

M. GHAVAMI • L. B. MICHAEL • R. KOHNO

Ultra Wideband

signals and systems
in communication
engineering

SECOND EDITION

 WILEY

Companion Website

TN915.142

G411
E2

Ultra Wideband Signals and Systems in Communication Engineering

Second Edition

M. Ghavami

King's College London, UK

L. B. Michael

Japan

R. Kohno

Yokohama National University, Japan



John Wiley & Sons, Ltd



E2008001812

Copyright © 2007 John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England
Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wiley.com

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

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

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 6045 Freemont Blvd, Mississauga, ONT, L5R 4J3, Canada

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 978-0-470-02763-9 (HB)

Typeset by Sunrise Setting Ltd, Torquay, Devon, UK.

Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, England.

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Ultra Wideband Signals and Systems in Communication Engineering

Second Edition

Preface

In the two years since this book was first published, ultra wideband (UWB) has advanced and consolidated as a technology, and many more people are aware of the possibilities for this exciting technology. We too have expanded and consolidated materials in this second edition in the hope that 'Ultra Wideband: Signals and Systems in Communication Engineering' will continue to prove a useful tool for many students and engineers to come to an understanding of the basic technologies for UWB.

In this book we focus on the basic *signal processing* that underlies current and future UWB systems. By looking at signal processing in this way, we hope that this text will be useful even as UWB applications mature and change or regulations regarding UWB systems are modified. The current UWB field is extremely dynamic, with new techniques and ideas being presented at every communications and signal-processing conference. However, the basic signal-processing techniques presented in this text will not change for some time to come. This is because we have taken a somewhat theoretical approach, which we believe is longer lasting and more useful to the reader in the long term than an up-to-the-minute summary that is out of date as soon as it is published.

We restrict our discussion in general to *ultra wideband communication*, looking in particular at *consumer communication*. What we mean by this is that although there are many and varied specialized applications for UWB, particularly for the military, we assume that the majority of readers will either be in academia or in industry. In any case, as this is a basic text, aimed mostly at the upper undergraduate or graduate student, these basics should stand the reader in good stead to be able to easily understand more advanced papers and make a contribution in this field for themselves.

We are painfully aware of the depth and breadth of this field, and regretfully pass on interesting topics such as UWB radar, including ground penetrating radar, and most military applications. For the former there is already a great deal of information available, while for the latter most material is classified.

The introduction to this book presents a brief look at why UWB is considered to be an exciting wireless technology for the near future. We examine Shannon's famous capacity equation and see that the large bandwidth promises possibilities for high-data-rate communication. A quick overview of the regulatory situation is presented.

Chapter 1 presents the basic properties of UWB. We examine the power spectral density, basic pulse shape, and spectral shape of these pulses. The regulatory requirements laid down by the Federal Communications Commission are briefly described. Why UWB is considered to be a multipath resistant form is also examined, and such basic figures of merit such as capacity and speed of data transmission are considered. We finish the chapter with a look at the cost, size, and power consumption that is forecast for UWB devices and chipsets.

Chapter 2 examines in detail how to generate basic pulse waveforms for UWB systems, for the simple Gaussian pulse shape. An introduction to damped sine waves and the difference between them and Gaussian waveforms is presented. Armed with this information, the reader can now proceed to more complex waveforms and theory associated with UWB signals and systems. We examine how to design pulses to fit spectral masks, such as mandated by regulators, or to avoid interference to other frequency bands.

Chapter 3 looks at different signal-processing techniques for UWB systems. The chapter begins with a review of basic signal-processing techniques, including both time and frequency domain techniques. The Laplace, Fourier, and z -transforms are reviewed and their application to UWB is discussed. Finally, some practical issues, such as pulse detection and amplification, are discussed.

The wireless indoor channel, and how it should be modeled for UWB communications, is considered in Chapter 4. Following our basic pattern we define and explore basic concepts of wideband channel modeling, and show a simplified UWB multipath channel model which is amendable to both theoretical analysis and simulation. Path loss effects and a two-ray model are presented. A frequency domain autoregressive model is discussed and, finally, IEEE proposals for a UWB channel model are explained.

Chapter 5 takes a look at some of the fundamental communication concepts and how they should be applied to UWB. First, modulation methods applicable to UWB are presented. A basic communication system consisting of transmitter, receiver, and channel is discussed. Since most consumer communication systems do not consist of only one user, multiple access techniques are introduced. The simple capacity of a UWB system is derived. Since other wireless consumer communication systems have already become popular, a comparison between UWB and other wideband techniques is included. Finally, the chapter ends with a look at interference to and from UWB systems.

