Practical Digital Wireless Signals

Do you need to know what signal type to select for a wireless application? Quickly develop a useful expertise in digital modulation with this practical guide, based on the author's industry experience of more than 30 years. You will understand the physical meaning behind the mathematics of wireless signals and learn the intricacies and trade-offs in signal selection and design.

Key features:

- Six modulation families and 12 modulation types are covered in depth
- A quantitative ranking of relative cost incurred to implement any of 12 different modulation types
- Extensive discussions of the Shannon Limit, Nyquist filtering, efficiency measures, and signal-to-noise measures
- Radio wave propagation and antennas, multiple access techniques, and signal coding principles are all covered
- Spread spectrum and wireless system operation requirements are presented.

Earl McCune is a practicing engineer and Silicon Valley entrepreneur. A graduate of UC Berkeley, Stanford University, and UC Davis, he has over 30 years of post-graduate industry experience in wireless communications circuits and systems. Now semi-retired, he has founded two successful start-up companies, each of them winning industrial awards for their technical innovation.

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Dedicated to the memory of my father
Earl McCune Sr.
for instilling in me the great value of intuitive understanding of technical fundamentals

Contents

Preface

Wireless communications is rapidly becoming one of the ubiquitous technological underpinnings of modern society (such as electric power, fossil fuels, automobiles, etc.). Few people think about the technology within their mobile phones, remote controls, garage door openers, GPS navigation devices, and so on. These devices are always at hand and reliably work for the user.

Yet even within the electrical engineering (EE) community, radio communication techniques have a reputation as a “Black Art” that can only be successfully practiced by “RF people”. This is changing, albeit slowly. Any significant progress in successfully opening this vital technology widely to more practitioners must remove this “Black Art” stigma. In my opinion this is best achieved through outreach from existing successful “RF people”. This outreach must occur through many channels, such as this book and new courses in both academic and industrial training.

Today it takes many years to train communications engineers in the intricacies of wireless signal modulation tradeoffs. I am a product of this decades-long process. Much of this difficulty, for me anyway, is a consequence of the mathematical approach taken to all modulation training. The objective of this book is to begin to add a comprehensive yet physical approach alongside this traditional modulation training.

The contents of this book are drawn from the nearly 40 years of experience I have with radio communication technology. Being much more of a physics-based person instead of a mathematician, to build my own understanding of this material over these decades I have put in a lot of effort to get through the mathematics and into also understanding the underlying physical relationships. Through these pages I can share my results with you.

One major premise of this book comes from advice I received from my father as I began learning electronics: “Don’t memorize equations to learn the material. Instead, carefully learn the fundamental principles. Then as you need an equation, if it is not memorized it can be quickly derived on the spot.” He lived by this rule, and it has definitely served me very well over the years. And now in the age where computers do much of the math anyway, it is vital to be able to check any computer output for reasonableness. A surprising output may be the result of a programming error which can be quickly fixed to avoid embarrassment. Then again, it may be a clue to a significant technology contribution. The difference can only be known if fundamental physical principles are well understood.

The presentation order within this book is carefully planned so that material needed to understand the topic at hand has been presented previously as much as possible. Cross references to important sections are included to facilitate connections to supporting material.

In this approach, mathematics is a tool for later illustration instead of the primary window through which to view and learn the material. Certainly, for those readers who wish to delve more deeply into the theory of any topic, a suggested list for further reading into the excellent theoretic literature is provided at the end of each chapter.

