MEHMET ŞAFAK

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Preface

Telecommunications is a rapidly evolving area of electrical engineering, encompassing diverse areas of applications, including RF communications, radar systems, ad-hoc networks, sensor networks, optical communications, radioastronomy, and so on. Therefore, a solid background is needed on numerous topics of electrical engineering, including calculus, antennas, wave propagation, signals and systems, random variables and stochastic processes and digital signal processing. In view of the above, the success in the telecommunications education depends on the background of the student in these topics and how these topics are covered in the curriculum. For example, the Fourier transform may not usually be taught in relation with time- and frequency-response of the systems. Similarly, concepts of probabiliy may not be related to random signals. On the other hand, students studying telecommunications may not be expected to know the details of the Maxwell's equations and wave propagation. However, in view of the fact that wireless communication systems comprise transmit/receive antennas and a propagation medium, it is necessary to have a clear understanding of the radiation by the transmit antenna, propagation of electromagnetic waves in the considered channel and the reception of electromagnetic waves by the receive antenna. Otherwise, the students may face difficulties in understanding the telecommunications process in the physical layer.

The engineering education requires a careful tradeoff between the rigour provided by the theory and the simple exposure of the corresponding physical phenomena and their applications in our daily life. Therefore, the book aims to help the students to understand the basic principles and to apply them. Basic principles and analytical tools are provided for the design of communication systems, illustrated with examples, and supported by graphical illustrations.

The book is designed to meet the needs of electrical engineering students at undergraduate and graduate levels, and those of researchers and practicing engineers. Though the book is on digital communications, many concepts and approaches presented in the book are also applicable for analog communication systems. The students are assumed to have basic knowledge of Maxwell's equations, calculus, matrix theory, probability and stochastic processes, signals and systems and digital signal processing. Mathematical tools required for understanding some topics are incorporated in the relevant chapters or are presented in the appendices. Each chapter contains graphical illustrations, figures, examples, references, and problems for better understanding the exposed concepts.

Chapter 1 Signal Analysis summarizes the time-frequency relationship and basic concepts of Fourier transform for deterministic and random signals used in the linear systems. The aim was to provide a handy reference and to avoid repeating the same basic concepts in the subsequent chapters. *Chapter 2 Antennas* presents the fundamentals of the antenna theory with emphasis on the telecommunication aspects rather than on the Maxwell's equations. *Chapter 3 Channel Modeling* presents the propagation processes following the conversion of the electrical signals in the transmitter into electromagnetic waves by the transmit antenna until they are reconverted into electrical signals by the receive antenna. *Chapter 4 System Noise* is mainly based on the standards for determining the receiver noise of internal and external origin and provides tools for calculating SNR at the receiver output; the SNR is known to be the figure-of-merit of communication systems since it determines the system performance. Chapters 2, 3 and 4 thus relate the wireless interaction between transmitter and receiver in the physical layer. It may be worth mentioning that, unlike many books on wireless communications, covering only VHF and UHF bands, Chapters 2, 3 and 4 extend the coverage of antennas, receiver noise and channel modeling to SHF and EHF bands. A thorough understanding of the materials provided in these chapters is believed to be critical for deeper understanding of the rest of the book. These three chapters are believed to close the gap between the approaches usually followed by books on antennas and RF propagation, based on the Maxwell's equations, and the books on digital communications, based on statistical theory of communications. One of the aims of the book is to help the students to fuse these two complementary approaches.

