NETWORKS AND TELECOMMUNICATIONS SERIES

Digital Communications 2

Digital Modulations

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First published 2015 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

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John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

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Library of Congress Control Number: 2015946706

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-84821-846-8

Digital Communications 2

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Preface

Humans have always used communication systems: in the past, native Americans used clouds of smoke, then Chappe invented his telegraph and Edison the telephone, which has deeply changed our lifestyle. Nowadays, smartphones enable us to make calls, watch videos and communicate on social networks. The future will see the emergence of the connected man and wider applications of smart objects. All current and future communication systems rely on a digital communication chain that consists of a source and a destination separated by a transmission channel, which may be a portion of a cable, an optical fiber, a wireless mobile or satellite channel. Whichever the channel, the processing blocks implemented in the communication chain have the same basis. This book aims at detailing them, across two volumes:

– the first volume deals with source coding and channel coding. After a presentation of the fundamental results of information theory, the different lossless and lossly source coding techniques are studied. Then, error-correcting-codes (block codes, convolutional codes and concatenated codes) are theoretically detailed and their applications provided;

– the second volume concerns the blocks located after channel coding in the communication chain. It first presents baseband and sine waveform transmissions. Then, the different steps required at the receiver to perform detection, namely synchronization and channel estimation, are studied. Two variants of these blocks which are used in current and future systems, multicarrier modulations and coded modulations, are finally detailed.

This book arises from the long experience of its authors in both the business and academic sectors. The authors are in charge of several diploma and higher-education teaching modules at *Conservatoire national des arts et métiers* (CNAM) concerning digital communication, information theory and wireless mobile communications.

The different notions in this book are presented with an educational objective. The authors have tried to make the fundamental notions of digital communications as understandable and didactic as possible. Nevertheless, some more advanced techniques that are currently strong research topics but are not yet implemented are also developed.

Digital Communications may interest students in the fields of electronics, telecommunications, signal processing, etc., as well as engineering and corporate executives working in the same domains and wishing to update or complete their knowledge on the subject.

The authors would like to thank their colleagues from CNAM, and especially from the EASY department.

Mylène Pischella would like to thank her daughter Charlotte and husband Benjamin for their presence, affection and support.

Didier Le Ruyet would like to thank his parents and his wife Christine for their support, patience and encouragements during the writing of this book.

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Paris, France
August 2015

List of Acronyms

ADSL: assymetric digital subscriber line

ASK: amplitude shift keying

BER: bit error rate

CD: compact disc

CFM: constellation's figure of merit

CMT: cosine modulated multitone

DFE: decision feedback equalizer

DWMT: discrete wavelet multitone

EFM: eight-to-fourteen modulation

EGF: extended Gaussian function

FBMC: filter bank multicarrier

FDDI: fiber distributed data interface

FFT: fast Fourier transform

FIR: finite impulse response

FMT: filtered multi-tone

FSK: frequency shift keying

GMSK: Gaussian minimum shift keying

GSM: global system for mobile communications

HDMI: high-definition multimedia interface

IFFT: inverse fast Fourier transform

IIR: infinite impulse response

IOTA: isotropic orthogonal transform algorithm

MAP: maximum a posteriori

MIMO: multiple input, multiple output

ML: maximum likelihood

MLSE: maximum likelihood sequence estimator

MLT-3: multilevel transmit 3

MMSE: minimum mean square error

MSK: minimum shift keying

NRZ: non-return to zero

NRZI: non-return to zero inverted

OFDM: orthogonal frequency division multiple access

OQAM: offset quadrature amplitude modulation

PAPR: peak to average power ratio

PSK: phase shift keying

QAM: quadrature amplitude modulation

QPSK: quadrature phase shift keying

RFID: radio frequency identification

RLL: run length limited

RZ: return to zero

SCH: synchronization channel

SMT: staggered multitone

SNR: signal-to-noise ratio

VDSL: very-high-bit-rate digital subscriber line

ZF: zero forcing

ZF-DFE: zero-forcing decision feedback equalizer

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Notations

B: bandwidth

B_c: coherence bandwidth

$b(t)$: baseband additive white Gaussian noise

$c_k = a_k + jb_k$: baseband complex symbol, with a_k its real part and b_k its imaginary part

