Preface

This text, like its previous four editions, is an introduction to communication systems written at a level appropriate for advanced undergraduates and first-year graduate students in electrical or computer engineering.

An initial study of signal transmission and the inherent limitations of physical systems establishes unifying concepts of communication. Attention is then given to analog communication systems, random signals and noise, digital systems, and information theory.

Mathematical techniques and models necessarily play an important role throughout the book, but always in the engineering context as means to an end. Numerous applications have been incorporated for their practical significance and as illustrations of concepts and design strategies. Some hardware considerations are also included to justify various communication methods, to stimulate interest, and to bring out connections with other branches of the field.

PREREQUISITE BACKGROUND

The assumed background is equivalent to the first two or three years of an electrical or computer engineering curriculum. Essential prerequisites are differential equations, steady-state and transient circuit analysis, and a first course in electronics. Students should also have some familiarity with operational amplifiers, digital logic, and matrix notation. Helpful but not required are prior exposure to linear systems analysis, Fourier transforms, and probability theory.

CONTENTS AND ORGANIZATION

New features of this fifth edition include (*a*) the addition of MATLAB† examples, exercises and problems that are available on the book's website, www.mhhe.com/carlsoncrilly; (*b*) new end-of-chapter conceptual questions to reinforce the theory, provide practical application to what has been covered, and add to the students' problem-solving skills; (*c*) expanded coverage of wireless communications and an introduction to radio wave propagation that enables the reader to better appreciate the challenges of wireless systems; (*d*) expanded coverage of digital modulation systems such as the addition of orthogonal frequency division modulation and ultra wideband systems; (*e*) expanded coverage of spread spectrum; (*f*) a discussion of wireless networks; and (*g*) an easy-to-reference list of abbreviations and mathematical symbols.

Following an updated introductory chapter, this text has two chapters dealing with basic tools. These tools are then applied in the next four chapters to analog communication systems, including sampling and pulse modulation. Probability, random signals, and noise are introduced in the following three chapters and applied to analog systems. An appendix separately covers circuit and system noise. The remaining

†MATLAB is a registered trademark of MathWorks Inc.

six chapters are devoted to digital communication and information theory, which require some knowledge of random signals and include coded pulse modulation.

All sixteen chapters can be presented in a yearlong undergraduate course with minimum prerequisites. Or a one-term undergraduate course on analog communication might consist of material in the first seven chapters. If linear systems and probability theory are covered in prerequisite courses, then most of the last eight chapters can be included in a one-term senior/graduate course devoted primarily to digital communication.

The modular chapter structure allows considerable latitude for other formats. As a guide to topic selection, the table of contents indicates the minimum prerequisites for each chapter section.

INSTRUCTIONAL AIDS

Each chapter after the first one includes a list of instructional objectives to guide student study. Subsequent chapters also contain several examples and exercises. The exercises are designed to help students master their grasp of new material presented in the text, and exercise solutions are given at the back. The examples have been chosen to illuminate concepts and techniques that students often find troublesome.

Problems at the ends of chapters are numbered by text section. They range from basic manipulations and computations to more advanced analysis and design tasks. A manual of problem solutions is available to instructors from the publisher.

Several typographical devices have been incorporated to serve as aids for students. Specifically,

- Technical terms are printed in boldface type when they first appear.
- Important concepts and theorems that do not involve equations are printed inside boxes.
- Asterisks (*) after problem numbers indicate that answers are provided at the back of the book.
- The symbol ‡ identifies the more challenging problems.

Tables at the back of the book include transform pairs, mathematical relations, and probability functions for convenient reference.

Communication system engineers use many abbreviations, so in addition to the index, there is a section that lists common abbreviations. Also included is a list of the more commonly used mathematical symbols.

Online Resources

The website that accompanies this text can be found at www.mhhe.com/carlsoncrilly and features new MATLAB problems as well as material on computer networks (TCP/IP) and data encryption. The website also includes an annotated bibliography in the form of a supplementary reading list and the list of references. The complete solutions manual, PowerPoint lecture notes, and image library are available online for instructors. Contact your sales representative for additional information on the website.