The following chapters are dedicated to statistical theory of digital communications. *Chapter 4 Pulse Modulation* treats the conversion of analog signals into digital for digital communication systems. Sampling, quantization and encoding tradeoffs are presented, line codes used for pulse transmission are related to the transmission bandwidth. Time division multiplexing (TDM) allows multiple digital signals to be transmitted as a single signal. At the receiver they are reconverted into analog for the end user. PCM and other pulse modulations as well as audio and video coding techniques are also presented. *Chapter 5 Baseband Modulation* focuses on the optimal reception of pulse modulated signals and intersymbol interference (ISI) between pulses, due to filtering so as to limit the transmission bandwidth or to minimize the received noise power. In an AWGN channel, the optimum receiver maximizes the output SNR by matching the receive filter characteristics to those of the transmitter. The optimal choice of pulse shape, for example, Nyquist, raised-cosine, or correlative-level coding (partial-response signaling) is also presented in order to mitigate the ISI. *Chapter 7 Optimum Receiver in AWGN Channels* is focused on the geometric representation of the signals so as to be able to identify the two functionalities (demodulation and detection) of an optimum receiver. Based on this approach, derivation of the bit error probability (BEP) is presented and upper bounds are provided when the BEP can not be obtained exactly. *Chapter 8 Passband Modulation Techniques* starts with the definition of bandwidth and the bandwidth efficiency, followed by the synchronization (in frequency, phase and symbol timing) between transmitted and received symbols. The PSD, bandwidth and power efficiencies and bit/symbol error probabilities are derived for M-ary coherent, differentially coherent and noncoherent modulations, for example, M-ary PSK, M-ary ASK, M-ary FSK, M-ary QAM and M-ary DPSK. This chapter also provides a comparasion of spectrum and power efficiencies of the above-cited passband modulation techniques. *Chapter 9 Error Control Coding* presents the principles of channel coding in order to control (detect and/or correct) Gaussian (random) and burst errors occuring in the channel due to noise, fading, shadowing and other potential sources of interference. Source coding is not addressed in the book. Channel coding usually comes at the expense of increased transmission rate, hence wider transmission bandwidth, due to the inclusion of additional (parity check) bits among the data bits. Use of parity check bits reduces energy per channel bits and hence leads to higher channel BEP. However, a good code is expected to correct more errors than it creates and the overall coded BEP decreases at the expense of increased transmission bandwidth. This tradeoff between the BEP and the transmission bandwidth is well-known in the coding theory. As shown by the Shannon capacity theorem, one can achieve error-free communications as the transmission bandwidth goes to infinity, that is, by using infinitely many parity check bits, as long as the ratio of the energy per bit to noise PSD (E_b/N_0) is higher than -1.6 dB. This chapter addresses block and convolutional codes which are capable of correcting random and burst-errors. Automatic-repeat request (ARQ) techniques based on error-detection codes and hybrid ARQ (HARQ) techniques exploiting codes which can both detect and correct channel bit errors are also presented. *Chapter 10 Broadband Transmission Techniques* is composed of mainly two sections, namely spread-spectrum (SS) and the orthogonal frequency division multiplexing (OFDM). SS and OFDM provide alternative approaches for transmission of multi-user signals over wide transmission bandwidths. In SS, spread multi-user signals are distinguished from each other by orthogonal codes, while, in OFDM, narrowband multi-user signals are transmitted with different orthogonal subcarriers. The chapter is focused on two versions of SS, namely the direct sequence (DS) SS and frequency-hopping (FH) SS. Intercarrier- and intersymbol-interference, channel estimation and synchronization, adaptive modulation and coding, peak-to-average power ratio, and multiple access in up- and down-links of OFDM systems are also presented. *Chapter 11 Fading Channels* accounts for the effects of multipath propagation and shadowing. Fading channels are usually characterized by delay and Doppler spread of the received signals. The fading may be slow or fast, frequency-flat or frequency-selective. If the receiver can not collect coherently all the incoming signal components spread in time and frequency, then the received signal power level will be decreased drastically, hence leading to sigificant performance losses. This chapter is focused on the principal approaches for the channel fading and shadowing, for example, Rayleigh, Rician, Nakagami, and log-normal. The effect of fading and shadowing on the BEP are presented. Resource allocation and scheduling in fading channels is also treated. *Chapter 12 Diversity and Combining Techniques* addresses the approaches to alleviate the degradation caused by fading and shadowing. This is achieved by providing the receiver with multiple, preferably independent, replicas (in time, frequency, space) of the transmitted signal, and combine these signals in various ways, for example, selection, equal-gain, maximal-ratio, square-law. The performance improvement provided by diversity and combining techniques is presented as a function of the correlation and power balance between the diversity branches. Transmit and receive diversity, pre-detection and post-detection combining of diversity branches and channel capacity in fading and shadowing channels are also addressed. In contrast with telecommunication systems with single-transmit and single receive antennas (i.e., the so-called single-input single-output (SISO) systems), Chapter 12 is also concerned with systems using multiple antennas at the receiver or the transmitter. The receive diversity systems with multiple receive antennas are also called as SIMO (single-input multiple-output). Similarly, the transmit diversity systems with multiple antennas at the transmitter are referred to as MISO (multiple-input single-output) systems. *Chapter 13 MIMO* (multiple-input multiple-output) Systems is concerned with telecommunication systems with multiple antennas both at the transmit and the receive sides. A MIMO system, equipped with N_t transmit and N_r receive antennas, can benefit an N_tN_r-fold antenna diversity (N_tN_r independent paths between transmitter and receiver). The MIMO channels is usually characterized by Wishart distribution, presented in Appendix E. The eigenvalues of random Wishart matrices determine the dominant characteristics of the MIMO channels, which may suffer correlation between the transmitted and/or received signals. This determines the number and the relative weights of the eigenmodes; water-filling algorithm can be used to equalize the transmit power or the data rate supported by each eignmode. Transmit antenna selection (TAS) implies the selection of one or a few of the multiple transmit antennas with highest instantaneous SNRs. TAS makes good use of the transmit diversity by dividing the transmit power only between the transmit antennas with highest instantaneous SNRs. MIMO systems enjoy full coordination between transmit and receive antennas. Consequently, by adjusting the complex antenna weights at the transmit- and receive-sides, the SNR at the output of a MIMO beamforming system can be maximized, hence minimizing the BEP. *Chapter 14 on Cooperative Communications* is based on dual-hop relaying with amplify-and-forward, detect-and-forward and coded cooperation protocols. The source-relay-destination link is modeled as a single link with an equivalent SNR, the relay with the highest equivalent SNR may be selected amongst a number of relays, and multiple antennas may be used at the source, at the relay and/or the destination. The source-destination link is usually selection- or maximal-ratio-combined with the source-relay-destination link. In coded cooperation, relaying and channel coding are simultaneously used to make better use of the cooperation.

