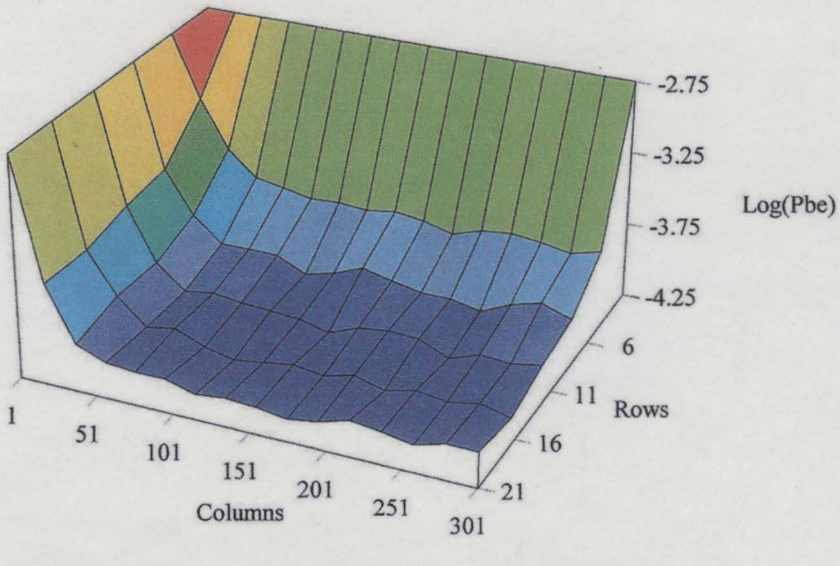

DIGITAL COMMUNICATIONS WITH EMPHASIS ON DATA MODEMS

THEORY, ANALYSIS, DESIGN, SIMULATION, TESTING, AND APPLICATIONS

RICHARD W. MIDDLESTEAD

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Thanks to:
My Lord and Savior Jesus Christ.
My Father in heaven without whose creative genius
science would be rudderless.
The Holy Spirit who inspires men and women beyond their own understanding.

Dedicated to:
My mother and father
and loving wife Donna
My children Lynn, Mark, and Leighann
and my grandchildren
Kasey, Erik, Jacob, Kaylee, Zachary, Mackenzie, Tyler, Hannah,
and great grandchildren Kaleigh and Isla

My prayer for my children is that wisdom, hard work, perseverance, and compassion will be the hallmark of their character.

PREFACE

The material in this book contains sufficient mathematical background to challenge the graduate student and to allow the experienced communication systems engineer to analyze, specify, and select optimum solutions for a variety of applications. Furthermore, it is hoped that the many performance plots, tables, and design concepts will prove beneficial to system design engineers who are less inclined to delve into the mathematical rigors. The importance of communication systems performance simulations cannot be overstated as a developmental tool prior to the software and hardware designs. Computer simulations allow the designer to predict the system performance beyond the assumptions leading to mathematical models. In nearly every chapter to follow, the results presented have been verified using computer simulations and found to be in agreement with the theoretical results.

Although the material presented in this book focuses on the modulator and demodulator (modem) subsystems, the transmitter and receiver (transceiver) subsystems and the corresponding antenna subsystems must be considered in order to evaluate the overall communication link performance. Furthermore, the design of these subsystems is influenced by the communication channels that are broadly characterized as wireline and wireless or radio frequency (RF) channels.

The modulator, transmitter, and transmitter antenna subsystems function together with inputs from an information source. Similarly, the receiver antenna, receiver, and demodulator subsystems perform the complementary functions providing optimum data estimates to the information destination or sink. In these roles, the modulator performs the important functions of preparing the source information data for subsequent transmission. This involves source coding, channel coding, and optimal mapping of the coded data to the selected symbol modulation format for transmission. Design considerations regarding the symbol modulation format selection involve bandwidth conservation and power efficiency that are largely influenced by the channel.

