Ultra-Wideband Communications Systems

Multiband OFDM Approach

W. Pam Siriwongpairat
K. J. Ray Liu

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To my parents, Sawai and Pimjai Siriwongpairat

—WPS

To Jeffry and Joanne Liu

—KJRL

PREFACE

Ultra-wideband (UWB) has emerged as a technology that offers great promise to satisfy the growing demand for low-cost, high-speed digital wireless indoor and home networks. The enormous bandwidth available, the potential for high data rates, and the potential for small size and low processing power along with low implementation cost all present a unique opportunity for UWB to become a widely adopted radio solution for future wireless home-networking technology.

UWB is defined as any transmission that occupies a bandwidth of more than 20% of its center frequency, or more than 500 MHz. In 2002, the Federal Communications Commission (FCC) has mandated that UWB radio transmission can legally operate in the range 3.1 to 10.6 GHz at a transmitter power of −41.3 dBm/MHz. The use of UWB technology under the FCC guidelines can provide enormous capacity over short ranges. This can be seen by considering Shannon's capacity equation, which shows that increasing channel capacity requires linear increases in bandwidth, whereas similar channel capacity increases would require exponential increases in power. Currently, UWB technology is able to support various data rates, ranging from 55 to 480 Mbps, over distances up to 10 meters. In addition, it is expected that UWB devices will consume very little power and silicon area, as well as provide low-cost solutions that can satisfy consumer market demands.

Nevertheless, to fulfill these expectations, UWB research and development have to cope with several challenges, including high-sensitivity synchronization, ability to capture the multipath energy, low-complexity constraints, strict power limitations, scalability, and flexibility. Such challenges require advanced digital signal-processing expertise to develop systems that could take advantage of the UWB spectrum and support future indoor wireless applications.

This book provides comprehensive coverage of the fundamental issues in UWB technology, with particular focus on the *multiband orthogonal frequency-division multiplexing* (multiband OFDM) approach, which has been a leading proposal in the IEEE 802.15.3a standard and has recently been adopted in the ECMA standard for wireless personal area networks. The book also explores several major advanced state-of-the-art technologies to enhance the performance of the standardized multiband OFDM approach.

In Chapter 1 we provide an introduction to UWB communications. In this chapter we present a comprehensive overview of UWB radios and review the historical development of UWB. Then we discuss the advantages, challenges, and applications of UWB technology.

In Chapter 2 we describe the characteristics of UWB channels and establish a mathematical channel model for the analysis in subsequent chapters.

Chapter 3 provides an overview of UWB single-band approaches. In this chapter we describe the signal modeling and transceiver design of single-band approaches. Then we derive the bit-error-rate performance of single-band UWB systems. Performance analysis is provided for both single- and multiple-antenna UWB systems.

Chapter 4 is an overview of the multiband OFDM approach. In this chapter we provide the fundamental background for the multiband OFDM approach used in subsequent chapters.

In Chapter 5 we extend the multiband OFDM approach to a multiple-antenna system. In this chapter we first describe a multiple-input multiple-output coding framework for UWB multiband OFDM systems. We show that a combination of space–time–frequency coding and hopping multiband OFDM modulation can fully exploit all of the available spatial and frequency diversities inherent in UWB environments.

In Chapter 6 we analyze the performance of UWB multiband OFDM systems under realistic UWB channels. We characterize pairwise error and outage probabilities in UWB multiband OFDM systems, based on the multipath-clustering phenomenon of UWB channels. The analysis is first provided for single-antenna systems, then extended to multiantenna systems.

Chapter 7 extends the performance analysis in Chapter 6 to a more practical scenario. Specifically, we provide a performance analysis of multiband OFDM systems that not only captures the characteristics of realistic UWB channels, but also takes into consideration the imperfection of frequency and timing synchronization and the effect of intersymbol interference.

In Chapter 8 we introduce a differential UWB scheme as an alternative approach that bypasses channel estimation and provides a good trade-off between performance and complexity in UWB communications systems. We review a basic concept of differential OFDM, then describe a differential multiband OFDM system and analyze its performance. Both single- and multiantenna differential UWB systems are considered.