The appendices are believed to provide convenient references, and useful background for better understanding of the relevant concepts. *Appendix A Vector Calculus in Spherical Coordinates* provides tools for conversion between spherical and polar coordinates required for Chapter 2 Antennas. *Appendix B Gaussian Q Function* is useful for determining the BEP of majority of modulation schemes. *Appendix C* presents a list of Fourier Transforms usually encountered in telecommunication applications. *Appendix D Mathematical Tools* presents series, integrals and functions used in the book, minimizing the need to resort to another mathematical handbook. *Appendix E Wishart Distribution* provides the necessary background for the Chapter 13 MIMO Systems. *Appendix F Probability and Random Variables* aims to help students with probabilistic concepts, widely used probability distributions and random processes.

Topics to be taught at undergraduate and graduate levels may be decided according to the priority of the instructor and the course contents. Some sections and/or chapters may be omitted or covered partially depending on the preferences of the instructor. However, it may not be easy to give a unique approach for specifying the curriculum.

During my career, I benefited from numerous excellent books, publications and Internet web pages. I would like to thank the authors of all sources who contributed for the accumulation of the knowledge reflected in this book. I would like to thank all my undergraduate and graduate students who, with their response to my teaching approaches, helped enormously for determining the contents and the coverage of the topics of this book. Valuable cooperation and help from Sandra Grayson, Preethi Belkese and Adalfin Jayasingh from John Wiley and Sons is highly appreciated.

Mehmet Şafak
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List of Abbreviations

ACK	acknowledgment
ADC	analog-to-digital conversion
ADM	adaptive delta modulation
AF	amplify and forward
AGC	automatic gain control
AJ	anti jamming
AMR	adaptive multi rate
AOA	angle of arrival
AOD	angle of departure
AOF	amount of fading
ARQ	automatic repeat request
ASK	amplitude shift keying
AT&T	American Telephone & Telegraph Company
AWGN	additive white Gaussian noise
BCH	Bose-Chaudhuri-Hocquenghem codes
BEP	bit error probability
BPSK	binary phase shift keying
BS	base station
BSC	binary symmetric channel
C/N	carrier-to-noise ratio
CCITT	International Telegraph and Telephone Consultative Committee
CD	compact disc
CDF	cumulative distribution function
CDMA	code division multiple access
CIR	channel impulse response
COST	European Cooperation for Scientific and Technical Research
CP	cyclic prefix
CPA	co-polar attenuation
CRC	cyclic redundancy check
CSI	channel state information
DAC	digital to analog conversion
DCT	discrete cosine transform
DF	detect and forward
DFT	discrete Fourier transform
DGPS	differential GPS
DM	delta modulation
DMC	discrete memoryless channel
DPCM	differential PCM
DPSK	differential phase shift keying
DS	direct sequence
DSSS	direct sequence spread spectrum
E1	European telephone multiplexing hierarchy
EGC	equal gain combining
EGNOS	European geostationary navigation overlay service
EHF	extremely high frequencies (30-300 GHz)
EIRP	effective isotropic radiative power
EP	elliptical polarization
ESD	energy spectral density