Communication systems are broadly defined in terms of point-to-point and network communications. Within these systems, there are three basic forms of transmissions: *simplex* refers to information transmission in one direction only as in commercial broadcast radio; *half-duplex* refers to transmission is one direction at a time as in push-to-talk radios; *full-duplex* refers to simultaneous transmissions in both directions. These forms of transmission require increasing degrees of complexity and performance capabilities. The data link performance analysis presented in the book typically applies to the physical layer corresponding to single carrier per channel (SCPC) point-to-point communication links. With the inclusion of the network controls [1] and the associated overhead functions, the physical layer performance can be applied directly to time division multiple access (TDMA) networks. The performance of frequency division multiple access (FDMA) and code division multiple access [2] (CDMA) networks can also be evaluated with the respective inclusion of adjacent channel interference (ACI) and co-channel interference (CCI) losses. In general, network centric protocols are specialized for specific applications and as such are beyond the scope of the book. However, because of its relative simplicity and utility in providing virtually error-free data transmission, the performance of automatic repeat request (ARQ) protocols requiring half or full-duplex networking capabilities is discussed.

A major performance measure of a digital communication system is the bit-error probability characterized as a function of the ratio of the received signal energy per source bit to the noise density. Many of these performance plots are obtained using Monte Carlo simulations with the goal of providing a smooth eye-appealing curve approximating the theoretical performance.[1] To this end, the number of Monte Carlo trials over the entire range of signal-to-noise ratios is selected to achieve a reasonable confidence level at the lowest bit-error probability of interest. The resulting performance curve is very accurate for the lower signal-to-noise ratios; however, the performance at the highest signal-to-noise ratio may appear as an outlier not conforming to the expected theoretical result. In these cases, the outlier data is brought into compliance with the smooth performance curve in one of two ways; the simulation is re-run using a minimum of 10 times the number of Monte Carl trials or the data point is brought into compliance manually by adjusting the bit-error probability; this approach is comparable to fitting a *French curve* to the lower signal-to-noise ratio data points and appropriately adjusting the outlier. Flaring of the performance curve due to nonlinearities or intersymbol interference is also taken into account.

The following is a brief description of the subjects in each chapter that often includes case studies to illustrate the methodology of the evaluation and the characteristics of the underlying performance measure.

Chapter 1 focuses on the description of techniques and analytical methods used throughout the book including real and analytic characterization of waveform modulations, Fourier transforms, an introduction to statistical analysis, optimum waveform detection and parameter estimation, a brief look at ARQ protocols, spectral control using windows, vector and matrix operations, and lists of commonly mathematical relationships. The chapter can be considered as reference material associated with the remaining chapters; however, the notion of the complex envelope or analytic representation of baseband signals should be thoroughly understood.

Chapter 2 discusses many fundamental relationships required for analysis involving digital signal processing. The notion of Nyquist sampling and the requirement for capturing the information contained in the received signal are described using baseband and bandpass sampling techniques. Multirate signal processing and rate conversion is examined using various rate conversion filters including the cascade integrate and comb (CIC) filter. The chapter includes a discussion of polyphase filters and Lagrange interpolation leading to the Farrow filter. The chapter concludes with the derivation of a parabolic interpolator for improvement of time and frequency estimation errors used during waveform acquisition and information detection and tracking. The material in the chapter provides essential insights into fundamental digital signal processing requirements for the design of the modem subsystem and, as such, each topic should be examined in sufficient detail to result in an optimum design.

[1] To aid in the simulation of a smooth eye-appealing performance curve, all of the noise generator seeds are reset at each signal-to-noise ratio.

Chapter 3 introduces the fundamental concepts of digital communication systems involving source and channel coding and optimum techniques for information recovery. The concepts are discussed using discrete memoryless and binary symmetric channels. Shannon's channel capacity limit forms the basis of the analysis and bounds on the bit error are examined using the computational cutoff rate. The chapter concludes with a discussion of the probability integral and the error function. The chapter, like Chapter 1, may be considered reference material; however, Shannon's error-free performance limit must be understood along with the many applications and forms of the error function.