Unique contributions in this book include:

- Detailed discussion on the consequences of the Shannon capacity, showing how this limit impacts bandwidth efficiency, transmitter power, and signal design.
- Introduction of a channel utilization factor U in Shannon's capacity equation, showing how system performance is affected when operation at the theoretical capacity is not attempted.
- A completely non-mathematical presentation on principles of coding for improved bandwidth efficiency (compression), for error control, and for spectral shaping and link control. This presentation includes examples of how the error correction process works when decoding convolutional codes.
- Clarification of the difference between signal-to-noise ratio and IBEND (also called E_b/N_0).
- Clarification of the difference between power efficiency and energy efficiency.
- Quantification of six different measures of energy efficiency.
- Details on the Generalized Nyquist Filter Construction (GNFC) technique, showing that the widely used spectral raised-cosine filter can be greatly improved.
- Resolution of the perceived ambiguity between "diplexer" and "duplexer" – these are very different.
- Introduction of a family of "maximally smooth" pulses/windows at their endpoints: the Derivative Zeroed pulses.
- Using the superposition lowpass filter (SLPF) to greatly reduce transmitter hardware and also eliminate the $x/\sin x$ corrector for conventional Nyquist filtering.
- Demodulation principles, listed separately for all modulation types.
- Complete description for FSK modulation index h for two normalizations: fixed frequency spacing, and fixed total deviation.
- Modified Carson's Rule for estimating the bandwidth of FSK signals "60 dB down".
- The first physical explanation I have ever seen for the FM threshold effect.
- Clarification of the difference between pure PSK, a constant envelope signal, and conventional PSK which really is a special case of QAM.
- Clarification that CPM is really a FSK, and is not a PSK.
- Presentation of OFDM-signal principles without using the inverse Fourier Transform – why the Fourier transform technique works for OFDM is derived later.
- Explanation of why, physically, matched filters work so well.
- Introduction of the Keep-it-Simple (KIS) technique of signal modulation selection.
- Quantified comparison among 12 digital modulation types to illustrate their relative costs of implementation.

This book is aimed at practitioners in industry who may be new to digital communications via radio. It assumes a basic familiarity with radio concepts, so it is not a tutorial in general radio technology. This book can be used as a supplementary reference for university and graduate study. Any architect of communications features in products will find this very useful – particularly if they are new to digital radio.

Basic familiarity with analog modulation for AM, FM, and PM is covered in tutorial Appendix C, to provide an internal reference to the important topics drawn from for digital modulations.

A *completely non-mathematical* discussion of signal and information coding is in Chapter 10. This chapter was a challenge because while coding is widely used and of vital importance to modern digital communications, its successful implementation requires intensive mathematical understanding. Yet to understand what coding is and why it works it is not necessary to use mathematics at all. For those needing to get into implementation details of coding a bibliography is presented for further study at the end of Chapter 10.

Saving the best for last, I wish to particularly acknowledge the tremendous help of Dr. Dietmar Wenzel in editing this manuscript, and to Professors Khaled Abdel-Ghaffar and Zhi Ding from the University of California Davis in helping work out the non-mathematical treatment of coding principles. Dr. Floyd M. Gardner remains a long-time inspiration and a particular guide for the ideas of Section 3.1 on consequences from Shannon's limit. The help of David Huynh, Dave Jackson, and Javier Castelblanco from Agilent Technologies in making the many measurements in Appendix G made that part possible.

Special thanks go to series editor Steve Cripps, who made it very clear to me that this book should be written NOW.

And the tolerance of my wife Barbara to the seemingly endless hours spent writing, drawing, rewriting, and editing needed for the preparation of this book is beyond measure. My gratitude to you is boundless!

I fervently hope that all who read this book, and who may use it as an additional reference, will enjoy this approach as much as I have enjoyed writing it.

Earl McCune

Definitions and acronyms

Term	Definition
Filter	a signal processing operation where the domain of the input and output signals is unchanged
Transform	a signal processing operation where the domain of the input and output signals is changed
Signal Circle	the circle of unit radius in the *I*-*Q* plane, containing all possible constellation points

