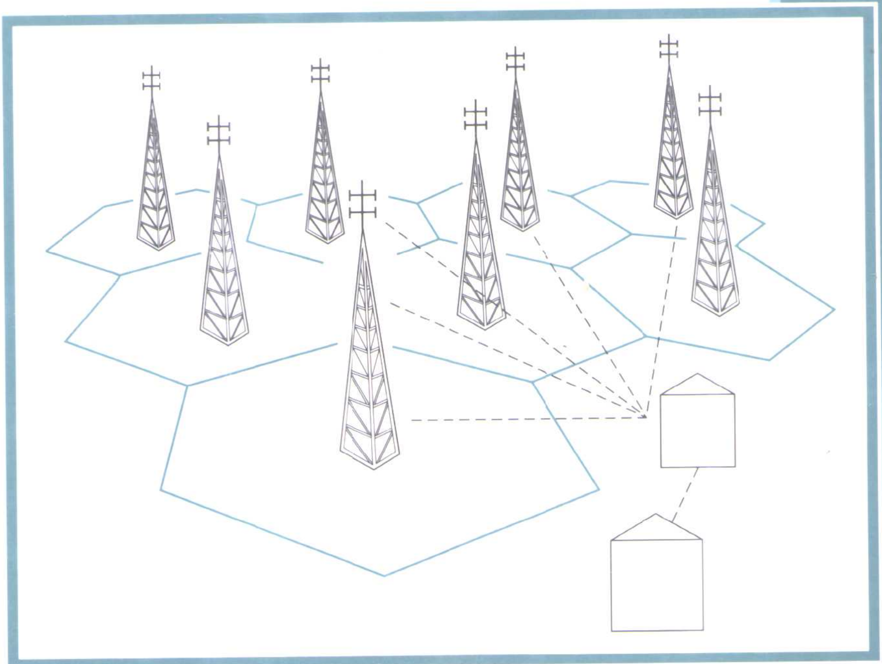
DIGITAL AND ANALOG COMMUNICATION SYSTEMS

SIXTH EDITION



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PREFACE

Continuing the tradition of the first to fifth editions of this book, this new edition provides the latest up-to-date treatment of digital communication systems. It includes a number of new study-aid examples and homework problems, many of which require solutions via a personal computer. It is written as a textbook for junior or senior engineering students and is also appropriate for an introductory graduate course or as a modern technical reference for practicing electrical engineers.

To learn about communication systems, it is essential to first understand *how communication systems work*. Based on the principles of communications (power, frequency spectra, and Fourier analysis) that are covered in the first five chapters of this book, this understanding is motivated by the use of extensive examples, study-aid problems, and the inclusion of adopted standards. Especially interesting is the material on wire and wireless communication systems. Also of importance is the effect of noise on these systems, since, without noise (described by probability and random processes), one could communicate to the limits of the universe with negligible transmitted power. In summary, this book covers the essentials needed for the understanding of wire and wireless communication systems and includes adopted standards. These essentials are

- How communication systems work: Chapters 1 through 5.
- The effect of noise: Chapters 6 and 7.
- Wire and Wireless Communication Systems: Chapter 8.

This book is ideal for either a one-semester or a two-semester course. For a one-semester course, the basics of how communication systems work may be taught by using the first five chapters (with selected readings from Chapter 8). For a two-semester course, the whole book is used.

This book covers *practical aspects* of communication systems developed from a sound *theoretical basis*.

THE THEORETICAL BASIS

- Digital and analog signals
- Magnitude and phase spectra
- Fourier analysis
- Orthogonal function theory
- Power spectral density
- Linear systems
- Nonlinear systems
- Intersymbol interference
- Complex envelopes
- Modulation theory
- Probability and random processes
- Matched filters
- Calculation of SNR
- Calculation of BER
- Optimum systems
- Block and convolutional codes

THE PRACTICAL APPLICATIONS

- PAM, PCM, DPCM, DM, PWM, and PPM baseband signaling
- OOK, BPSK, QPSK, MPSK, MSK, OFDM, and QAM bandpass digital signaling
- AM, DSB-SC, SSB, VSB, PM, and FM bandpass analog signaling
- Time-division multiplexing and the standards used
- Digital line codes and spectra
- Circuits used in communication systems
- Bit, frame, and carrier synchronizers
- Software radios
- Frequency-division multiplexing and the standards used
- Telecommunication systems
- Telephone systems
- Digital subscriber lines
- Satellite communication systems