In Chapter 6, which is in many ways an extension of Chapter 2 but requiring many of the concepts presented in Chapters 3 to 5, more complex pulse shapes and

their use in a communication system are explained. An extensive treatment of the more complex orthogonal pulses, including Hermite pulses, prolate spheroidal wave functions, and wavelet packets is presented.

Chapter 7 is concerned with UWB antennas and arrays of antennas. This is considered one of the most difficult problems that must be overcome before the widespread commercialization of UWB devices takes place. Antenna fundamentals are first introduced, including Maxwell's equations for free space, antenna field regions, directivity, and gain. The suitability of conventional antennas for UWB transmission and reception is discussed in detail. More suitable impulse antennas are then introduced. Arrays of antennas and beamforming for UWB systems are given a brief treatment.

Positioning and location, using both traditional techniques and UWB, are discussed in Chapter 8. Traditional location systems are first introduced and their pros and cons discussed. The advantages of UWB, particularly the extremely precise positioning that is theoretically possible, are examined. Finally, several possible scenarios are discussed where the precise location capabilities and high data rate of UWB can be combined to produce some new and exciting applications.

New applications made possible by UWB technology are among the most exciting reasons to use UWB. Chapter 9 has a brief look at some applications that use UWB technology, as well as an overview of some chipsets and possible future UWB products. Emphasis is on consumer communication and medicine; however, military applications are also given a brief treatment.

Chapter 10, an additional chapter for the second edition, presents an introduction and overview of the main UWB standards bodies. In particular, the IEEE 802.15.3a and IEEE 802.15.4a efforts are summarized. The two main physical layer proposals for UWB, direct sequence UWB and multiband UWB, and their respective advantages are then presented in detail.

Chapter 11 presents advanced topics in UWB communication systems, and is also an addition for the second edition. This chapter looks at novel communication systems that have matured recently. In particular, UWB ad-hoc and sensor networks, UWB vehicular radars and the effects of interference with Wi-Max are examined.

For the reader who wants a fast-track understanding of UWB and some knowledge of the current situation, we recommend the introduction, Chapter 1 (Basic properties of UWB signals and systems), Chapter 9 (Applications), and Chapter 10 (UWB communication standards).

For students who want to look at UWB in more detail, they should then proceed to look at Chapter 2 (Generation of UWB waveforms), Chapter 3 (Signal processing techniques for UWB systems), and then Chapters 4 through to 8 as required. We have strived to make each chapter complete in itself as far as possible and provide as much basic theory as practicable, including derivations where appropriate. We have made constant reference to the literature, a significant part of which is covered here.

As an extra resource we have set up a companion website for our book containing a solutions manual, Matlab programs for the examples and problems, and a sample chapter. Also, for those wishing to use this material for lecturing purposes, electronic

versions of most of the figures from our book are available. Please take a look at <http://www.wiley.com/go/ghavami>.

We hope that you will find this book useful as both a reference, a learning tool, and a stepping stone to further your own efforts in this exciting field.

M. Ghavami
L. B. Michael
R. Kohno

London, January 2007

Acknowledgments

The authors would like to thank the following people for their efforts and contributions to the second edition of *Ultra Wideband Signals and Systems in Communication Engineering*:

– Sarah Hinton, our editor, for her tireless and unending efforts to make this publication timely and well received, as well as for helping us with the ins and outs of writing a textbook;

– Dr X. Chu, Dr F. Heliot, S. Ciolino, K. Sarfaraz, Dr R. S. Dilmaghani, W. Horie, N. Riaz and K. Kang (King's College London) for their valuable contributions.

M. Ghavami would like to thank:

my wife Mahnaz and my children Navid and Nooshin who have suffered the long period of preparation of this book and who have been continually supportive.

L. B. Michael would like to thank:

my wife and children for their support and patience during the weekends and nights while I was preparing and editing material for this book.

