX	multiplexer
	NAMPS	narrowband advanced mobile phone system
	NRZ	non-return-to-zero
	NTACS	narrowband total access communication systems
	OFDM	orthogonal frequency division multiplexing
	OOK	on–off keying
	OQPSK	offset quadrature phase shift keying
	PCS	personal communication system
	PD	pin photodiode
	PDC	Pacific (or personal) digital cellular system
	PDF	probability distribution function
	pdf	probability density function
	$\pi/4$ -DQPSK	$\pi/4$ shift differential quadrature phase shift keying
	PLL	phase-locked loop

> xxxiii List of abbreviations PN pseudo-noise PSK phase shift keying (binary phase shift keying) PSTN public switched telephone network **QPSK** quadrature phase shift keying Reed-Solomon code RS SC selection combining SCM station class mark SFH slow frequency hop SIMO single-input multiple-output signal-to-interference and noise ratio SINR **SINR** path signal-to-interference-and-noise ratio SINR₀ output signal-to-interference plus noise ratio SIR signal-to-interference ratio SIR_i input signal-to-interference ratio output signal-to-interference ratio SIR₀ SJNR₀ output signal-to-jamming-plus-noise ratio SJR_i input signal-to-jamming ratio $SJR_{i, p}$ input signal-to-pulse jamming ratio SJR₀ output signal-to-jamming ratio $SJR_{0, p}$ output signal-to-pulse jamming ratio **SNR** signal-to-noise ratio **SNR** diversity symbol signal-to-noise ratio SNR_0 output signal-to-noise ratio SPA sum product algorithm TCM trellis coded modulation TDMA time division multiple access TIA/EIA Telecommunication Industry Association/Electronic Industry Association USB upper sideband USDC US digital cellular voltage-controlled oscillator VCO wideband CDMA (3G CDMA) WCDMA WLAN wireless local area network WMAN wireless metropolitan area network WSCS wide-sense cyclostationary WSS wide-sense stationary **ZF-DFE** zero-forcing decision-feedback equalizer ZF-LE zero-forcing linear equalizer