

COMMUNICATIONS ENGINEERING SERIES



# Ultra Wideband Systems

Technologies and Applications

Edited by

**Robert Aiello  
and Anuj Batra**



# Ultra Wideband Systems

This Page Intentionally Left Blank

# Ultra Wideband Systems

## Technologies and Applications

**Roberto Aiello**  
Staccato Communications

**Anuj Batra**  
Texas Instruments



AMSTERDAM • BOSTON • HEIDELBERG • LONDON  
NEW YORK • OXFORD • PARIS • SAN DIEGO  
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Newnes is an imprint of Elsevier



Newnes is an imprint of Elsevier  
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA  
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

Copyright © 2006, Elsevier Inc. 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, or otherwise, without the prior written permission of the publisher.

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone: (+44) 1865 843830, fax: (+44) 1865 853333, E-mail: [permissions@elsevier.com](mailto:permissions@elsevier.com). You may also complete your request on-line via the Elsevier homepage (<http://elsevier.com>), by selecting "Support & Contact" then "Copyright and Permission" and then "Obtaining Permissions."

Recognizing the importance of preserving what has been written, Elsevier prints its books on acid-free paper whenever possible.

#### **Library of Congress Cataloging-in-Publication Data**

Application submitted

#### **British Library Cataloguing-in-Publication Data**

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

ISBN 13: 978-0-7506-7893-3

ISBN: 0-7506-7893-3

For information on all Newnes publications  
visit our Web site at [www.books.elsevier.com](http://www.books.elsevier.com)

05 06 07 08 09 10 10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

Working together to grow  
libraries in developing countries

[www.elsevier.com](http://www.elsevier.com) | [www.bookaid.org](http://www.bookaid.org) | [www.sabre.org](http://www.sabre.org)

ELSEVIER

BOOK AID  
International

Sabre Foundation

*This book is dedicated to my wife, Michela,  
and to my children, Lorenzo and Francesco.*

—R. A.

This Page Intentionally Left Blank

# Table of Contents

<b>Preface</b> .....	ix
by Edmond J. Thomas	
<b>Introduction</b> .....	xiii
by Roberto Aiello	
<b>Chapter</b>	
1 <i>History of Ultra Wideband Communication Systems</i> .....	1
by Roberto Aiello	
2 <i>UWB Spectrum and Regulations</i> .....	17
by Robert Sutton	
3 <i>Interference and Coexistence</i> .....	53
by Roberto Aiello	
4 <i>UWB Antennas</i> .....	73
by James S. McLean and Heinrich Foltz	
5 <i>Direct-Sequence UWB</i> .....	147
by Michael McLaughlin	
6 <i>Multiband Approach to UWB</i> .....	167
by Charles Razzell	
7 <i>Spectral Keying<sup>TM</sup>: A Novel Modulation Scheme for UWB Systems</i> .....	191
by Naiel K. Askar, Susan C. Lin, and David S. Furuno	
8 <i>Multiband OFDM</i> .....	211
by Jaiganesh Balakrishnan and Anuj Batra	
9 <i>MAC Designs for UWB Systems</i> .....	249
by Larry Taylor	
10 <i>Standards for UWB Communications</i> .....	285
by Jason L. Ellis	
11 <i>Commercial Applications</i> .....	299
by Roberto Aiello	
<b>About the Contributors</b> .....	313
<b>Index</b> .....	317

This Page Intentionally Left Blank

# *Foreword*

*by Edmond J. Thomas*

It was Valentine's Day 2002, and I was the chief engineer of the Federal Communications Commission. I sat before an open meeting of the commission and recommended, on behalf of the Office of Engineering and Technology, that it approve a Report & Order authorizing ultra wideband (UWB) for use in the United States. This ended one of the most contentious proceedings in the history of the commission.