In Chapter 9 we present a power-controlled channel allocation scheme for multiband OFDM systems. The scheme allocates subbands and transmitted power among UWB users to minimize overall power consumption. This allows a UWB multiband OFDM system to operate at a low transmitter power level while still achieving the performance desired.

In Chapter 10 we introduce cooperative communications in UWB systems to enhance the performance and coverage of UWB by exploiting the broadcasting nature of wireless channels and cooperation among UWB devices. The principal concept of cooperative communications is presented, and then it is applied to multiband OFDM

systems. Performance analysis and optimum power allocation of cooperative UWB multiband OFDM systems are provided.

We would like to express our gratitude to Dr. Thanongsak Himsoon, who contributed the major part of Chapter 8, and to Hung-Quoc Lai for his contributions to Chapters 4 and 7. We also would like to thank Dr. Weifeng Su, Dr. Zhu Han, and Dr. Masoud Olfat for their research represented in several works described in the book.

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1

INTRODUCTION

In the near future, indoor communications of any digital data—from high-speed signals carrying multiple HDTV programs to low-speed signals used for timing purposes—will be shared over a digital wireless network. Such indoor and home networking is unique, in that it simultaneously requires high data rates (for multiple streams of digital video), very low cost (for broad consumer adoption), and very low power consumption (for embedding into battery-powered handheld appliances). With its enormous bandwidth, *ultra-wideband* (UWB) provides a promising solution to satisfying these requirements and becomes an attractive candidate for future wireless indoor networks.

We begin with an overview of UWB radios and review the historical development of UWB. Next, we present the key benefits of UWB. Then we discuss the application potential of UWB technology for wireless communications. Finally, an overview of UWB transmission schemes is presented, and the challenges in designing UWB communication systems are discussed.

1.1 OVERVIEW OF UWB

The concept of UWB was developed in the early 1960s through research in time-domain electromagnetics, where impulse measurement techniques were used to characterize the transient behavior of a certain class of microwave networks [Ros63]. In the late 1960s, impulse measurement techniques were applied to the design of wideband antenna elements, leading to the development of short-pulse radar and communications systems. In 1973, the first UWB communications patent was awarded for a short-pulse receiver [Ros73]. Through the late 1980s, UWB was referred to as *baseband*, *carrier-free*, or *impulse* technology. The term *ultra-wideband* was coined in approximately 1989 by the U.S. Department of Defense. By 1989, UWB theory, techniques, and many implementation approaches had been developed for a wide range of applications, such as radar, communications, automobile collision avoidance,

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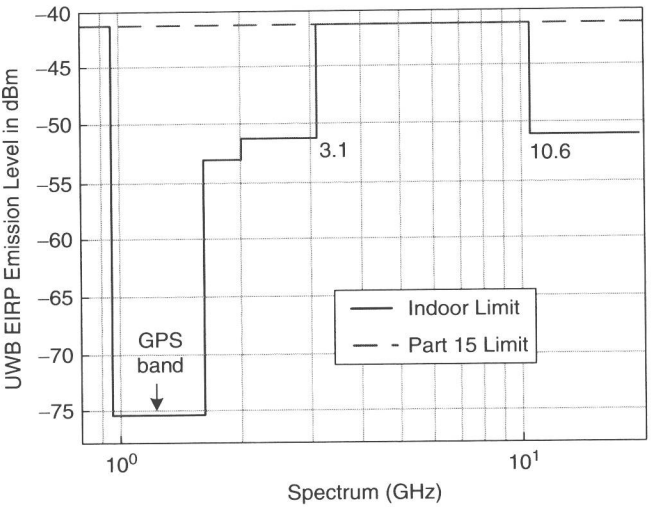

Figure 1.1 UWB spectral mask for indoor communication systems.

positioning systems, liquid-level sensing, and altimetry. However, much of the early work in the UWB field occurred in the military or was funded by the U.S. government within classified programs. By the late 1990s, UWB technology had become more commercialized and its development had accelerated greatly. For an interesting and informative review of UWB history, the interested reader is referred to [Bar00].