- Effective input-noise temperature and noise figure
- Link budget analysis
- SNR at the output of analog communication systems
- BER for digital communication systems
- Fiber-optic systems
- Spread-spectrum systems
- AMPS, GSM, iDEN, TDMA, and CDMA cellular telephone and PCS systems
- Digital and analog television systems
- Technical standards for AM, FM, TV, DTV, and CATV
- Protocols for computer communications
- Technical standards for computer communications
- MATLAB M files
- Mathematical tables
- Study-aid examples
- Over 550 homework problems with selected answers
- Over 60 computer-solution homework problems
- Extensive references
- Emphasis on the design of communication systems

Many of the equations and homework problems are marked with a personal computer symbol, , which indicates that the given equation or problem has a MATLAB and MATHCAD solution on an available floppy disk or via the Internet at www.couch.ece.ufl.edu or www.prenhall.com/couch.

This book is an outgrowth of my teaching at the University of Florida and is tempered by my experiences as an amateur radio operator (K4GWQ). I believe that the reader will not understand the technical material unless he or she works some homework problems. Consequently, over 550 problems have been included. Some of them are easy, so that the beginning student will not become frustrated, and some are difficult enough to challenge the more advanced students. All the problems are designed to provoke thought about, and understanding of, communication systems.

I appreciate the help of the many persons who contributed to this book and the very helpful comments that have been provided by the reviewers—in particular, Marvin Siegel of the Department of Electrical Engineering at the University of Michigan and J. B. O'Neal of North Carolina State University. I also appreciate the help of my colleagues at the University of Florida. I thank my wife, Dr. Margaret Couch, who typed the original and revised manuscripts.

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LIST OF SYMBOLS

There are not enough symbols in the English and Greek alphabets to allow the use of each letter only once. Consequently, some symbols may be employed to denote more than one entity, but their use should be clear from the context. Furthermore, the symbols are chosen to be generally the same as those used in the associated mathematical discipline. For example, in the context of complex variables, x denotes the real part of a complex number (i.e., $c = x + jy$), whereas in the context of statistics, x might denote a random variable.

Symbols

a_n	a constant
a_n	quadrature Fourier series coefficient
A_c	level of modulated signal of carrier frequency f_c
A_e	effective area of an antenna
b_n	quadrature Fourier series coefficient
B	baseband bandwidth

B_p	bandpass filter bandwidth
B_T	transmission (bandpass) bandwidth
c	a complex number ($c = x + jy$)
c	a constant
c_n	complex Fourier series coefficient
C	channel capacity
C	capacitance
°C	degrees Celsius
dB	decibel
D	dimensions/s, symbols/s ($D = N/T_0$), or baud rate
D_f	frequency modulation gain constant
D_n	polar Fourier series coefficient
D_p	phase modulation gain constant
e	error
e	the natural number 2.7183
E	modulation efficiency
E	energy
$\mathscr{E}(f)$	energy spectral density (ESD)
E_b/N_0	ratio of energy per bit to noise power spectral density
f	frequency (Hz)
$f(x)$	probability density function (PDF)
f_c	carrier frequency
f_i	instantaneous frequency
f_0	a (frequency) constant; the fundamental frequency of a periodic wavefonn
f_s	sampling frequency
F	noise figure
$F(a)$	cumulative distribution function (CDF)
$g(t)$	complex envelope
$\tilde{g}(t)$	corrupted complex envelope
G	power gain
$G(f)$	power transfer function
h	Planck's constant, 6.2×10^{-34} joule-s
$h(t)$	impulse response of a linear network
$h(x)$	mapping function of x into $h(x)$
H	entropy
$H(f)$	transfer function of a linear network
i	an integer
I_j	information in the jth message
j	the imaginary number $\sqrt{-1}$
j	an integer
k	Boltzmann's constant, 1.38×10^{-23} joule/K
k	an integer
$k(t)$	complex impulse response of a bandpass network
K	number of bits in a binary word that represents a digital message
K	degrees Kelvin (°C + 273)

