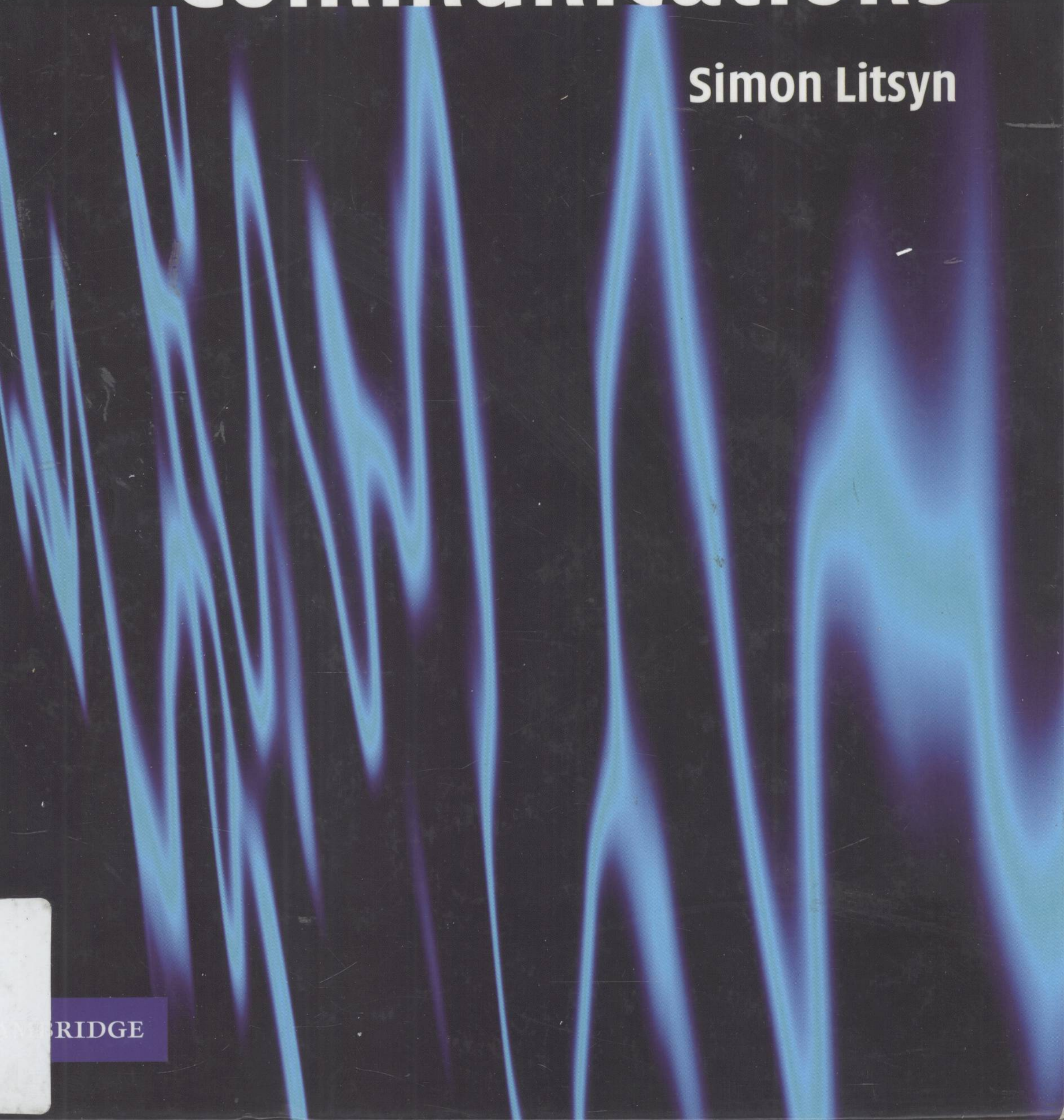
Peak Power Control in Multicarrier Communications