Contents

<i>Preface</i>	<i>xiii</i>
<i>Acknowledgments</i>	<i>xvii</i>
<i>List of Figures</i>	<i>xix</i>
<i>List of Tables</i>	<i>xxix</i>
<i>Introduction</i>	<i>1</i>
<i>I.1 Ultra wideband overview</i>	<i>1</i>
<i>I.2 A note on terminology</i>	<i>2</i>
<i>I.3 Historical development of UWB</i>	<i>2</i>
<i>I.4 UWB regulation overview</i>	<i>3</i>
<i>I.4.1 Basic definitions and rules</i>	<i>4</i>
<i>I.5 Key benefits of UWB</i>	<i>5</i>
<i>I.6 UWB and Shannon's theory</i>	<i>6</i>
<i>I.7 Challenges for UWB</i>	<i>7</i>
<i>I.8 Summary</i>	<i>7</i>
<i>1 Basic properties of UWB signals and systems</i>	<i>9</i>
<i>1.1 Introduction</i>	<i>9</i>
<i>1.2 Power spectral density</i>	<i>10</i>
<i>1.3 Pulse shape</i>	<i>11</i>

1.4	<i>Pulse trains</i>	14
1.5	<i>Spectral masks</i>	16
1.6	<i>Multipath</i>	17
1.7	<i>Penetration characteristics</i>	20
1.8	<i>Spatial and spectral capacities</i>	20
1.9	<i>Speed of data transmission</i>	21
1.10	<i>Cost</i>	22
1.11	<i>Size</i>	22
1.12	<i>Power consumption</i>	23
1.13	<i>Summary</i>	23
2	<i>Generation of UWB waveforms</i>	25
2.1	<i>Introduction</i>	25
2.1.1	<i>Damped sine waves</i>	26
2.2	<i>Gaussian waveforms</i>	28
2.3	<i>Designing waveforms for specific spectral masks</i>	31
2.3.1	<i>Introduction</i>	32
2.3.2	<i>Multiband modulation</i>	33
2.4	<i>Practical constraints and effects of imperfections</i>	39
2.5	<i>Summary</i>	40
3	<i>Signal-processing techniques for UWB systems</i>	43
3.1	<i>The effects of a lossy medium on a UWB transmitted signal</i>	43
3.2	<i>Time domain analysis</i>	46
3.2.1	<i>Classification of signals</i>	46
3.2.2	<i>Some useful functions</i>	48
3.2.3	<i>Some useful operations</i>	51
3.2.4	<i>Classification of systems</i>	54
3.2.5	<i>Impulse response</i>	57
3.2.6	<i>Distortionless transmission</i>	57
3.3	<i>Frequency domain techniques</i>	57
3.3.1	<i>Fourier transforms</i>	57
3.3.2	<i>Frequency response approaches</i>	58
3.3.3	<i>Transfer function</i>	60
3.3.4	<i>Laplace transform</i>	63
3.3.5	<i>z-transform</i>	64
3.3.6	<i>The relationship between the Laplace transform, the Fourier transform, and the z-transform</i>	67

3.4	<i>UWB signal-processing issues and algorithms</i>	68
3.5	<i>Detection and amplification</i>	71
3.6	<i>Summary</i>	72
4	<i>UWB channel modeling</i>	75
4.1	<i>A simplified UWB multipath channel model</i>	76
4.1.1	<i>Number of resolvable multipath components</i>	78
4.1.2	<i>Multipath delay spread</i>	78
4.1.3	<i>Multipath intensity profile</i>	79
4.1.4	<i>Multipath amplitude-fading distribution</i>	80
4.1.5	<i>Multipath arrival times</i>	81
4.2	<i>Path loss model</i>	83
4.2.1	<i>Free space loss</i>	83
4.2.2	<i>Refraction</i>	84
4.2.3	<i>Reflection</i>	84
4.2.4	<i>Diffraction</i>	85
4.2.5	<i>Wave clutter</i>	85
4.2.6	<i>Aperture-medium coupling loss</i>	85
4.2.7	<i>Absorption</i>	85
4.2.8	<i>Example of free space path loss model</i>	85
4.3	<i>Two-ray UWB propagation model</i>	87
4.3.1	<i>Two-ray path loss</i>	88
4.3.2	<i>Two-ray path loss model</i>	91
4.3.3	<i>Impact of path loss frequency selectivity on UWB transmission</i>	93
4.4	<i>Frequency domain autoregressive model</i>	96
4.4.1	<i>Poles of the AR model</i>	99
4.5	<i>IEEE proposals for UWB channel models</i>	100
4.5.1	<i>An analytical description of the IEEE UWB indoor channel model</i>	101
4.6	<i>Summary</i>	106
5	<i>UWB communications</i>	109
5.1	<i>Introduction</i>	109
5.2	<i>UWB modulation methods</i>	110
5.2.1	<i>PPM</i>	111
5.2.2	<i>BPM</i>	112
5.3	<i>Other modulation methods</i>	113
5.3.1	<i>OPM</i>	115