l	an integer
ℓ	number of bits per dimension or bits per symbol
L	inductance
L	number of levels permitted
m	an integer
m	mean value
$m(t)$	message (modulation) waveform
$\tilde{m}(t)$	corrupted (noisy received) message
M	an integer
M	number of messages permitted
n	an integer
n	number of bits in message
$n(t)$	noise waveform
N	an integer
N	number of dimensions used to represent a digital message
N	noise power
N_0	level of the power spectral density of white noise
$p(t)$	an absolutely time-limited pulse waveform
$p(t)$	instantaneous power
$p(m)$	probability density function of frequency modulation
P	average power
P_e	probability of bit error
$P(C)$	probability of correct decision
$P(E)$	probability of message error
$\mathcal{P}(f)$	power spectral density (PSD)
$Q(z)$	integral of Gaussian function
$Q(x_k)$	quantized value of the kth sample value, x_k
$r(t)$	received signal plus noise
R	data rate (bits/s)
R	resistance
$R(t)$	real envelope
$R(\tau)$	autocorrelation function
$s(t)$	signal
$\tilde{s}(t)$	corrupted signal
S/N	ratio of signal power to noise power
t	time
T	a time interval
T	absolute temperature (Kelvin)
T_b	bit period
T_e	effective input-noise temperature
T_0	duration of a transmitted symbol or message
T_0	period of a periodic waveform
T_0	standard room temperature (290 K)
T_s	sampling period
u_{11}	covariance

$v(t)$	a voltage waveform
$v(t)$	a bandpass waveform or a bandpass random process
$w(t)$	a waveform
$W(f)$	spectrum (Fourier transform) of $w(t)$
x	an input
x	a random variable
x	real part of a complex function or a complex constant
$x(t)$	a random process
y	an output
y	an output random variable
y	imaginary part of a complex function or a complex constant
$y(t)$	a random process
α	a constant
β	a constant
β_f	frequency modulation index
β_p	phase modulation index
δ	step size of delta modulation
δ_{ij}	Kronecker delta function
$\delta(t)$	impulse (Dirac delta function)
ΔF	peak frequency deviation (Hz)
$\Delta\theta$	peak phase deviation
ϵ	a constant
ϵ	error
η	spectral efficiency [(bits/sec)/Hz]
$\theta(t)$	phase waveform
λ	dummy variable of integration
λ	wavelength
$\Lambda(r)$	likelihood ratio
π	3.14159
ρ	correlation coefficient
σ	standard deviation
τ	independent variable of autocorrelation function
τ	pulse width
$\varphi_j(t)$	orthogonal function
ϕ_n	polar Fourier series coefficient
ω_c	radian carrier frequency, $2\pi f_c$
$\equiv$	mathematical equivalence
$\triangleq$	mathematical definition of a symbol

DEFINED FUNCTIONS

$J_n(\cdot)$	Bessel function of the first kind, nth order
$\ln(\cdot)$	natural logarithm
$\log(\cdot)$	base 10 logarithm

$\log_2(\cdot)$	base 2 logarithm
$Q(z)$	integral of a Gaussian probability density function
$\mathrm{Sa}(z)$	$(\sin z)/z$
$u(\cdot)$	unit step function
$\Lambda(\cdot)$	triangle function
$\Pi(\cdot)$	rectangle function

OPERATOR NOTATION

$\mathrm{Im}\{\cdot\}$	imaginary part of
$\mathrm{Re}\{\cdot\}$	real part of
$\overline{[\cdot]}$	ensemble average
$\langle[\cdot]\rangle$	time average
$[\cdot] * [\cdot]$	convolution
$[\cdot]^*$	conjugate
$\underline{/[\cdot]}$	angle operator or angle itself, see Eq. (2–108)
$\lvert[\cdot]\rvert$	absolute value
$[\hat{\cdot}]$	Hilbert transform
$\mathscr{F}[\cdot]$	Fourier transform
$\mathscr{L}[\cdot]$	Laplace transform
$[\cdot] \cdot [\cdot]$	dot product