Simon Litsyn

BRIDGE

PEAK POWER CONTROL IN MULTICARRIER COMMUNICATIONS

SIMON LITSYN
School of Electrical Engineering, Tel Aviv University

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521855969

First published 2007

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

ISBN-13 978-0-521-85596-9 hardback
ISBN-10 0-521-85596-9 hardback

PEAK POWER CONTROL IN MULTICARRIER COMMUNICATIONS

The implementation of multicarrier (MC) modulation in wireless and wireline communication systems, such as OFDM and DMT, is restricted by peak signal power, due to a sensitivity of the technique to distortions introduced by nonlinear devices. By controlling the peak power, the negative influence of signals with high peaks on the performance of the transmission system is greatly reduced. This book describes the tools necessary for analyzing and controlling the peak-to-average power ratio in MC systems, and how these techniques are applied in practical designs. The author starts with an overview of MC signals and basic tools and algorithms, before discussing properties of MC signals in detail: discrete and continuous maxima; statistical distribution of peak power, and codes with constant peak-to-average power ratio are all covered, concluding with methods to decrease peak power in MC systems. Current knowledge, problems, methods, and definitions are summarized using rigorous mathematics, with an overview of tools for the engineer. This book is aimed at graduate students and researchers in electrical engineering, computer science, and applied mathematics, as well as practitioners in the telecommunications industry. Further information on this title is available at www.cambridge.org/9780521855969.

SIMON LITSYN received his Ph.D. in Electrical Engineering from the Leningrad Electrotechnical Institute in 1982. He is currently a professor in the Department of Electrical Engineering Systems at the Tel Aviv University, where he has been since 1991. From 2000 to 2003 he served as an Associate Editor for Coding Theory in the IEEE Transactions on Information Theory. His research interests include coding theory, communications, and applications of discrete mathematics. He is the author of more than 150 journal articles.

To the memory of my mother.

Abbreviations

ACE	active constellation extension
ACI	adjacent channel interference
ACPR	adjacent channel power ratio
ADC	analog-to-digital converter
AM/PM	amplitude modulation/phase modulation
BCH	Bose–Chaudhuri–Hocquenghem (codes)
BER	bit error rate
(B)PSK	(binary) phase-shift keying
BS	block scaling
CCDF	complementary cumulative distribution function
CDMA	code division multiple access
CF	crest factor
CS	codes of strength
DAB	digital audio broadcasting
DAC	digital-to-analog converter
DC	direct current
(I)DFT	(inverse) discrete Fourier transform
DMT	discrete multitone
(A/H)DSL	(asymmetric/high speed) digital subscriber line
DVB	digital video broadcasting
EVM	error vector magnitude
(I)FFT	(inverse) fast Fourier transform
GI	guard interval
HIPERLAN	high performance radio local area network
HPA	high-power amplifier
IBO/OBO	input/output back-off
ICI	inter-carrier interference
ISI	inter-symbol interference

LDPC	low-density parity-check (codes)
LPF	low-pass filter
MC	multicarrier
MIMO	multiple-input multiple-output
OFDM	orthgonal frequency division multiplexing
OFDMA	orthgonal frequency division multiple access
PAPR	peak-to-average power ratio
PMEPR	peak-to-mean envelope power ratio
(Q)PSK	(quadrature) phase-shift keying
PRC	peak reduction carriers
PTS	partial transmit sequences
QAM	quadrature amplitude modulation
RM	Reed–Muller (codes)
RP	random phasor
RS	Reed–Solomon (codes)
SER	symbol error rate
SI	side information
SLM	selective mapping
SL	soft limiter
SNR	signal-to-noise ratio
SSPA	solid-state power amplifier
TI	tone injection
TS	trellis shaping
TWTA	traveling-wave tube amplifier
UWB	ultra wide band
WLAN	wireless local area network
WMAN	wireless metropolitan area network
WPAN	wireless personal area network