d_{min}: minimum distance

$E[x]$: expected value of a random variable x

E_b: average energy per bit

E_s: average energy per symbol

f_c: carrier frequency of narrowband passband signal

$g_c(t)$: impulse response of the transmit baseband channel

$g(t)$: transmit filter

$g_r(t)$: matched filter at the receiver

$\gamma_{xx}(f)$: power spectrum density of a random process x

$h(t)$: impulse response of the narrowband passband channel

$H(z)$: linear digital equalization filter

N: noise power,or number of samples in an OFDM or FBMC symbol

N_{CP}: number of samples in OFDM cyclic prefix

$n(t)$: noise filtered by the receive filter

N_0: one-sided noise power spectrum density

M: alphabet size of the modulation's constellation

P: signal power

P_e: error probability per symbol

p: probability of a random variable

$p(t) = g(t) * g_c(t) * g_r(t)$: complete equivalent channel

Ψ: phase of the passband signal

$R_{ss}(t)$: autocorrelation function of random process s

$r(t)$: output signal of narrowband passband channel

$s(t)$: input signal of narrowband passband channel

T: symbol period

T_b: transmission duration of a bit

T_m: maximum delay of the channel

T_N: transmission duration of an OFDM or FBMC symbol

$u(t)$: step function

$x(t)$: transmitted signal on the baseband channel

$\mathbf{y}$: received signal at channel's output after matched filter and sampling

$y(t)$: received baseband signal after matched filter

Introduction

The fundamental objective of a communication system is to reproduce at a destination point, either exactly or approximately, a message selected at another point. This was theorized by Claude Shannon in 1948 [SHA 48].

The communication chain is composed of a source (also called transmitter) and a destination (also called receiver). They are separated by a transmission channel, which may, for instance, be a wired cable if we consider assymetric digital subscriber line (ADSL) transmission, optical fiber, a wireless mobile channel between a base station and a mobile terminal or between a satellite and its receiver, a hard drive and so forth. The latter example indicates that when we refer to *point*, we may consider either location or time. The main issue faced by communication systems is that the channel is subject to additional noise, and may also introduce some distortions on the transmitted signal. Consequently, advanced techniques must be implemented in order to decrease the impact of noise and distortions on the performances as much as possible, so that the receiver signal may be as similar as possible to the transmitted signal.

The performance of a transmission system is evaluated by either computing or measuring the error probability per received information bit at the receiver, also called the bit error rate. The other major characteristics of a communication system are its complexity, its bandwidth, its consumed and transmitted power and the useful data rate that it can transmit. The bandwidth of many communication systems is limited; it is thus highly important to maximize the spectral efficiency, which is defined as the ratio between the binary data rate and the bandwidth. Nevertheless, this should be done without increasing the bit error rate.

This book consists of two volumes. It aims at detailing all steps of the communication chain, represented in Figure I.1. Source and channel coding are deeply studied in the first volume: *Digital Communications 1: Source and Channel Coding*. Even though both volumes can be read independently, we will sometimes refer to some of the notions developed in the first volume. The present volume focuses on the following blocks: modulation, synchronization and equalization. Once source and channel coding have been performed, data have first been compressed, and then encoded by adding some well-chosen redundancy that protects the transmitted bits from the channel's disruptions. In this second volume, we are first located at the modulator's input. The modulator takes the binary data at the output of the channel encoder in order to prepare them for transmission on the channel.