Abbreviations

ac	alternating current
ADC	analog-to-digital conversion
ADM	adaptive delta modulation
AM	amplitude modulation
ANSI	American National Standards Institute
APLL	analog phase-locked loop
ASCII	American Standard Code for Information Interchange
ATM	Asynchronous transfer mode
AT&T	American Telephone and Telegraph
AWGN	additive white Gaussian noise
BER	bit error rate
BPSK	binary phase shift keying
CATV	cable antenna television system
CCITT	Consultative Committee for International Telephone and Telegraph
CDMA	code-division multiple access
CFT	continuous Fourier transform
CMOS	complementary metal oxide conductor
CO	central telephone office
CRT	cathode-ray tube
dB	decibel
dc	direct current
DCE	data communications equipment
DFT	discrete Fourier transform
DM	delta modulation
DPCM	differential pulse code modulation
DSB-SC	double-sideband suppressed carrier
DSL	digital subscriber loop
DTE	data terminal equipment
DTV	digital television
EIRP	effective isotropic radiated power
EIA	Electronics Industries Association
ERP	effective radiated power
FCC	Federal Communications Commission (United States)
FDM	frequency-division multiplexing
FET	field-effect transistor
FFT	fast Fourier transform
FM	frequency modulation
FSK	frequency shift keying
GSM	group special mobile (cellular phone)
HDLC	high-level data link control protocol
HDTV	high-definition (digital) television
HF	high frequency
IEEE	Institute of Electrical and Electronics Engineers
IF	intermediate frequency
IMD	intermodulation distortion
ISDN	integrated service digital network
ISI	intersymbol interference
ISO	International Organization for Standardization
ITU	International Telecommunications Union of the United Nations
LED	light-emitting diode
LO	local oscillator
LOS	line of sight

LPF	low-pass filter
LSSB	lower single sideband
MAP	maximum a posteriori (criterion)
MPSK	M-ary phase shift keying
MQAM	M-ary quadrature amplitude modulation
MSK	minimum-shift keying
NBFM	narrowband frequency modulation
NRZ	nonreturn-to-zero
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
OQPSK	offset quadrature phase shift keying
OSI	open system interconnection protocol model
PAM	pulse amplitude modulation
PCM	pulse code modulation
PCS	personal communication service
PD	phase detection
PDF	probability density function
PEP	peak envelope power
PLL	phase-locked loop
PM	phase modulation
PPM	pulse position modulation
PSD	power spectral density
PSK	phase shift keying
PTM	pulse time modulation
PWM	pulse width modulation
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
rms	root-mean-square
RF	radio frequency
RT	remote telephone terminal
RZ	return-to-zero
SAW	surface acoustics wave
SDLC	synchronous data link control protocol
SDTV	standard definition digital television
S/N or SNR	signal-to-noise ratio
SS	spread spectrum (system)
SSB	single sideband
TDM	time-division multiplexing
TDMA	time-division multiplex access
TELCO	telephone company
THD	total harmonic distortion
TTL	transistor-transistor logic
TV	television
TVRO	TV receive only terminal
TWT	traveling-wave tube
UHF	ultra high frequency
USSB	upper single sideband
VCO	voltage-controlled oscillator
VF	voice frequency
VHF	very high frequency
VSB	vestigial sideband
WBFM	wideband frequency modulation

TABLE 2–1 SOME FOURIER TRANSFORM THEOREMS[a]

Operation	Function	Fourier Transform
Linearity	$a_1 w_1(t) + a_2 w_2(t)$	$a_1 W_1(f) + a_2 W_2(f)$
Time delay	$w(t - T_d)$	$W(f)\ e^{-j\omega T_d}$
Scale change	$w(at)$	$\frac{1}{\lvert a \rvert} W\left(\frac{f}{a}\right)$
Conjugation	$w^*(t)$	$W^*(-f)$
Duality	$W(t)$	$w(-f)$
Real signal frequency translation [$w(t)$ is real]	$w(t) \cos(\omega_c t + \theta)$	$\frac{1}{2}[e^{j\theta} W(f - f_c) + e^{-j\theta} W(f + f_c)]$
Complex signal frequency translation	$w(t)\ e^{j\omega_c t}$	$W(f - f_c)$
Bandpass signal	$\text{Re}\{g(t)\ e^{j\omega_c t}\}$	$\frac{1}{2}[G(f - f_c) + G^*(-f - f_c)]$
Differentiation	$\frac{d^n w(t)}{dt^n}$	$(j2\pi f)^n W(f)$
Integration	$\int_{-\infty}^{t} w(\lambda)\ d\lambda$	$(j2\pi f)^{-1} W(f) + \frac{1}{2} W(0)\ \delta(f)$
Convolution	$w_1(t) * w_2(t) = \int_{-\infty}^{\infty} w_1(\lambda) \cdot w_2(t - \lambda)\ d\lambda$	$W_1(f) W_2(f)$
Multiplication[b]	$w_1(t) w_2(t)$	$W_1(f) * W_2(f) = \int_{-\infty}^{\infty} W_1(\lambda)\ W_2(f - \lambda)\ d\lambda$
Multiplication by t^n	$t^n w(t)$	$(-j2\pi)^{-n} \frac{d^n W(f)}{af^n}$