Chapters 4 through 7 provide a comprehensive analysis of various waveform modulations and the corresponding power spectral density (PSD) and bit-error performance. Constant envelope modulations ranging from multiphase shift keying (MPSK) to Gaussian minimum shift keying (GMSK) are examined. Spectral efficiency achieved through phase shaping while maintaining a constant envelope is a major topic. The simplicity and robustness of differentially coherent waveform modulation and demodulation is also examined. The spectral root-raised-cosine (SRRC) waveform, although not a constant envelope modulation, results in superior spectral efficiency. The spectrums of these modulated waveforms are compared to industry-standard transmit spectral masks. Chapter 5 examines the bit-error performance and PSD of frequency shift keying with coherent and noncoherent detection. Chapter 6 examines the performance of amplitude shift keying (ASK) including binary on–off keying (OOK), pulse amplitude modulation (PAM), and quadrature amplitude modulation (QAM). Chapter 6 concludes with a discussion of partial response modulation focusing on the modified and multilevel duobinary modulations. Chapter 7 discusses *M*-ary coded waveforms focusing on the coherent and noncoherent detection of *M*-ary orthogonal and biorthogonal waveforms.

Chapter 8 focuses on coding for improved communications, beginning with the description of commonly used pulse code modulation (PCM) waveforms. Coding techniques that are generally applied to a variety of waveform modulations include gray and differential coding, binary cyclic coding, cyclic redundancy check (CRC) coding, data randomizers, and block and convolutional interleaving. The chapter also includes descriptions and performance results for Wagner coding, convolutional coding with Viterbi decoding, turbo and turbo-like parallel concatenated convolutional coding (PCCC) or turbo coding, serial concatenated convolutional coding (SCCC), low-density parity-check (LDPC) coding, and turbo product codes (TPCs). The chapter concludes with Bose–Chaudhuri–Hocquenghem (BCH), Reed–Solomon (RS), and Reed–Solomon Viterbi (RSV) coding.

Chapter 9 focuses on forward error correction (FEC) codes without bandwidth expansion. In these cases, additional modulation states are included as redundant states for maximum likelihood error correction in a trellis decoder. The implementation and performance of multi-*h* *M*-ary continuous phase modulation (CPM) is compared to that of MPSK trellis-coded modulation (TCM).

Chapter 10 provides a detailed analysis and performance evaluation of carrier acquisition and tracking using first through third-order phaselock loops. The tracking performance using classical control theory is compared to that using the maximum a posteriori probability (MAP) estimation procedure. Detailed implementations diagrams and performance results are provided for MPSK and MSK waveform modulations. A procedure is discussed to optimize the phaselock loop gains in simulation and hardware designs to conform to the theoretical response under prescribed input conditions. Case studies are provided that demonstrate the dynamic and steady-state tracking conditions.

Chapter 11 discusses the signal presence detection and acquisition of a received waveform using a data preamble; the topics including automatic gain control (AGC), coarse and fine carrier frequency estimation and acquisition, symbol synchronization, and start-of-message (SOM) detection. The chapter concludes with various methods of estimating signal and noise powers and the received signal-to-noise ratio.

Chapter 12 analyzes various adaptive estimation algorithms beginning with a discussion of the orthogonality principle and Wiener's solution to the optimum filtering problem. Various estimation techniques are examined with algorithms developed for the finite impulse response (FIR) and least mean-square (LMS) adaptive filters. Adaptive equalization algorithms include the zero-forcing, linear feedforward, nonlinear decision feedback, fractionally spaced and the recursive least-squares (RLS) equalizers. Interference and noise cancellation algorithms are also discussed.

Chapter 13 provides a detailed study of the spread spectrum communications focusing on direct-sequence spread-spectrum (DSSS), frequency-hopping spread-spectrum (FHSS), and time-hopping spread-spectrum (THSS). The link geometry and link margins are characterized for anti-jam (AJ) and low probability of intercept (LPI) communications. The probability of detecting and intercepting spread-spectrum waveforms is examined for various interceptor detection algorithms. The communicator's performance with intentional jamming is evaluated under the following conditions: BPSK and QPSK with a continuous wave (CW) jammer; *M*-ary FSK and DC-MPSK with partial band noise jammers; and FHSS with multitone jammers. A simplified analytical computation of the upper bound on the bit-error performance with various modulations and jammers is outlined. The chapter concludes with a case study of a terrestrial jammer encounter using the Longley–Rice irregular terrain model (ITM).