A substantial change in UWB history occurred in February 2002, when the, U.S. Federal Communications Commission (FCC) issued UWB rulings that provided the first radiation limitations for UWB transmission and permitted the operation of UWB devices on an unlicensed basis [FCC02]. According to the FCC rulings, UWB is defined as any transmission scheme that occupies a fractional bandwidth greater than 0.2 or a signal bandwidth of more than 500 MHz. The fractional bandwidth is defined as B/f_c, where $B \triangleq f_H - f_L$ represents the -10 dB bandwidth and $f_c \triangleq (f_H + f_L)/2$ denotes the center frequency. Here f_H and f_L are the upper frequency and the lower frequency, respectively, measured at -10 dB below the peak emission point. Based on [FCC02], UWB systems with $f_c > 2.5$ GHz need to have a -10 dB bandwidth of at least 500 MHz, whereas UWB systems with $f_c < 2.5$ GHz need to have a fractional bandwidth of at least 0.2. The FCC has mandated that UWB radio transmission can legally operate in the range 3.1 to 10.6 GHz, with the power spectral density (PSD) satisfying a specific spectral mask assigned by the FCC. In particular, Fig. 1.1 illustrates the UWB spectral mask for indoor communications under Part 15 of the FCC's rules [FCC02]. According to the spectral mask, the PSD of a UWB signal measured in the 1-MHz bandwidth must not exceed -41.3 dBm, which complies with the Part 15 general emission limits for successful control of radio interference. For particularly sensitive bands such as the global positioning system (GPS) band (0.96 to 1.61 GHz), the PSD limit is much lower. As depicted in

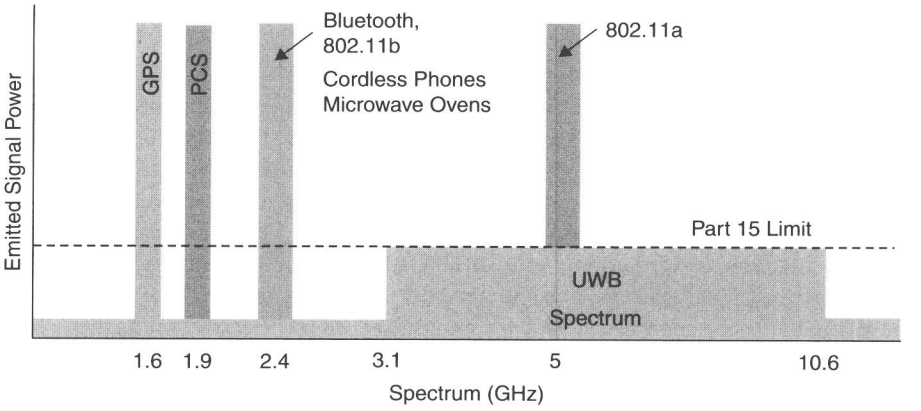

Figure 1.2 Spectrum of UWB and existing narrowband systems.

Fig. 1.2, such a ruling allows UWB devices to overlay existing narrowband systems while ensuring sufficient attenuation to limit adjacent channel interference. Although at present, UWB operation is permitted only in the United States, regulatory efforts are under way in many countries, especially in Europe and Japan [Por03]. Market drivers for UWB technology are many, even at this early stage, and are expected to include new applications in the next few years.

1.2 ADVANTAGES OF UWB

Due to its ultra-wideband nature, UWB radios come with unique benefits that are attractive for radar and communications applications. The principal advantages of UWB can be summarized as follows [Kai05]:

- Potential for high data rates
- Extensive multipath diversity
- Potential small size and processing power together with low equipment cost
- High-precision ranging and localization at the centimeter level

The extremely large bandwidth occupied by UWB gives the potential of very high theoretical capacity, yielding very high data rates. This can be seen by considering *Shannon's capacity equation* [Pro01],

$$C = B \log\left(1 + \frac{S}{N}\right), \tag{1.1}$$

where C is the maximum channel capacity, B the signal bandwidth, S the signal power, and N the noise power. Shannon's equation shows that the capacity can be improved by increasing the signal bandwidth or the signal power. Moreover, it shows that increasing channel capacity requires linear increases in bandwidth, while similar channel capacity increases would require exponential increases in power. Thus, from

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