Notation

$\mathbb{Z}$	integer numbers
$\mathbb{N}$	natural numbers
$\mathbb{R}$	real numbers
$\mathbb{C}$	complex numbers
$\mathbb{F}$	finite field
$\Re(\cdot)$	real part
$\Im(\cdot)$	imaginary part
$\imath$	$\sqrt{-1}$
a^*	complex conjugate of $a \in \mathbb{C}$
$\lvert a \rvert$	absolute value of $a \in \mathbb{C}$
$\arg(a)$	argument of a
$\mathbf{a}$	vector
$(\mathbf{a}, \mathbf{b})$	dot product of vectors **a** and **b**
$\lVert\mathbf{a}\rVert$	norm of **a**
A^t	transposed matrix A
E_{av}	average energy of constellation
$E_{\max}$	maximum energy of a constellation point
f_0	carrier frequency
f_{s}	tone bandwidth
$\mathcal{M}_{\mathrm{c}}$	continuous maximum
$\mathcal{M}_{\mathrm{d}}$	discrete maximum
g.c.d.	greatest common divisor
i.i.d.	independent identically distributed
p.d.f.	probability density function
p.s.d.	power spectral density
deg	degree of a polynomial
sinh	hyperbolic sine
cosh	hyperbolic cosine
sign	sign

Contents

Figures

1

Introduction

In the mountains the shortest way is from peak to peak, but for that route thou must have long legs.

F. Nietzsche, *Thus Spake Zarathustra*

Multicarrier (MC) modulations such as orthogonal frequency division multiplexing (OFDM) and discrete multitone (DMT) are efficient technologies for the implementation of wireless and wireline communication systems. Advantages of MC systems over single-carrier ones explain their broad acceptance for various telecommunication standards (e.g., ADSL, VDSL, DAB, DVB, WLAN, WMAN). Yet many more appearances are envisioned for MC technology in the standards to come. A relatively simple implementation is possible for MC systems. Low complexity is due to the use of fast discrete Fourier transform (DFT), avoiding complicated equalization algorithms. Efficient performance of MC modulation is especially vivid in channels with frequency selective fading and multipath. Nonetheless, still a major barrier for implementing MC schemes in low-cost applications is its nonconstant signal envelope, making the transmission sensitive to nonlinear devices in the communication path. Amplifiers and digital-to-analog converters distort the transmit signals leading to increased symbol error rates, spectral regrowth, and reduced power efficiency compared with single carrier systems. Naturally, the transmit signals should be restricted to those that do not cause the undesired distortions. A reasonable measure of the relevance of the signals is the ratio between the peak power values to their average power (PAPR). Thus the goal of peak power control is to diminish the influence of transmit signals with high PAPR on the performance of the transmission system. Alternatives are either the complete exclusion of such signals or an essential decrease in the probability of their appearance. Neither of these goals can be achieved without a decrease in the efficient transmission rate or performance penalty.

In this monograph I describe methods of analysis and control of peak power effects on the performance of MC communication systems. This includes analysis of statistical properties of peak distributions in MC signals, descriptions of MC signals with low peaks, and approaches to decreasing high peaks in transmitted signals. Consequently, the organization of the book is as follows. In Chapter 2, I provide general definitions related to MC communication systems and MC signals, and introduce the main definitions related to peaks of MC signals. This is followed by a description of nonlinearities in power amplifiers and their influence on the performance. In Chapter 3, necessary mathematical tools are described. This is necessary since the mathematical arsenal of the peak power control research consists of many seemingly unrelated methods. Among them are harmonic analysis, probability, algebra, combinatorics, and coding theory. In Chapter 4, I explain how the continuous problem of peak estimation can be reduced to the discrete problem of analysis of maxima in the sampled MC signal. Chapter 5 deals with statistical distribution of peaks in MC signals. It is shown that the peak distribution is concentrated around a typical value and the proportion of signals that are essentially different from the typical maximum of the absolute value is small. Chapter 6 extends the analysis of the previous chapter to MC signals defined by coded information. In Chapter 7, I describe methods to construct MC signals with much smaller peaks than is typical. Finally, in Chapter 8, I analyze approaches for decreasing peaks in MC signals. Several algorithms are introduced and compared. Notes in the end of each chapter provide historical comments and attribute the results appearing in the chapter.

Several related topics are not treated in this monograph. For peak power control in CDMA see, e.g., [43, 64, 118, 228, 230, 231, 285, 299, 300, 308, 309, 324, 325, 326, 363, 421, 422, 423, 445] and references therein. Peak power reduction in MIMO systems is discussed in, e.g., [1, 66, 67, 154, 234, 235, 241, 278, 338, 389, 395, 411, 456]. For analysis of peak power control in OFDMA see, e.g., [154, 315, 427, 453]. Aspects of peak power reduction in radar systems are considered in [55, 236, 237, 238, 279, 430]. Peak power control in optical signals is considered in [371, 375].