The opposition to UWB stemmed from the fact that for the first time in its history, the FCC was considering authorizing a technology that could occupy 7.5 GHz (3.1 to 10.6 GHz) of already licensed spectrum. Although the proposed transmitted power was extremely low ( $-41$  dbm/MHz), the incumbents opposed it with vigor, concerned—needlessly in my view—about the possibility of interference.

Since the proposed spectrum for UWB would cover so much bandwidth if authorized, it also would utilize spectrum already assigned by the National Telecommunications and Information Agency (NTIA) to government users. Some government agencies opposed UWB with the same vigor as the private-sector incumbents. Press articles appeared suggesting that aviation safety, cell phones, GPS, military communications, and satellite communication would be significantly and dangerously impaired by UWB operations. Scientific studies were presented with unrealistic assumptions in support of these kinds of claims. Finally, based on what they were hearing from both government agencies and incumbent private-sector licensees, many members of Congress raised concerns about authorizing UWB.

In spite of all the resistance, on February 14, 2002, the FCC approved the UWB Report & Order, thus giving UWB an opportunity to succeed in the U.S. marketplace. There are too many people to mention both at the FCC and NTIA who deserve credit for supporting and promoting this exciting and innovative technology. However, the following people stand out among the many and deserve mention for their unwavering dedication to get at the truth and do the right thing:

- Michael Powell, former chairman of the FCC
- Kathleen Abernathy, former FCC commissioner
- Kevin Martin, former FCC commissioner, presently FCC chairman

- Michael Copps, FCC commissioner
- Jonathan Adelstien, FCC commissioner
- Bruce Franca, deputy chief of the FCC Office of Engineering and Technology
- Julius Knapp, deputy chief of the FCC Office of Engineering and Technology
- Nancy Victory, former assistant secretary of commerce in charge of NTIA
- Michael Gallagher, assistant secretary of commerce in charge of NTIA

On March 2005, the FCC made another significant decision. It granted a waiver that, in effect, made Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM) UWB technology practical. Today MB-OFDM and direct-sequence impulse are the two primary technologies being commercialized for UWB.

It is not very often that an industry's exact date of birth can be identified. However, UWB's birthday certainly was Valentine's Day 2002. In my view, it was a great Valentine's Day present from the FCC to the nation.

At this writing four years later, the UWB industry is healthy and growing. Today, innovative products are being delivered to U.S. customers, and the technology is beginning to be accepted around the world.

The strength of UWB technology lies in its ability to transfer broadband multimedia content over short distances (100 ft.) efficiently and economically. At the 2006 Consumer Electronics Show in Las Vegas, Nevada, many chip and product manufacturers exhibited and demonstrated products. These companies included Intel, Hewlett-Packard, Motorola, Samsung, Philips, Staccato, Freescale, and Alereon, to name but a few. Demonstrated applications included wireless video streaming, MP3 downloads, multimedia print file transfers, disk backup, and digital camera image transfers.

On the international front, UWB is beginning to be recognized worldwide. On December 8, 2005, ECMA (formerly the European Computer Manufacturer's Association) adopted the MB-OFDM U.S. UWB standard. ECMA is now cooperating with the European Telecommunications Standards Institute (ETSI) to establish a European standard. Also, UWB is on the fast track to becoming an International Standards Organization standard, and the Bluetooth Special Interest Group is moving to adopt UWB as a Bluetooth standard. Finally, MB-OFDM has been accepted as a wireless USB standard. As a result of all this standards activity, it is probable that by the end of 2006, Europe, Korea, and Japan will authorize UWB. China, New Zealand, Australia, Canada, Singapore, and Hong Kong will probably follow shortly thereafter.

It is estimated that in 2006 over 13 million products will ship containing UWB technology, and if the world market develops as anticipated, over 190 million products will ship in 2009 containing the technology. This corresponds to a growth rate in excess of 140 percent.