5.3.2	<i>PAM</i>	115
5.3.3	<i>OOK</i>	116
5.3.4	<i>Summary of UWB modulation methods</i>	116
5.4	<i>Pulse trains</i>	116
5.4.1	<i>Gaussian pulse train</i>	117
5.4.2	<i>PN channel coding</i>	117
5.4.3	<i>Time-hopping PPM UWB system</i>	119
5.5	<i>UWB transmitter</i>	120
5.6	<i>UWB receiver</i>	121
5.6.1	<i>Detection</i>	122
5.6.2	<i>Pulse integration</i>	123
5.6.3	<i>Tracking</i>	123
5.6.4	<i>Rake receivers</i>	123
5.7	<i>Multiple access techniques in UWB</i>	123
5.7.1	<i>Frequency division multiple access UWB</i>	124
5.7.2	<i>Time division multiple access</i>	124
5.7.3	<i>Code division multiple access</i>	124
5.7.4	<i>Orthogonal pulse multiple access system</i>	124
5.8	<i>Capacity of UWB systems</i>	125
5.9	<i>Comparison of UWB with other wideband communication systems</i>	128
5.9.1	<i>CDMA</i>	130
5.9.2	<i>Comparison of UWB with DSSS and FHSS</i>	130
5.9.3	<i>OFDM</i>	133
5.10	<i>Interference and coexistence of UWB with other systems</i>	136
5.10.1	<i>WLANs</i>	137
5.10.2	<i>Bluetooth</i>	139
5.10.3	<i>GPS</i>	140
5.10.4	<i>Cellular systems</i>	141
5.10.5	<i>Wi-Max</i>	141
5.10.6	<i>The effect of narrowband interference on UWB systems</i>	143
5.11	<i>Summary</i>	146
6	<i>Advanced UWB pulse generation</i>	149
6.1	<i>Hermite pulses</i>	149
6.1.1	<i>Hermite polynomials</i>	150
6.1.2	<i>Orthogonal modified Hermite pulses</i>	151

6.1.3	<i>Modulated and modified Hermite pulses</i>	154
6.2	<i>Orthogonal prolate spheroidal wave functions</i>	156
6.2.1	<i>Introduction</i>	157
6.2.2	<i>Fundamentals of PSWFs</i>	158
6.2.3	<i>PSWF pulse generator</i>	161
6.3	<i>Wavelet packets in UWB PSM</i>	166
6.3.1	<i>PSM system model</i>	168
6.3.2	<i>Receiver structure</i>	169
6.4	<i>Summary</i>	170
7	<i>UWB antennas and arrays</i>	173
7.1	<i>Antenna fundamentals</i>	174
7.1.1	<i>Maxwell's equations for free space</i>	174
7.1.2	<i>Wavelength</i>	176
7.1.3	<i>Antenna duality</i>	176
7.1.4	<i>Impedance matching</i>	176
7.1.5	<i>Voltage standing wave ratio and reflected power</i>	177
7.1.6	<i>Antenna bandwidth</i>	177
7.1.7	<i>Directivity and gain</i>	177
7.1.8	<i>Antenna field regions</i>	178
7.1.9	<i>Antenna directional pattern</i>	178
7.1.10	<i>Beamwidth</i>	180
7.2	<i>Antenna radiation for UWB signals</i>	180
7.2.1	<i>Dispersion due to near-field effects</i>	183
7.3	<i>Suitability of conventional antennas for the UWB system</i>	184
7.3.1	<i>Resonant antennas</i>	184
7.3.2	<i>Nonresonant antennas</i>	187
7.3.3	<i>Difficulties with UWB antenna design</i>	187
7.4	<i>Impulse antennas</i>	188
7.4.1	<i>Conical antenna</i>	188
7.4.2	<i>Monopole antenna</i>	189
7.4.3	<i>D-dot probe antenna</i>	190
7.4.4	<i>TEM horn antenna</i>	190
7.4.5	<i>Small-size UWB antenna</i>	191
7.4.6	<i>Conclusion</i>	192

