CHAPTER 1

Introduction to Ultra Wideband

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1.1 INTRODUCTION

Wireless communication systems have evolved substantially over the last two decades. The explosive growth of the wireless communication market is expected to continue in the future, as the demand for all types of wireless services is increasing. New generations of wireless mobile radio systems aim to provide flexible data rates (including high, medium, and low data rates) and a wide variety of applications (like video, data, ranging, etc.) to the mobile users while serving as many users as possible. This goal, however, must be achieved under the constraint of the limited available resources like spectrum and power. As more and more devices go wireless, future technologies will face spectral crowding, and coexistence of wireless devices will be a major issue. Therefore, considering the limited bandwidth availability, accommodating the demand for higher capacity and data rates is a challenging task, requiring innovative technologies that can coexist with devices operating at various frequency bands.

Ultra wideband (UWB), which is an underlay (or sometimes referred as shared unlicensed) system, coexists with other licensed and unlicensed narrowband systems. The transmitted power of UWB devices is controlled by the regulatory agencies [such as the Federal Communications Commission (FCC) in the United States], so that narrowband systems are affected from UWB signals only at a negligible level. UWB systems, therefore, are allowed to coexist with other technologies only under stringent power constraints. In spite of this, UWB offers attractive solutions for many wireless communication areas, including wireless personal area networks (WPANs), wireless telemetry and telemedecine, and wireless sensors networks. With its wide bandwidth, UWB has a potential to offer a capacity much higher than the current narrowband systems for short-range applications.

According to the modern definition, any wireless communication technology that produces signals with a bandwidth wider than 500 MHz or a fractional

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bandwidth[1] greater than 0.2 can be considered as UWB. A possible technique for implementing UWB is impulse radio (IR), which is based on transmitting extremely short (in the order of nanoseconds) and low power pulses. Rather than sending a single pulse per symbol, a number of pulses determined by the processing gain of the system are transmitted per symbol. The processing gain serves as a parameter to flexibly adjust data rate, bit error rate (BER), and coverage area of transmission. Pulses can occupy a location in the frame based on the specific pseudo random (PN) code assigned for each user (as in the case of time-hopping UWB). Other implementations, such as direct sequence spreading, are also popularly used with impulse radio-based implementations. Impulse radio is advantageous in that it eliminates the need for up- and down-conversion and allows low-complexity transceivers. It also enables various types of modulations to be employed, including on–off keying (OOK), pulse-amplitude-modulation (PAM), pulse-position-modulation (PPM), phase-shift-keying (PSK), as well as different receiver types such as the energy detector, rake, and transmitted reference receivers.

Another strong candidate for UWB is multicarrier modulation, which can be realized using orthogonal frequency division multiplexing (OFDM). OFDM has become a very popular technology due to its special features such as robustness against multipath interference, ability to allow frequency diversity with the use of efficient forward error correction (FEC) coding, capability of capturing the multipath energy efficiently, and ability to provide high bandwidth efficiency through the use of sub-band adaptive modulation and coding techniques. OFDM can overcome many problems that arise with high bit rate communication, the most serious of which is time dispersion. In OFDM, the data-bearing symbol stream is split into several lower rate streams, and these sub-streams are transmitted on different carriers. Since this increases the symbol period by the number of nonoverlapping carriers (sub-carriers), multipath echoes affect only a small portion of neighboring symbols. Remaining intersymbol interference (ISI) can be removed by cyclically extending the OFDM symbol.

1.1.1 Benefits of UWB

The unique advantages of UWB systems are numerous. First of all, it introduces unlicensed usage of an extremely wideband spectrum, as mentioned above. The underlay usage of spectrum greatly increases spectral efficiency and opens new doors for wireless applications. The introduction of cognitive features along with opportunistic spectrum usage will further enhance current UWB applications.

UWB (both impulse radio and multicarrier) also offers great flexibility of spectrum usage. This system is characterized in fact by a variety of parameters that can enable the design of adaptive transceivers and that can be used for optimizing system performance as a function of the required data rate, range, power, quality-of-service, and user preference. UWB technology is likely to provide high data

[1]Fractional bandwidth $= 2 \cdot (F_H - F_L)/(F_H + F_L)$, where F_H and F_L are the upper and lower edge frequencies, respectively.

rates (on the order of 1 Gbps) over very short range (less than 1 m). The data rate can, however, be easily traded-off for extension in range by designing appropriate adaptive transceivers. Similarly, data rate and range can be traded-off for power, especially for low data rate and short range applications. Most importantly, *the same device* can be designed to provide service for multiple applications with a variety of requirements without the need for additional hardware.

The high temporal resolution of UWB signals results in low fading margins, implying robustness against multipath. Since UWB signals span a very wide frequency range (down to very low frequencies), they show relatively low material penetration losses, giving rise to better link margins. Moreover, often many distinct multipath components can be observed at the receiver (due to the large number of resolvable paths), and the system, therefore, has an excellent energy capturing capability. For example, rake receivers (with coherent combining) can be implemented to lock into multipath echoes, collect energy, and hence improve performance.