Chapter 14 describes various acceptance and rejection procedures suitable for modem pre- and postproduction testing. Modem subsystem modeling and Monte Carlo simulation techniques are also described leading to the bit-error performance evaluation through various types of channels. The chapter concludes with the description of the bit-error performance evaluation using quadrature integration. Several case studies are provided to demonstrate the methodology and utility of the evaluation procedures.

Chapter 15 describes the link budget analysis using the communication range equation. This is an essential chapter that outlines fundamental system requirements and related analysis that must be established prior to a detailed subsystem design. The link budget essentially establishes the cost-effective subsystem conditions to ensure that the signal-to-noise ratio at the receiver input is sufficient for reliable communications under the specified channel condition. The chapter highlights the important topics involving high-power amplifier (HPA) nonlinearities, transmitter and antenna effective isotropic radiated power (EIRP), receiver antenna gain-temperature ratio (G/T), receiver noise figure, antenna polarization, system phase noise, and channel rain losses.

Chapter 16 analyzes various satellite orbits focusing on the link range and signal dynamics. The results correspond to terrestrial or airborne satellite links and satellite cross-links and are used in establishing a satellite link budget as discussed in Chapter 15.

Chapter 17 discusses the transmission information through a bandlimited time-invariant channel. The channel response to an input data symbol is examined in terms of the channel amplitude and phase functions. This analysis forms the bases for evaluating the performance of baseband PCM modulated waveforms using wireline medium.

Chapter 18 discusses communicating through a Ricean fading channel characterized in terms of the specular-to-random power ratio with limits corresponding to the Rayleigh and Gaussian channel models. The bit-error performance of fast and slowing nonselective fading channels is examined for coherent BPSK, differentially coherent BPSK, and noncoherent BFSK waveform modulations. The relationship between the channel coherence time and bandwidth is, respectively, associated with Doppler spread and time dispersion. The channel concludes with a discussion to diversity combining techniques to mitigate the loss associated with fading channels. This material is considered to be a prerequisite for the material in Chapters 19 and 20.

Chapter 19 discusses various aspects of atmospheric propagation using the spherical 4/3 effective Earth radius model. The topics discussed include line of sight (LOS) propagation, reflection from the Earth's surface, tropospheric and ionospheric refraction, and diffraction. Several propagation loss models are characterized for urban, suburban, rural environments with applications to land mobile and satellite communications. The chapter concludes with the characterization of communication links involving impulsive noise induced by lightning strikes, ocean wind-waves, and dispersion of optical pulses through clouds.

Chapter 20 discusses various aspects of ionospheric propagation beginning with the characterization of electron densities in the natural and nuclear-disturbed environments. The refractive index is characterized in terms of the magnetic field strength and electron collisions from which the signal absorption and phase functions are established. Signal fading is characterized in terms of the scintillation index and the Rytov parameter. The dependence of the signal-decorrelation time and the frequency-selective bandwidth on the carrier frequency is also identified. A methodology is described for seamlessly concatenating an unlimited number of fading channel temporal FFT generated records to facilitate accurate Monte Carlo performance simulations in a stressed environment. Based on the electron density profiles, the Rayleigh channel fading model corresponding to severe signal scintillation is used to evaluate the link performance using several robust waveform modulations. Monte Carlo simulations are used to compare the performance of DEPSK, DCBPSK, and 8-ary FSK modulations with and without FEC coding in the slow Rayleigh fading channel. The simulated performance of interleaved RSV coded DCBPSK and DCQPSK is also examined over the range of fast to slow Rayleigh fading regimes.

The book concludes with three appendices:

Appendix A discusses the following classical analog filters: Butterworth, Chebyshev, Bessel, and Elliptic. The filter functions are implemented as digital filters and used in several chapters and case studies.

Appendix B is a brief discussion of the design and implementation of digital filters. The filter functions are used in several chapters and case studies.

Appendix C discusses the theoretical detection and false-alarm probabilities of signals in noise under a variety of conditions are examined, including coherent and noncoherent detection using single and multiple pulse integration with and without fading. The results are based on the classical radar related work of J.I. Marcum and P. Swerling and are selectively applied principally to the detection and acquisition of communication waveforms.