ETSI	European Telecommunications Standards Institute
FDM	frequency division multiplexing
FEC	forward error correction
FFT	fast Fourier transform
FH	frequency hopping
FHSS	frequency hopping spread spectrum
FIR	finite impulse response
FOM	figure of merit
FSK	frequency shift keying
FT	Fourier transform
G/T	figure of merit of a receiver (antenna gain to system noise temperature ratio)
GALILEO	European global navigation satellite system
GBN	go-back-N ARQ
GEO	geostationary
GLONASS	Russian global navigation satellite system
GNSS	global navigation satellite systems
GPS	global positioning system
GS	greedy scheduling
GSC	generalized selection combining
GSM	global system for mobile communications
H.264/AVC	advanced video coding
HARQ	hybrid ARQ
HDD	hard decision decoding
HDTV	high definition TV
HEVC	high efficiency video coding
HF	high frequencies (3-30 MHz)
HPA	high power amplifier
ICI	inter carrier interference
IDFT	inverse discrete Fourier transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	inverse fast Fourier transform
IMT-2000	international mobile telephone standard
IP	Internet protocol
ISI	inter symbol interference
ISM	industrial, scientific, and medical frequency band
ISU	international system of units
ITU	International Telecommunications Union
JPEG	joint photographic experts group
Ka-band	26.5-40 GHz band
Ku-band	12.4-18 GHz band
L band	1-2 GHz band
LAN	local area network
LDPC	low-density parity check codes
LEO	low Earth orbiting
LF	low frequencies (30-300 kHz)
LHCP	left hand circular polarization
LMS	least mean square
LNA	low noise amplifier
LORAN-C	radio navigation system by land based beacons
LOS	line of sight
LP	linear polarization
LPF	low pass filter
LPI	low probability of intercept
LTI	linear time invariant
MAC	multiple access
MAI	multiple access interference
MAP	maximum a posteriori
MEO	medium Earth orbit
MF	medium frequencies (300-3000 kHz)
MGF	moment generating function
MIMO	multiple-input multiple-output
MIP	multipath intensity profile
MISO	multiple-input single-output
ML	maximum likelihood
MLD	maximum likelihood detection
MPEG	motion photograpic experts group
MRC	maximal ratio combining
MS	mobile station
MUD	multiuser detection
MUI	multiuser interference
NACK	negative acknowledgment
NAVSTAR	NAVigation Satellite Timing And Ranging (GPS satellite network)
NFC	near field communications
NRZ	non return to zero
OC	optimum combining

OFDM	orthogonal frequency division multiplexing
OLC	optical lattice clock
OOK	on-off keying
OVSF	orthogonal variable spreading factor
PAL	phase alternating line
PAM	pulse amplitude modulation
PAPR	peak to average power ratio
PCM	pulse code modulation
PDF	probability density function
PDM	pulse duration modulation
PFS	proportionally fair scheduling
PLL	phase lock loop
PN	pseudo noise
PPM	pulse position modulation
PPS	precise positioning system
PRS	partial response signaling
PSD	power spectral density
PSK	phase shift keying
QAM	quadrature-amplitude modulation
QPSK	quadrature phase shift keying
RCPC	rate compatible punctured convolutional
RD	relay destination link
RFID	radio frequency identification
RGB	red green blue
RHCP	right hand circular polarization
RPE-LTP	regular pulse excited long term prediction
RR	round robin
RS	Reed-Solomon
RSC	recursive systematic convolutional
RZ	return to zero
SA	selective availability
SATCOM	satellite communications
SC	selection combining
SC-FDMA	single carrier frequency division multiple access
SDTV	standard definition TV
SF	spreading factor
SGT	satellite ground terminal
SHF	super high frequencies (3-30 gHz)
SIMO	single-input multiple-output
SINR	signal-to-interference and noise ratio
SIR	signal-to-interference ratio
SISO	single-input single-output
SLC	square-law combining
SNR	signal-to-noise ratio
SPS	standard positioning system
SR	source-relay link
SRD	source-relay-destination link
SRe	selective repeat ARQ
SS	spread spectrum
SSC	switch-and-stay combining
SW	stop-and-wait ARQ
T1	AT&T telephone multiplexing hierarchy
TAS	transmit antenna selection
TDM	time division multiplexing
TEC	total electron content
TPC	transmit power control
UHF	ultra high frequencies (300-3000 MHz)
ULA	uniform linear array
UMTS	universal mobile telecommunications system
UTC	universal coordinated time
VHF	very-high frequencies (30-300 MHz)
WAN	wide area networks
WCDMA	wideband code division multiple access (CDMA)
WiFi	wireless fidelity
WiMax	worldwide interoperability for microwave access
X-band	8.2-12.4 GHz band
XPD	cross polar discrimination
XPI	cross polar isolation

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