Acronym	Meaning
ACK	acknowledgement
ACP	adjacent-channel power
ACPR	adjacent-channel power ratio
ADC	analog-to-digital converter
AGC	automatic gain control
AltCP	alternate channel power
AM	amplitude modulation
ARQ	automatic repeat request
ASK	amplitude-shift keying
BASK	binary amplitude-shift keying
BER	bit error rate
BFSK	binary frequency-shift keying
BH3	Blackman–Harris 3-term pulse (window)
bps	bits per second
B-PSD	bounded power spectral density
BPSK	binary phase-shift keying
BW	bandwidth
CCC	cubic congruence codes
CCDF	complementary cumulative density function
CCK	complementary code keying
CDF	cumulative distribution function
CDM	code-division multiplexing
CDMA	code-division multiple access
CE	constant envelope

CMOS	complementary metal-oxide-semiconductor
CNR	carrier-to-noise ratio
CORDIC	coordinated-rotation digital computer (algorithm)
cp	cyclic prefix
CP	continuous phase
CPFSK	continuous-phase frequency-shift keying
CPM	continuous-phase modulation
cPSK	conventional PSK
CRC	cyclic redundancy check
CSMA	carrier-sense multiple access
CTS	clear to send
DAC	digital-to-analog converter
dB	decibel
dBc	decibels relative to carrier (total signal) power
DC	direct current
DDFS	direct digital frequency synthesis
DDS	direct digital synthesizer
DFF	D type flip-flop
DFT	discrete Fourier Transform
DLL	delay-locked loop
DMT	discrete multi-tone
D-PSK	differential phase-shift keying
DS	direct sequence
DSB	double sideband
DSP	digital signal processing
DSSS	direct-sequence spread spectrum
DWC	digital wireless communication
DZEn	derivative-zeroed even pulse (window) of order n
DZn	derivative-zeroed pulse (window) of order n
EC	error correction
ECC	error-correction code
ED	error detection
EDGE	enhanced data rates for GSM evolution
EDR	envelope dynamic range
EIRP	effective isotropic radiated power
EM	electromagnetic
ENB	equivalent noise bandwidth
ENSB	equivalent noise signal bandwidth
EV	envelope varying
EVM	error-vector magnitude
EVP	error-vector phase
FD	full-duplex
FDM	frequency division multiplexing

FDMA	frequency division multiple access
FEC	forward error correction
FET	field effect transistor
FFH	fast frequency hopping
FFT	fast Fourier Transform
FH	frequency hopping
FHSS	frequency-hopping spread spectrum
FIBP	fractional in-band power
FIR	finite impulse response
FLL	frequency-lock loop
FM	frequency modulation
FOOB	fractional out-of-band power
FR	full response
FSK	frequency-shift keying
FUR	Fourier uncertainty relation
GFSK	Gaussian-filtered frequency-shift keying
GHz	gigahertz (billion cycles per second)
GLPF	Gaussian lowpass filter
GMSK	Gaussian-filtered minimum shift keying
GNFC	generalized Nyquist filter construction
GPRS	general packet radio service
GSM	global system of mobile communication
HD	half-duplex
I	in-phase axis; in-phase signal component
IBEND	Information-Bit-Energy-to-Noise Density ratio
IEEE	Institute of Electrical and Electronic Engineers ™
IIR	infinite impulse response
ISI	inter-symbol interference
ISR	interference-to-signal ratio
kHz	kilohertz (thousand cycles per second)
KIS	keep-it-simple
LFSR	linear feedback shift register
LO	local oscillator
LOS	line of sight
LPF	lowpass filter
LTE	long-term evolution of the third generation cellular network
M	signal order, number of available signal states
MA	multiple access
MAI	multiple access interference
M-ASK	M-ary amplitude-shift keying
M-FSK	M-ary frequency-shift keying
MHz	megahertz (million cycles per second)
MIMO	multiple-input multiple-output