In the not too distant future, I believe that UWB chip sets will cost less than \$5 (probably around \$2). Also, effective operating range will increase to approximately 150 ft. Therefore, in my judgment, UWB will replace today's Bluetooth in applica-

tions requiring broadband information transfer and will become the technology of choice for short-range broadband access. It will replace much of today's wiring which connects equipment to computer workstations and laptops, such as printers, monitors, disk drives, scanners, cameras, and the like. It will do the same for components used in entertainment systems, such as tuners, speakers, HDTV monitors, DVD players, and the like. It will also be the technology of choice for personal local area networks. In short, it will revolutionize short-range broadband access.

Dr. Roberto Aiello is uniquely qualified to edit this book and write sections of it. He is a cofounder and CTO at Staccato Communications, and for years he has led the way to making UWB a commercial reality. He was previously founder, president, and CEO at Fantasma Networks, a UWB product company. Prior to his work at Fantasma, in 1996, Dr. Aiello had joined Interval Research, Paul Allen's research laboratory, to work on advanced wireless technologies; there he built the first documented UWB network.

Dr. Aiello is a recognized leader in the UWB community and is actively involved in regulatory and standards-setting committees. He is a founding member of several standards committees, such as the UWB Working Group, the Multiband Coalition, and the Multiband OFDM Alliance, and he now serves as an officer on the WiMedia's board of directors.

Through Dr. Aiello's efforts, in my view, this book will become the definitive UWB reference. In one place it describes the following:

- The history of UWB communication systems
- FCC rules and testing procedures
- Interference considerations
- Antenna designs
- Direct-sequence and MB-OFDM technologies
- Industry standards
- UWB roles and applications

I recommend the book to both engineers and regulators worldwide. In fact, in my judgment it should be required reading for anyone who is interested in an informed and unbiased description of this exciting new technology. In short, it establishes the reality and destroys the myths surrounding UWB. I congratulate Dr. Aiello and his cocontributors for a job well done.

Edmond J. Thomas  
Former Chief Engineer,  
Federal Communications Commission  
Technical Policy Advisor and Partner  
Harris Wiltshire Grannis  
ethomas@harriswiltshire.com

This Page Intentionally Left Blank

# *Introduction*

*by Roberto Aiello*

I discovered Ultra Wideband (UWB) in 1996 when I joined Interval Research, a research and technology incubator company funded by Paul Allen, to lead their wireless activities. At the time, we were exploring the opportunity to enable connectivity of personal and wearable devices, such as video cameras, stereo headsets, head-mounted displays, personal storage, and so forth.

We needed a high-performance, short-range, low-power wireless network. We studied the options of using spectrum in the 2.4 GHz and 900 MHz bands, infrared, or inductive coupling. Each has its advantages, but none of them could solve our problem. Then, I read an article about impulse radios published by Time Domain, and I decided to explore that opportunity.

As I was introduced to the world of UWB, I had the privilege to meet and collaborate with many UWB pioneers whose contributions made UWB a reality today: Bob Fleming and Cherie Kushner at Aetherwire, Bob Fontana at Multispectral Solutions, Larry Fullerton and Paul Withington at Time Domain, Martin Rofheart and John McCorkle at XtremeSpectrum, Bob Scholtz at University of Southern California. All of these individuals were driven by different interests: to work on new engineering development, to research novel communications areas, or to create a new business. Their passion and dedication have greatly contributed to the current success of UWB.

Even though UWB research dates far back to the beginning of radios, it was reborn as a result of the Federal Communications Commission (FCC) Report and Order in 2002, when spectrum was made available for unlicensed use, and companies recognized a business opportunity. This resulted from the effort of a lot of people who actively promoted UWB at the FCC and in the government.

One of the biggest contributions, in my opinion, was Jim Lovette's. With his endless energy and dedication, he worked extremely hard and efficiently to explain what UWB was about to both engineers and policy makers. Jim was a self-defined "unlicensed spectrum advocate"; he was the originator of the Apple petition that led to the unlicensed national information infrastructure (UNII) band spectrum allocation in the 5 GHz band and unlicensed personal communication services (PCS) in the 1.9 GHz band. We worked together for 18 months to lobby the FCC, National

Telecommunications and Information Agency (NTIA), Congress and Senate to allocate UWB spectrum in the United States. He and I had several heated discussions during that time, and I obviously had different opinions in many situations, but in hindsight, I must admit that he was right in most cases! He passed away on June 29, 2002.