In the process of writing the book I enjoyed advice, ideas and assistance from many friends and collaborators. Their expertise was crucial in determining the best ways of presenting the material and avoiding wrong concepts and mistakes. Here is a definitely incomplete (alphabetical) list of colleagues without whose kind support this book would definitely not have been written: Idan Alrod, Ella Barzani, Gregory Freiman, Masoud Sharif, Eran Sharon, Alexander Shpunt, Dov Wulich, Gerhard Wunder, and Alexander Yudin.

I also wish to thank the staff and associates of Cambridge University Press for their valuable assistance with production of this book. In particular I am grateful to editorial manager Dr. Philip Meyler, assistant editors Ms. Emily Yossarian and Ms. Anna Littlewood, production editor Ms. Dawn Preston, and copy editor Dr. Alison Lees.

2

Multicarrier signals

In this chapter, I introduce the main issues we will deal with in the book. In Section 2.1, I describe a multicarrier (MC) communication system. I introduce the main stages that the signals undergo in MC systems and summarize advantages and drawbacks of this technology. Section 2.2 deals with formal definitions of the main notions related to peak power: peak-to-average power ratio, peak-to-mean envelope power ratio, and crest factor. In Section 2.3, I quantify the efficiency of power amplifiers and its dependence on the power of processed MC signals. Section 2.4 introduces nonlinear characteristics of power amplifiers and describes their influence on the performance of communication systems.

2.1 Model of multicarrier communication system

The basic concept behind multicarrier (MC) transmission is in dividing the available spectrum into subchannels, assigning a carrier to each of them, and distributing the information stream between subcarriers. Each carrier is modulated separately, and the superposition of the modulated signals is transmitted. Such a scheme has several benefits: if the subcarrier spacing is small enough, each subchannel exhibits a flat frequency response, thus making frequency-domain equalization easier. Each substream has a low bit rate, which means that the symbol has a considerable duration; this makes it less sensitive to impulse noise. When the number of subcarriers increases for properly chosen modulating functions, the spectrum approaches a rectangular shape. The multicarrier scheme shows a good modularity. For instance, the subcarriers exhibiting a disadvantageous *signal-to-noise ratio* (SNR) can be discarded. Moreover, it is possible to choose the constellation size (bit loading) and energy for each subcarrier, thus approaching the theoretical capacity of the channel.

Figure 2.1 presents the structure of a MC transmitter. Let n be the number of subcarriers in this system. The following processing stages are employed to derive the transmit signal. Redundancy defined by an error-correcting code is appended to