Electronic Textbook Options

This text is offered through CourseSmart for both instructors and students. CourseSmart is an online resource where students can purchase the complete text online for one year at almost half the cost of a traditional text. Purchasing the eTextbook allows students to take advantage of CourseSmart's web tools for learning, which include full text search, notes and highlighting, and email tools for sharing notes between classmates. To learn more about CourseSmart options, contact your sales representative or visit www.CourseSmart.com.

ACKNOWLEDGMENTS

I am indebted to the many people who contributed to previous editions. I want to thank Professors Marshall Pace, Seddick Djouadi, and Aly Fathy for their feedback and the use of their libraries; the University of Tennessee Electrical Engineering and Computer Science Department for support; Ms. Judy Evans, Ms. Dana Bryson, Messrs. Robert Armistead, Jerry Davis, Matthew Smith, and Tobias Mueller for their assistance in manuscript preparation.

Thanks, too, for the wonderful feedback from our reviewers: Ali Abdi, *New Jersey Institute of Technology*; Venkatachalam Anantharam, *University of California–Berkeley*; Nagwa Bekir, *California State University–Northridge*; Deva K. Borah, *New Mexico State University*; Sohail Dianat, *Rochester Institute of Technology*; David C. Farden, *North Dakota State University*; Raghvendra Gejji, *Western Michigan University*; Christoforos Hadjicostis, *University of Illinois*; Dr. James Kang, *California State Polytechnic University–Pomona*; K.R. Rao, *University of Texas at Arlington*; Jitendra K. Tugnait, *Auburn University.*

Thanks go to my friends Ms. Anissa Davis, Mrs. Alice Lafoy and Drs. Stephen Derby, Samir ElGhazaly, Walter Green, Melissa Meyer, and John Sahr for their encouragement; to my brother Peter Crilly for his encouragement; and to my children Margaret, Meredith, Benjamin, and Nathan Crilly for their support and sense of humor. Special thanks go to Dr. Stephen Smith of Oak Ridge National Laboratory for the many hours he spent reviewing the manuscript. I also want to thank Dr. Lonnie Ludeman, who as a role model demonstrated to me what a professor should be. Finally, I am indebted to the late A. Bruce Carlson, who created within me the desire and enthusiasm to continue my education and pursue graduate study in communication systems.

Paul B. Crilly

List of Abbreviations

1× EV-DO	evolution data optimized one time
1G, 2G, 3G	first-, second- and third-generation wireless phones
3GPP	third-generation partnership project
AC	alternating current
ACK	positive acknowledgment
ADC	analog-to-digital converter
ADSL	asynchronous DSL
AFC	automatic frequency control
AGC	automatic gain control
AM	amplitude modulation
AMI	alternate mark inversion
AMPS	Advanced Mobile Phone Service
APK	amplitude-phase shift keying
ARQ	automatic repeat request
ASK	amplitude-shift keying
ASCII	American Standard Code for Information Interchange
AVC	automatic volume control
AWGN	additive white gaussian noise
BER	bit error rate or bit error probability
BJT	bipolar junction transistor
BPF	bandpass filter
BPSK	binary PSK
BSC	binary symmetric channel
CCD	charge-coupled devices
CCIR	International Radio Consultative Committee
CCIT	International Telegraph and Telephone Consultative Committee of the Internationals Union
CD	compact disc
CDF	cumulative distribution function
CDMA	code-division multiple access
CIRC	cross-interleave Reed-Solomon error control code
CNR	carrier-to-noise ratio
CPFSK	continuous-phase FSK
CPS	chips
CRC	cyclic redundancy code or cyclic reduncancy check
CSMA	carrier sense multiple access
CVSDM	continuously variable slope delta modulation
CW	continuous-wave
DAC	digital-to-analog converter
dB	decibels
dBm	decibel milliwatts
dBW	decibel watts
DC	direct current, or direct conversion (receiver)