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2. A.J. Viterbi, *CDMA Principles of Spread Spectrum Communications*, Addison-Wesley Publishing Company, Reading, MA, 1995, Seventh Printing 1998.

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SUMMARY OF NOTATIONS

Notation	Description
T	Modulation symbol duration[†] ($= 1/R_s$)
T_b	Information bit duration ($= 1/R_b$)
Tx	Transmitter subsystem
Rx	Receiver subsystem
N_o	One-sided white noise spectral density
$=$	Equal
$\cong$	Approximately equal
$\neq$	Not equal
$\sim$	Asymptotically equal
$<, >; \leq, \geq$	Inequality; inclusion
o.w.	Otherwise all values not indicated
$\rightarrow$	Approaches in the limit
$\forall$	For all
$\triangleq$	Definition
$\Rightarrow$	Implies
$\Leftrightarrow$	Transform pair
$1/ab$	Inline division: $1 \div ab$
$\lfloor x \rfloor$	Floor: greatest integer $\leq x$
$\lceil x \rceil$	Ceiling: smallest integer $\geq x$
$(x_{t1}, \ldots, x_{tn})$	Finite time sequence of elements x_t
$\{x_1, \ldots, x_n\}$	Finite set of elements x
$\langle x(t) \rangle$	Time average
$\Sigma_i' x_i$	Summation over all i except $i = 0$
$[x]$, $int(x)$	Integer value of x

Notation	Description
$[x]_n$, $nint(x)$	Nearest integer to x computed as: $[x+.5]$: $x > 0$ and $[x-.5]$; $x \leq 0$
$\binom{m}{n}$, ${}_mC_n$	Binomial coefficient
$[A]^T$	Matrix transpose
$[A]^*$	Matrix conjugation
$[A]^+$	Matrix complex conjugate transpose
$\lvert A \rvert$, $\lvert A \rvert_{det}$	Determinate of matrix
δ_{ij}	Kronecker delta function: $\delta_{ij} = 1$: $i = j$; *o.w.* $\delta_{ij} = 0$
$\delta(t)$	Delta function: $\int_{-\infty}^{\infty} \delta(t)dt = 1$
$sinc(fT)$	$\sin(\pi fT)/\pi fT$
$rect(t/T) = 1 : \lvert t \rvert \leq T/2$; $= 0$ o.w.	
$rect_T(t/T,n)$	$rect((t - nT)/T)$[‡]
$Sign(a,x) = a$: $x \geq 0$; $= -a$: *o.w.*	
$N(m,\sigma)$	Gaussian (normal) distributed random variable
$E[x]$	Statistical average (expectation)
pdf	Probability density function
pmf	Probability mass function
cdf	Cumulative distribution function
iid	Independently and identically distributed
id	Identically distributed
iff	If and only if

[†]Almost exclusively used as the symbol duration.
[‡]Repetition notation for P.M. Woodward's $rect(t/T)$ function.

ABOUT THE COVER

The three-dimensional plot on the cover depicts the bit-error performance as a function of the number of rows and columns of a deterministic block interleaver and deinterleaver operating in a Rayleigh fading channel. The plot corresponds to a signal-to-noise ratio of $E_b/N_o = 6.5$ dB and is generated using a Monte Carlo simulation with 10 M bits at each row–column combination. The source data bits are coded using a rate 1/2, constraint length 7, convolutional encoder and are decoded using the Viterbi algorithm with a trellis depth or memory of 31 coded bits. The coded bits are sequentially entered into the interleaver row by row and removed column by column and applied to a binary phase shift keying (BPSK) symbol modulator. The channel is modeled as a correlated Gaussian random process with the correlation coefficient selected to result in a decorrelation time corresponding to six coded bits. In the region of the plot corresponding to the lowest bit-error performance, the loss in E_b/N_o at $P_{be} = 10^{-5}$ compared to the additive white Gaussian noise channel is 2.7 dB. Based on these conditions and results, a reasonably sized (row,column) block interleaver is (11,51).