The FCC was a great supporter of UWB from the beginning, and the tireless work of Julie Knapp, Dale Hatfield, and Ed Thomas greatly contributed to the final UWB spectrum allocation.

After 2002, the scenario changed, and a push began to capitalize on the UWB spectrum available and to develop commercial opportunities. Today, UWB is one of the hottest wireless technologies in the industry.

The purpose of this book is to introduce the reader to high-performance UWB communication systems and to UWB's commercial applications. I did not include other applications, such as low-bit-rate communications, radar, and radio frequency (RF) tags, among other others. Nor did I include a chapter on impulse radios, mainly because, even though it was one of the main methods developed for UWB, it has not found a place in high-performance communication applications. Furthermore, quite a few publications and books have been written on the topic.

The book is logically divided into three parts: introduction to UWB (Chapters 1–4), different UWB techniques (Chapters 5–8), and communication applications (Chapters 9–11).

The main theme of the book is that UWB is not a specific technology, modulation, or multiple access technique; nor is it a specific application. Rather, it is defined as available spectrum that needs to be used according to specific rules. This spectrum is characterized by transmitters that emit very low average power and, as such, generate a very low level of interference with other systems sharing the same spectrum. This enables the unique property of UWB, which is spectrum open to many services that do not cause harmful interference with each other. This results in a new and more efficient use of the spectrum.

Several technologies have been developed to use the UWB spectrum so far. The more successful commercially are based on well-known communication techniques, such as direct sequence spread spectrum or orthogonal frequency division multiplexing (OFDM). They also differentiate each other by using a single band or multiple bands in the same system.

The main applications developed to date, allowing the best use of the UWB spectrum, focus on two extreme cases: (1) very high bit rate, low power, and short range, and (2) very low power, low bit rate. Useful features of such systems are also location and positioning. These applications have emerged because their requirements are a good fit for UWB and because they are not currently served by other wireless systems. As mentioned above, this book focuses on high-bit-rate systems.

Industry standards have been developed to support commercial applications and to facilitate interoperability among multiple vendors. Such standards are also described in the book.

---

The authors are all “A” players in the space and have been key contributors to the development of modern UWB and to the technologies that have moved UWB from the laboratory to commercial products.

This book is organized as follows:

- *Chapter 1: History of Ultra Wideband Communication Systems.* UWB was originally developed as impulse radio, using its characteristics for low probability of intercept and low probability of detection for military applications. This chapter describes its origins and the motivations that led to the development of UWB systems. It summarizes the history of UWB, focusing on the more recent events that led to the pursuit of commercial applications.
- *Chapter 2: UWB Spectrum and Regulations.* UWB is defined as available spectrum. As of today, it has been regulated in the United States, while the rest of the world is still working toward a global spectrum allocation. UWB rules are different from any other existing spectrum regulations, and UWB transmitters need to meet very stringent requirements to be allowed to operate. This chapter describes the FCC rules and the measurement procedure required to test a UWB transmitter for compliance.
- *Chapter 3: Interference and Coexistence.* UWB systems need to coexist with other systems sharing the same frequency spectrum. They also use a very large bandwidth to compensate for the very low allowed transmit power. This chapter describes some of the issues related to interference and coexistence.
- *Chapter 4: UWB Antennas.* The subject of antennas has great importance for UWB technology: a system that employs very large bandwidth presents challenges to the antenna designer. This chapter describes some of these challenges and some of the antennas that are adequate for commercial applications, including design details and an explanation of their differences from conventional narrow-channel antennas.
- *Chapter 5: Direct Sequence UWB.* This chapter describes a direct sequence UWB system (the most popular version of the original impulse radios for high-performance systems), its characteristics, and its advantages.
- *Chapter 6: Multiband Approach to UWB.* A multiband system is based on the principle of transmitting different symbols in different frequency bands in a periodic sequence. This chapter describes the general principles that led to the development of multiband techniques, their advantages, and their characteristics.
- *Chapter 7: Spectral Keying: A Novel Modulation Scheme for UWB Systems.* This chapter describes a modulation scheme based on multibands, which uses the relationship between bands to encode information.
- *Chapter 8: Multiband OFDM.* This chapter describes a system based on multiband and OFDM that has become attractive in terms of cost-performance ratio for high-bit-rate, short-range systems.