DCT	discrete cosine transform
DDS	direct digital synthesis
DFT	discrete Fourier transform
DLL	delay-locked loop
DM	delta modulation
DPCM	differential pulse-code modulation
DPSK	differentially coherent PSK
DSB or DSB-SC	double-sideband-suppressed carrier modulation
DSL	digital subscriber line
DSM	delta-sigma modulator
DSP	digital signal processing or digital signal processor
DSSS or DSS	direct-sequence spread-spectrum
DTV	digital TV
EIRP	effective isotropic radiated power
EV-DV	evolution, data, and voice
FCC	Federal Communications Commission (USA)
FDD	frequency-division duplex
FDM	frequency-division multiplexing
FDMA	frequency-division multiple access
FDX	full duplex
FEC	forward error correction
FET	field effect transistor
FFT	fast Fourier transform
FHSS	frequency-hopping spread-spectrum
FM	frequency modulation
FOH	first order hold
FSK	frequency-shift keying
GMSK	gaussian filtered MSK
GPRS	general packet radio system
GPS	global positioning system
GSM	Group Special Mobile, or Global System for Mobile Communications
HDSL	high bit rate DSL
HDX	half duplex
HDTV	high definition television
HPF	highpass filter
Hz	hertz
IDFT	inverse discrete Fourier transform
IFFT	inverse fast Fourier transform
IF	intermediate frequency
IMT–2000	international mobile telecommunications–2000
IP	internet protocol
IS-95	Interim Standard 95
ISDN	integrated services digital network
ISI	intersymbol interference

ISM	industrial, scientific, and medical
ISO	International Standards Organization
ITU	International Telecommunications Union
JFET	junction field-effect transistor
kHz	kilohertz
kW	kilowatt
LAN	local area network
LC	inductor/capacitor resonant circuit
LO	local oscillator
LOS	line of sight
LPC	linear predictive code
LPF	lowpass filter
LSSB or LSB	lower single-sideband modulation
LTI	linear time-invariant systems
MA	multiple access
MAI	multiple access interference
MAP	maximum a posteriori
MC	multicarrier modulation
MHz	megahertz
MMSE	minimum means-squared error
modem	modulator/demodulator
MPEG	motion picture expert group
MSK	minimum shift keying
MTSO	mobile telephone switching office
MUF	maximum useable frequency
MUX	multiplexer
NAK	negative acknowledgment
NAMPS	narrowband advanced mobile phone service
NBFM	narrowband frequency modulation
NBPM	narrowband phase modulation
NET	network
NF	noise figure
NIST	National Institute of Standards and Technology
NRZ	nonreturn-to-zero
NTSC	National Television System Committee
OFDM	orthogonal frequency multiplexing
OFDMA	orthogonal frequency-division multiple access
OOK	on-off keying
OQPSK	offset quadrature phase shift keying
OSI	open systems interconnection
PAM	pulse-amplitude modulation
PAR	peak-to-average ratio (power)
PCC	parallel concatenated codes
PCM	pulse-code modulation
PCS	personal communications systems or services

PD	phase discriminator
PDF	probability density function
PEP	peak envelope power
PLL	phase-locked loop
PM	phase modulation
PN	pseudonoise
POT	plain old telephone
PPM	pulse-position modulation
PRK	phase reverse keying
PSD	power spectral density
PSK	phase shift keying
PWM	pulse width modulation
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadriphase PSK
RC	time constant: resistance-capacitance
RF	radio frequency
RFC	radio frequency choke
RFI	radio frequency interference
RMS	root mean squared
RS	Reed-Solomon
RV	random variable
RZ	return-to-zero
SDR	software-defined radio
SIR	signal-to-interference ratio
S/N, SNR	signal-to-noise ratio
SDSL	symmetrical DSL
SONET	Synchronous Optical Network
SS	spread-spectrum
SSB	single-sideband modulation
SX	simplex
TCM	trellis-coded modulation
TCP/IP	transmission control protocol/Internet protocol
TDD	time division duplex
TDM	time-domain multiplexing
TDMA	time-domain multiple access
TH	time-hopping
THSS	time-hopping spread-spectrum
TH-UWB	time-hopping ultra-wideband
TR	transmit reference
TRF	tuned RF receiver
UHF	ultrahigh frequency
UMTS	universal mobile telecommunications systems, or 3G
USSB or USB	upper single-sideband modulation
UWB	ultra-wideband