[a] $\omega_c = 2\pi f_c$.

[b] $*$ denotes convolution as described in detail by Eq. (2–62).

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TABLE 2–2 SOME FOURIER TRANSFORM PAIRS

Function	Time Waveform $w(t)$	Spectrum $W(f)$
Rectangular	$\Pi\left(\frac{t}{T}\right)$	$T[\mathrm{Sa}(\pi f T)]$
Triangular	$\Lambda\left(\frac{t}{T}\right)$	$T[\mathrm{Sa}(\pi f T)]^2$
Unit step	$u(t) \triangleq \begin{cases} +1, & t > 0 \\ 0, & t < 0 \end{cases}$	$\frac{1}{2}\delta(f) + \frac{1}{j2\pi f}$
Signum	$\mathrm{sgn}(t) \triangleq \begin{cases} +1, & t > 0 \\ -1, & t < 0 \end{cases}$	$\frac{1}{j\pi f}$
Constant	1	$\delta(f)$
Impulse at $t = t_0$	$\delta(t - t_0)$	$e^{-j2\pi f t_0}$
Sinc	$\mathrm{Sa}(2\pi W t)$	$\frac{1}{2W}\,\Pi\left(\frac{f}{2W}\right)$
Phasor	$e^{j(\omega_0 t + \varphi)}$	$e^{j\varphi}\,\delta(f - f_0)$
Sinusoid	$\cos(\omega_c t + \varphi)$	$\frac{1}{2}e^{j\varphi}\,\delta(f - f_c) + \frac{1}{2}e^{-j\varphi}\,\delta(f + f_c)$
Gaussian	$e^{-\pi(t/t_0)^2}$	$t_0 e^{-\pi(f t_0)^2}$
Exponential, one-sided	$\begin{cases} e^{-t/T}, & t > 0 \\ 0, & t < 0 \end{cases}$	$\frac{T}{1 + j2\pi f T}$
Exponential, two-sided	$e^{-\lvert t\rvert/T}$	$\frac{2T}{1 + (2\pi f T)^2}$
Impulse train	$\sum_{k=-\infty}^{k=\infty} \delta(t - kT)$	$f_0 \sum_{n=-\infty}^{n=\infty} \delta(f - n f_0)$, where $f_0 = 1/T$

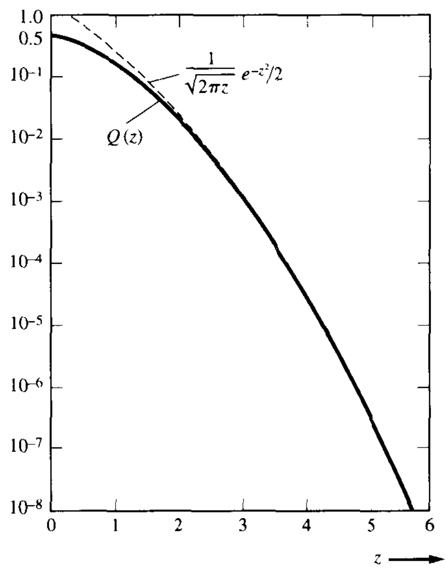

Figure B–7 The function $Q(z)$ and an overbound, $\frac{1}{\sqrt{2\pi}\,z}\, e^{-z^2/2}$.

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