- *Chapter 9: MAC Designs for UWB Systems.* UWB systems are characterized by unique constraints, different from other wireless communication systems. This chapter describes MAC architecture optimized for UWB systems.
- *Chapter 10: Standards for UWB Communications.* Industry standards are necessary for the successful development of wireless systems. This chapter describes the status of the ongoing standard effort related to UWB systems.
- *Chapter 11: Commercial Applications.* The success of wireless products depends on several factors: technical characteristics, target applications, market timing, and economics. This chapter describes how these various aspects are relevant to UWB products.

This book is intended for students, engineers, and marketing and business people, because it covers a broad set of fundamental issues related to UWB.

It has been a pleasure to work on this book with so many friend and colleagues. Many individuals have helped with support, advice, discussion, comments, and constructive criticism: Mark Bowles, Billy Brackenridge, Jeff Foerster, Anita Giani, Harry Helms, Kursat Kimyacioglu, Dave Leeper, Janine Love, Sid Shetty, Jarvis Tou, and Stephen Wood. I am most in debt to the individuals who encouraged me to continue working on UWB for so many years: most shared my drive to create something new (a technology or business), and some were motivated by the prospect of financial return (Venture Capitalists that invested in my companies).

But most importantly, I couldn't have been successful in pursuing my interest in technology and in fulfilling my entrepreneurial drive without the support of my wife of sixteen years, Michela, who has shown an amazing amount of patience and continuous encouragement over the years.

# *History of Ultra Wideband Communication Systems*

*by Roberto Aiello*

From its humble beginnings more than 45 years ago, ultra wideband (UWB) technology has traveled an interesting road from the lab, to the military, back to the lab, and finally into commercial prototyping and implementation. Known throughout the years by a number of different names, fundamentally, UWB offers a different mechanism for wirelessly transporting voice, video, and data. And, due to its broad bandwidth, it enables both high-data-rate personal-area network (PAN) wireless connectivity and longer-range, low-data-rate applications.

The term *ultra wideband* was coined in the late 1980s, apparently by the U.S. Department of Defense [1], and the actual technology behind UWB has been known by many other names throughout its history, including baseband communication, carrier free communication, impulse radio, large relative bandwidth communication, nonsinusoidal communication, orthogonal functions, sequency theory, time domain, video-pulse transmission, and Walsh waves communication [2].

More recently, with the UWB spectrum allocation in the United States, a better definition for UWB is “available spectrum,” independent of the type of technique used to transmit the signal. In this case, it is imperative that transmissions over the UWB spectrum be able to coexist with other services without causing harmful interference.

The credit for developing UWB technology belongs to many innovative thinkers and scientists over the last 50 years. Interest in the technology has been steady, with more than 200 technical papers published in journals between 1960 and 1999 on the topic and more than 100 U.S. patents issued on UWB or UWB-related technology [3]. It should be noted that, given the lack of spectrum regulations, the early work was performed without specific commercial applications in mind, which would eventually become necessary for successful product deployment.

After decades of development, UWB is now most compelling in that its standards are in place and the timing is finally right for this enabling technology to achieve mass adoption. It is particularly interesting that early work on pulse-based transmission led to the UWB spectrum allocation. In the United States, UWB spectrum allocation allowed development of commercial products that led to non-pulse-based transmission techniques.