7.5	<i>Beamforming for UWB signals</i>	192
7.5.1	<i>Basic concepts</i>	193
7.5.2	<i>A simple delay-line transmitter wideband array</i>	194
7.6	<i>Radar UWB array systems</i>	201
7.7	<i>Summary</i>	202
8	<i>Position and location with UWB signals</i>	205
8.1	<i>Wireless positioning and location</i>	205
8.1.1	<i>Types of wireless positioning systems</i>	206
8.1.2	<i>Wireless distance measurement</i>	206
8.1.3	<i>Microwave positioning systems</i>	207
8.2	<i>GPS techniques</i>	210
8.2.1	<i>Differential GPS (DGPS)</i>	211
8.2.2	<i>GPS tracking modes</i>	211
8.2.3	<i>GPS error sources</i>	212
8.3	<i>Positioning techniques</i>	213
8.3.1	<i>Introduction</i>	213
8.3.2	<i>Network-based techniques</i>	213
8.3.3	<i>Handset-based techniques</i>	218
8.3.4	<i>Hybrid techniques</i>	220
8.3.5	<i>Other techniques</i>	220
8.4	<i>Time resolution issues</i>	221
8.4.1	<i>Narrowband systems</i>	221
8.4.2	<i>Wideband systems</i>	221
8.4.3	<i>Super-resolution techniques</i>	222
8.4.4	<i>UWB systems</i>	225
8.5	<i>UWB positioning and communications</i>	227
8.5.1	<i>Potential user scenarios</i>	227
8.5.2	<i>Potential applications</i>	227
8.6	<i>Summary</i>	228
9	<i>Applications using UWB systems</i>	231
9.1	<i>Military applications</i>	231
9.1.1	<i>Precision asset location system</i>	232
9.2	<i>Commercial applications</i>	233
9.2.1	<i>Time Domain</i>	234
9.2.2	<i>XtremeSpectrum</i>	236
9.2.3	<i>Intel Corporation</i>	236

9.2.4	<i>Motorola</i>	237
9.2.5	<i>Freescale</i>	237
9.2.6	<i>Communication Research Laboratory</i>	238
9.2.7	<i>General atomics</i>	238
9.2.8	<i>Wisair</i>	239
9.2.9	<i>Artimi</i>	239
9.2.10	<i>Ubisense</i>	240
9.2.11	<i>Home networking and home electronics</i>	240
9.2.12	<i>PAL system</i>	242
9.3	<i>UWB potentials in medicine</i>	243
9.3.1	<i>Fundamentals of medical UWB radar</i>	246
9.3.2	<i>UWB radar for remote monitoring of patient's vital activities</i>	246
9.3.3	<i>UWB respiratory monitoring system</i>	247
9.4	<i>Summary</i>	249
10	<i>UWB communication standards</i>	251
10.1	<i>UWB standardization in wireless personal area networks</i>	251
10.1.1	<i>WPAN standardization overview</i>	252
10.1.2	<i>IEEE 802.15.3a</i>	253
10.1.3	<i>IEEE 802.15.4a</i>	255
10.2	<i>DS-UWB proposal</i>	255
10.2.1	<i>DS-UWB operating bands</i>	256
10.2.2	<i>Advantages of DS-UWB</i>	258
10.3	<i>MB-OFDM UWB proposal</i>	258
10.3.1	<i>Frequency band allocation</i>	259
10.3.2	<i>Channelization</i>	260
10.3.3	<i>Advantages of MB-OFDM UWB</i>	261
10.4	<i>A short comment on the term 'impulse radio'</i>	261
10.5	<i>Summary</i>	262
11	<i>Advanced topics in UWB communication systems</i>	263
11.1	<i>UWB ad-hoc networks</i>	263
11.1.1	<i>Introduction</i>	263
11.1.2	<i>Applications of an UWB ad-hoc network</i>	264
11.1.3	<i>Technologies involved in UWB ad-hoc networks</i>	264
11.2	<i>UWB sensor networks</i>	267

11.3	<i>Multiple inputs multiple outputs and space-time coding for UWB systems</i>	270
11.4	<i>Self-interference in high-data-rate UWB communications</i>	271
11.5	<i>Coexistence of DS-UWB with Wi-Max</i>	275
11.5.1	<i>Interference thresholds</i>	276
11.5.2	<i>UWB signal model</i>	278
11.5.3	<i>Interference model</i>	279
11.5.4	<i>Interference scenario</i>	281
11.5.5	<i>Some numerical results</i>	281
11.5.6	<i>Conclusion</i>	282
11.6	<i>Vehicular radars in the 22–29 GHz band</i>	283
11.6.1	<i>Environment sensing for vehicular radar</i>	284
11.7	<i>Summary</i>	286
	<i>References</i>	287
	<i>Index</i>	297