VCC	voltage-controlled clock
VCO	voltage-controlled oscillator
VDSL	very high-bit DSL
VHDL	VHSIC (very high speed integrated circuit) hardware description language
VHF	very high frequency
VLSI	very large-scale integration
VOIP	voice-over-Internet protocol
VSB	vestigial-sideband modulation
W	watts
WBFM	wideband FM
WCDMA	wideband code division multiple access
WiLan	wireless local area network
WiMAX	Worldwide Interoperability for Microwave Access
Wi-Fi	Wireless Fidelity, or wireless local area network
WSS	wide sense stationary
ZOH	zero-order hold

Mathematical Symbols

A, A_c	amplitude constant and carrier amplitude constant
A_e	aperture area
A_m	tone amplitude
$A_v(t)$	envelope of a BP signal
B	bandwidth in hertz (Hz)
B_T	transmission bandwidth, or bandwidth of a bandpass signal
C	channel capacity, bits per second, capacitance in Farads, or check vector
$C_{vw}(t_1, t_2)$	covariance function of signals $v(t)$ and $w(t)$
D	deviation ratio, or pulse interval
DR	dynamic range
$DFT[\ ]$, $IDFT[\ ]$	discrete and inverse discrete Fourier transorm
E	error vector
E, E_1, E_0, E_b	signal energy, energy in bit 1, energy in bit 0, and bit energy
$E[\ ]$	expected value operator
$F_X(x)$	cumulative distribution function of X
$F_{XY}(x,y)$	joint cumulative distribution of X and Y
G	generator vector
$G_x(f)$	power spectral density of signal $x(t)$
$G_{vw}(f)$	cross-spectral density functions of signals $v(t)$, $w(t)$
$H(f)$	transfer or frequency-response function of a system
$H_C(f)$	channel's frequency response
$H_{eq}(f)$	channel equalizer frequency response
$H_Q(f)$	transfer function of quadrature filter
IR	image rejection
$J_n(\beta)$	Bessell function of first kind, order n, argument β
L, L_{dB}	loss in linear and decibel units
L_u, L_d	uplink and downlink losses
M	numerical base, such that $q = M^v$ or message vector
N_D	destination noise power
N_R	received noise power
N_0	power spectral density or spectral density of white noise
NF, or F	noise figure
$N(f)$	noise signal spectrum
P	power in watts
P_c	unmodulated carrier power
$P(f)$	pulse spectrum
P_e, P_{e0}, P_{e1}	probability of error, probability of zero error, probability of 1 error
P_{be}, P_{we}	probability of bit and word errors
P_{out}, P_{in}	output and input power (watts)
P_{dBW}, P_{dBmW}	power in decibel watts and milliwatts
P_{sb}	power per sideband
$P(A)$, $P(i,n)$	probability of event A occurring and probability of i errors in n-bit word
$Q[\ ]$	gaussian probability function

R	resistance in ohms
$R(\tau)$	autocorrelation function for white noise
R_c	code rate
$R_v\ (t_1, t_2)$	autocorrelation function of signal $v(t)$
$R_{vw}\ (t_1, t_2)$	cross-correlation function of signals $v(t)$ and $w(t)$
S_T	average transmitted power
S_X	message power
S/N, $(S/N)_R$, $(S/N)_D$	signal-to-noise ratio (SNR), received SNR, and destination SNR
S_D	destination signal power
S_R	received signal power
T_b	bit duration
T_0, T	repetition period
T_c	chip interval for DSSS
T_s	sample interval or period
$V_{bp}\ (f)$	frequency domain version of a bandpass signal
W	message bandwidth
X	code vector
X, Y, Z	random variables
Y	received code vector
$X(f)$,$Y(f)$	input and output spectrums
$X_{bp}\ (f)$	bandpass spectrum
a_u	utn symbol
a_n, b_n	trigonometric Fourier series coefficients
c	speed of light in kilometer per second
c_n	nth coefficient for exponential Fourier series, or transversal filter weight
c_n^{k+1}	$(k + 1)$th estimate of the nth tap coefficient
$c(t)$	output from PN generator or voltage-controlled clock
d	physical distance
$d_{\min}$	code distance
f	frequency in hertz
$f(t)$	instantaneous frequency
f_c	carrier or center frequency
f_c'	image frequency
f_d	frequency interval
f_{IF}	intermediate frequency
f_{LO}	local oscillator frequency
f_k, f_n	discrete frequency
f_m	tone frequency
f_Δ	frequency deviation constant
f_0	center frequency
f_s	sample rate
g, g_T, g_R	power gain and transmitter and receiver power gains
g_{dB}	power gain in decibels (dB)