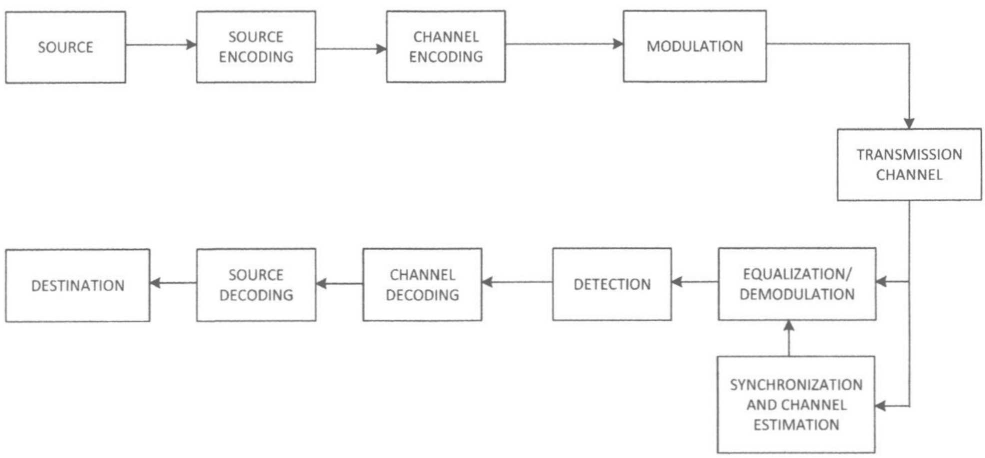

Figure I.1. *Block diagram of the communication chain*

The coded bits are then associated with symbols that will be transmitted during a given symbol period. They are shaped by a transmit filter before being sent on the channel. At the stage, transmission techniques vary, depending on whether baseband transmission (when the signal is carrier by the null frequency) or sine waveform transmission takes place. In the latter case, the frequency carrier is far larger than the bandwidth. In the former case, symbols are carried by the specific value of a line code; whereas in the latter case, they are carried by either the signal's amplitude, phase or carrier frequency value. Baseband transmissions are detailed in Chapter 2. Digital modulations on sine waveforms are studied in Chapter 3. Furthermore, advanced digital modulation techniques, called coded modulations, are presented in Chapter 6. They associate modulations and channel encoding in order to increase the spectral efficiency. Chapter 2 introduces some fundamental notions such as optimum detection on the additive white Gaussian noise channel, and Chapter 3 explains the connection between baseband transmissions and sine waveform transmissions. Modulations' performances are determined in terms of bit error rate depending on the signal-to-noise ratio and on the bandwidth.

The demodulator aims at extracting samples while maximizing a given criterion (signal-to-noise ratio, bit error rate, etc.). The detector's objective is to determine the most likely transmitted symbol. If channel decoding takes hard inputs, the detector directly provides the estimated binary sequence. If channel decoding takes soft inputs, then the detector provides soft information on bits, which generally are logarithms of likelihood ratio.

In order to have an efficient detection, the input samples should be as close as possible to the transmitted ones. Yet, the channel may generate distortions on the transmitted signal, as well as delays which may result in a loss of the symbol period, or frequency shifts. Demodulation and detection must consequently be preceded by a synchronization at the receiver with the transmitted signal in order to correct these shifts. Thus, if the channel has introduced distortions that lead to intersymbol interference, an equalization step must be added in order to estimate the transmitter symbols. These two steps are presented in Chapter 4. We can notice that synchronization may be blind, which means that it is performed without any channel knowledge, in which case its performances will be far lower than if synchronization is based on a training sequence. Similarly, equalization requires channel estimation, which must be implemented prior to these two steps.

In order not to use equalization at the receiver, most recent communication systems split the original wideband channel into several subchannels, where each subchannel only produces a constant signal attenuation but no distortion. This step modifies the modulation block and is thus located before transmission on the channel. Multi-carrier modulations are detailed in Chapter 5.

Finally, we can notice that some useful mathematics and digital signal processing background are provided in Chapter1.

The summary of the contributions of this book shows that we have tried to be as exhaustive as possible, while still studying a large spectrum of the digital communications domain. Some topics have not been considered due to lack of space. For instance, the wireless mobile channel's characteristics or the multiple-access techniques on this channel have not been mentioned, as well as multiple antenna *multiple input, multiple output* (MIMO) techniques. Moreover, we have only focused on the most modern techniques, only considering older techniques with an educational objective, when the latter allow us to better understand more complex modern techniques.

Most of the chapters detail fundamental notions of digital communications and are thus necessary to comprehend the whole communication chain. They provide several degrees of understanding by giving an introduction to these techniques, while still giving some more advanced details. In addition, they are illustrated by examples of implementations in current communications systems. Some exercises are proposed at the end of each chapter, so that the readers may take over the presented notions.

We can nevertheless notice that Chapter 6 proposes an opening to advanced modulation and coding techniques. It may be read as a complement in order to strengthen knowledge.

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