M-PSK	M-ary phase-shift keying
MSK	minimum-shift keying
NACK	not acknowledged
NBFM	narrowband frequency modulation
NBPM	narrowband phase modulation
NFI	near-far interference
NLOS	non line of sight
OB	occupied bandwidth
OBO	output backoff
OFDM	orthogonal frequency division multiplexing, or orthogonal frequency division modulation (preferred)
O-FDMA	orthogonal frequency division multiple access
OOB	out of band
OOK	on-off keying
O-PSK	offset phase-shift keying
PA	power amplifier
PAE	power-added efficiency
PAM	pulse amplitude modulation
PAN	personal area network
PAPR	peak-to-average power ratio
PD	phase detector
pdf	probability density function
PDF	envelope probability density function
PDMA	polarization division multiple access
PFD	phase-frequency detector
PG	process gain
PLL	phaselock loop
PM	phase modulation
ppm	part per million
pPSK	pure PSK
PR	partial response
PRN	pseudo-random number
PSD	power spectral density
PSK	phase-shift keying
Q	quadrature axis; quadrature signal component
QAM	quadrature amplitude modulation
QCC	quadratic congruence codes
QD	quadrature demodulator
QM	quadrature modulator
QPSK	quaternary phase-shift keying
RBW	resolution bandwidth
RF	radio frequency
RKE	remote keyless entry

RLL	run-length limited
RSC	recursive systematic convolutional (encoder)
RSSI	received signal-strength indication
RTS	request to send
RX	receiver
SAR	specific absorption rate
SC	suppressed carrier
SC-FDMA	single carrier frequency division multiple access
SFH	slow frequency hopping
SLPF	superposition lowpass filter
SNR	signal-to-noise ratio
Sps	symbols per second
SRC	spectral raised cosine
SRRC	spectral square-root raised cosine
SS	spread spectrum
SSQAM	step-square quadrature amplitude modulation
TDM	time division multiplexing
TDMA	time division multiple access
TETRA	TErresTrial RAdio, a TDMA network designed for public service applications
tQAM	triangular arrangement of QAM constellation points
TSAD	time-shift angle demodulator
TX	transmitter
TXP	transmitter power
UHF	ultra high frequency (300–3000 MHz)
UMTS	universal mobile telephone service
VCO	voltage-controlled oscillator
VHF	very high frequency (30–300 MHz)
WBFM	wideband frequency modulation
W-CDMA	wideband code division multiple access
WLAN	wireless local area network

Terminology and notation

There are two conventions followed in the use of terminology within this book. They are:

1. Terms and ratios in linear units are in lower case letters
2. Terms and ratios in logarithmic (dB) units are in UPPER CASE letters

One of the tendencies I have noted in the literature is that this separation is rarely applied. This forces a reader to infer what an author is trying to convey from either the wider context of the writing, or from long contemplation after finishing reading in order to discern the author's intent. Both of these are causes for ambiguity, and at a minimum are opportunities for misunderstanding. In any work that is trying to teach principles and concepts this is certainly bad.

I have tried to contribute toward adding clarity by following these two conventions. This means that within each discussion if needed I have invented a lower case or upper case term as appropriate. While a reader who goes directly to a particular chapter in this book and does not read this page might think that the unconventional notation may be a typographical error, I can assure you that this is very deliberate on my part.

I hope that these conventions actually do contribute to additional clarity in the understanding of wireless communications signals.

List of terms new in this book

BW_{FSK}	modified Carson's Rule result for estimating FSK signal bandwidth, with units of frequency. (This does not follow the convention: capitalized BW is the traditional acronym for bandwidth.)
cp	cyclic prefix factor, value is between 0 and 1
cPSK	conventional PSK, a QAM signal with envelope variations where the signal constellation is restricted to points on the unit circle
edr	envelope dynamic range, the ratio of peak signal amplitude over minimum signal amplitude
EDR	decibel conversion of edr
γ	B/C, the inverse of channel capacity density
ibend	individual bit energy to noise density ratio, a descriptive name for E_b/N_0
IBEND	decibel conversion of ibend
papr	peak to average power ratio
PAPR	decibel conversion of papr

pPSK	pure PSK, a constant envelope signal modulated solely in phase
snr	direct ratio of signal power over noise power in a specified bandwidth
SNR	decibel conversion of snr
U	channel capacity utilization factor, value is between 0 and 1
ψ_{PE}	power efficiency, one property of a signal constellation