$h(t)$	impulse-response function of a system
$h_C(t)$	impulse-response function of a channel
$h_k(t)$, $h_k(n)$	impulse-response function of *k*th portion of subchannel
$h_Q(t)$	impulse-response function of a quadrature filter
Im[x] and Re[x]	imaginary and real components of x
j	imaginary number operator
l	length in kilometers
m	number of repeater sections
m_k, $\hat{m}_k$	actual and estimated k message symbol
$n(t)$	noise signal
$p(t)$	pulse signal
$p^0(t)$, $p^1(t)$	gaussian and first-order monocycle pulses
$\tilde{p}_n$	output of transversal filter's *n*th delay element
$\tilde{p}(t)$	input to equalizing filter
$p_{eq}(t_k)$	output of an equalizing filter
$p_X(x)$	probability density function of X
$p_{XY}(x)$	joint probability density function of X and Y
q	number of quantum levels
r, r_b	signal rate, bit rate
$s(t)$	switching function for sampling
$s_o(t)$, $si(t)$	inputs to multiplier of correlation detector
sgn(t)	signum function
t	time in seconds
t_d	time delay in seconds
t_k	*k*th instant of time
t_r	rise time in seconds
$u(t)$	unit step function, or output from rake diversity combiner
v	number of bits
$v(t)$	input to a detector
$v_k\ (t)$	*k*th subcarrier function
$\langle v(t) \rangle$	average value of $v(t)$
$v_{bp}(_t)$	time-domain expression of a bandpass signal
$w^*(t)$	complex conjugate of $w(t)$
$\hat{x}$	Hilbert transform of x, or estimate of x
$x(t)$, $y(t)$	input and output time functions
$x(t)$	message signal
$x(k)$, $x(kT_s)$	sampled version of $x(t)$
$X(n)$	discrete Fourier transform of $x(k)$
$x_b(t)$	modulated signal at a subcarrier frequency
$x_c(t)$	modulated signal
$x_q(k)$	quantized value for *k*th value of x
$y(t)$	detector output
$x_k(t)$, $y_k(t)$	subchannel signal
$y_D(t)$	signal at destination
$z_m(t)$	output of matched filter or correlation detector

α	loss coefficient in decibels per kilometer, or error probability
γ	baseband signal to noise ratio
γ, γ_{TH}	threshold signal to noise ratio (baseband)
$\gamma_b = E_b / N_0$	bit energy signal-to-noise ratio
δ	incremental delay
$\delta(t)$	unit impulse, or Dirac delta function
$\boldsymbol{\varepsilon}(t)$, $\boldsymbol{\varepsilon}$, $\boldsymbol{\varepsilon}_k$	error, increment, and quantization error
Δ	quantization step size
λ	wavelength, meters, or time delay
μ	modulation index, or packet rate
σ	standard deviation
σ_Y, σ_Y^2	standard deviation and variance of Y
τ	pulse width, or time constant
ϕ	phase angle
$\phi(t)$	instantaneous phase
ϕ_Δ	phase deviation constant
$\phi_v(t)$	phase of a BP signal
ω_c	carrier frequency in radians per second
ω_m	tone frequency in radians per second
$\Pi(t/\tau)$	rectangular pulse
$\Lambda(t/\tau)$	triangle pulse
L	Laplace operator
$\mathcal{F}$, $\mathcal{F}^{-1}$	Fourier transform operator and its inverse
$*$	convolution operator
$\Im$, $\Im_0$, $\Im_N$	noise temperatures