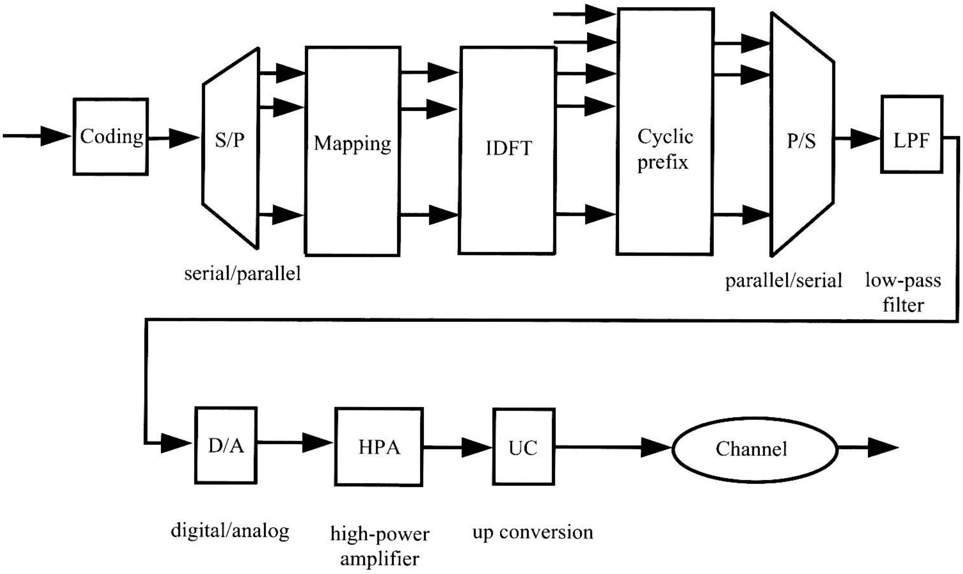


Figure 2.1 MC transmitter

the input information. The encoded data is converted to parallel form, and is mapped to n complex numbers defining points in the constellation used for modulation (e.g., QAM or PSK). These n complex numbers are inserted into an inverse discrete Fourier transform (IDFT) block, which outputs the time equidistributed samples of the baseband signal. The next block introduces a *guard interval* (GI) intended for diminishing the effect of the delay of the multipath propagation. The guard interval is usually implemented as a cyclic prefix (CP). Because of the CP, the transmit signal becomes periodic, and the effect of the time-dispersive multipath channel becomes equivalent to a cyclic convolution, discarding the GI at the receiver. Thus the effect of the multipath channel is limited to a pointwise multiplication of the transmitted data constellations by the channel transfer function, that is, the subcarriers remain orthogonal. Being converted back to the serial form, the samples are transformed by a low-pass filter (LPF) to give a continuous signal. This continuous signal is amplified by a high-power amplifier (HPA). Finally, if necessary, the baseband signal becomes passband by translation to a higher frequency. The reverse steps are performed by the receiver.

Implementation advantages of the MC communication system come from the simple structure of the DFT, which can be realized with a complexity proportional to $n \ln n$. Also, the equalization required for detecting the data constellations is an elementwise multiplication of the DFT output by the inverse of the estimated channel transfer function.

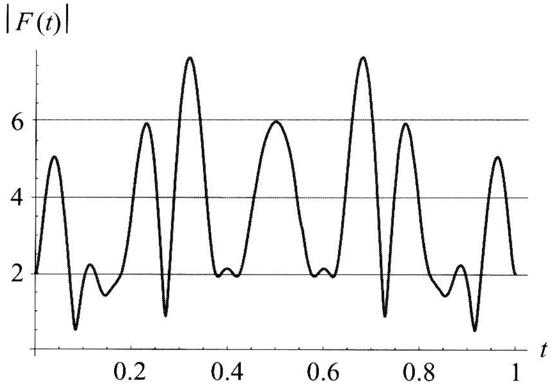


Figure 2.2 Envelope of a BPSK modulated MC signal for $n = 16$

However, several disadvantages arise with this concept, the most severe of which is the highly nonconstant envelope of the transmit signal (see Fig. 2.2), making MC modulation very sensitive to nonlinear components in the transmission path. A key component is the high-power amplifier (HPA). Owing to cost, design, and, most importantly, power efficiency considerations, the HPA cannot resolve the dynamics of the transmit signal and inevitably cuts off the signal at some point, causing additional in-band distortion and adjacent channel interference. The power efficiency penalty is certainly the major obstacle to implementing MC systems in low-cost applications. Moreover, in power-limited regimes determined by regulatory bodies, the average power is reduced in comparison to single-carrier systems, in turn reducing the range of transmission.

The main goal of peak power control is to diminish the influence of high peaks in transmit signals on the performance of the transmission system.

2.2 Peak power definitions

Let me give a more detailed description of the signals in the MC communication system. Denote by n the number of subcarriers (tones). The system receives at each time instant $0, \Upsilon, 2\Upsilon, \dots$ a collection of n constellation symbols a_k, $k = 0, \dots, n-1$, where $a_k \in \mathbb{C}$, carrying the information to be transmitted. The subset $\mathcal{Q}$ of possible values of a_k depends on the type of the carrier modulation. The most popular complex constellations are BPSK, M-QAM, and M-PSK. We assume

$$\text{BPSK} = \{-1, 1\},$$
$$M\text{-QAM} = \left\{A\left((2m_1 - 1) + \imath\,(2m_2 - 1)\right), m_1, m_2 \in \left\{-\frac{m}{2} + 1, \dots, \frac{m}{2}\right\}\right\},$$