Excellent time resolution is another key benefit of UWB signals for ranging applications. Due to the extremely short duration of transmitted pulses, subdecimeter ranging is possible. In IR-UWB systems, no up/down-conversion is required at the transceivers, with the potential benefit of reducing the cost and size of the devices. Other benefits of UWB include low power transmission and robustness against eavesdropping (since UWB signals look like noise).

1.1.2 Applications

UWB has several applications all the way from wireless communications to radar imaging, and vehicular radar. The ultra wide bandwidth and hence the wide variety of material penetration capabilities allows UWB to be used for radar imaging systems, including ground penetration radars, wall radar imaging, through-wall radar imaging, surveillance systems, and medical imaging. Images within or behind obstructed objects can be obtained with a high resolution using UWB.

Similarly, the excellent time resolution and accurate ranging capability of UWB can be used for vehicular radar systems for collision avoidance, guided parking, etc. Positioning location and relative positioning capabilities of UWB systems are other great applications that have recently received significant attention.

Last but not least is the wireless communication application, which is arguably the reason why UWB became part of the wireless world, including wireless home networking, high-density use in office buildings and business cores, UWB wireless mouse, keyboard, wireless speakers, wireless USB, high-speed WPAN/WBAN, wireless sensors networks, wireless telemetry, and telemedecine.

1.1.3 Challenges

In spite of all the advantages of UWB, there are several fundamental and practical issues that need to be carefully addressed to ensure the success of this technology in the wireless communication market. Multiaccess code design, multiple access interference (MAI) cancellation, narrowband interference (NBI) detection and cancellation, synchronization of the receiver to extremely narrow pulses, accurate modeling of UWB channels, estimation of multipath channel delays and coefficients, and adaptive transceiver design are some of the issues that still require a great deal of investigation. In addition to the above physical layer issues, the fundamental role of UWB technology in wireless networks is still open, and a wide range of research questions continue to present challenges, such as the particular role of UWB in wireless ad-hoc and sensors networks.

Among the challenges of UWB, a limited list can be given as follows:

- Coexistence with other services and handling strong narrowband interference;
- Shaping (adapting) spectrum of transmitted signals (multiband, OFDM-based UWB, etc.);
- Practical, simple, and low-power transceiver design;
- Accurate synchronization and channel parameter estimation;
- High sampling rate for digital implementations;
- Powerful processing capabilities for high performance and coherent digital receiver structures;
- Wideband RF component designs (such as antennas, low noise amplifiers, etc.);
- Multiple accessing, multiple access code designs, and multiuser interference;
- Accurate modeling of the ultra wideband channel in various environments;
- Adaptive system design and cross-layer adaptation for UWB;
- UWB tailored network design.

1.2 SCOPE OF THE BOOK

This book covers several aspects of the UWB technology, starting from the radio aspects all the way to UWB networking and UWB applications with the aim of shedding light on the UWB challenges listed at the end of the previous section. Although more emphasis is given to impulse radio UWB, OFDM-based UWB is also discussed throughly.

In UWB, the transmission bandwidth is extremely large, leading to multiple resolvable paths. At a given total transmitted power, power is distributed over an extremely large bandwidth. In the time domain, the high resolvability due to ultra wide bandwidth can affect the receiver performance. Since the total power is distributed over many multipath components, the power on each path might be very low [1]. Also, due to the broadband nature of UWB signals, the components propagating along different paths may undergo different frequency selective distortions. As a result, a received signal is made up of pulses with different pulse shapes, which makes synchronization, channel estimation, and optimal receiver design more challenging than in other wideband systems. In addition, implementation of standard techniques in digital UWB receivers would require very fast analog-to-digital (A/D) converters, operating in the gigahertz range, and thus high power consumption. As a result, synchronization and channel estimation are two of the most important issues in UWB. Therefore, one whole chapter will be devoted to discussion of synchronization and channel estimation issues. The problem of low-complexity channel estimation and synchronization issues in digital UWB receivers will be considered in detail in Chapter 2, "UWB Channel Estimation and Synchronization."

A very close subject to UWB synchronization is the accurate estimation of time of arrival of UWB signals. Accurate synchronization and fine resolution in time of arrival are not only important for reception and detection, but also for accurate ranging. Locationing and ranging applications can be developed on the basis of proper and low complex synchronization algorithms. Hence, Chapter 3, "Ultra Wideband Geolocation," covers this aspect. An overview of conventional ranging and positioning techniques, as well as the study of their performance for range estimation, is provided in this chapter.

Selecting the appropriate modulation technique for UWB still remains a major challenge. There are various possible modulation options depending on the application, design specifications and constraints, range, transmission and reception power, quality of service requirements, regulatory requirements, hardware complexity, data rate, reliability of channel, and capacity. Therefore, it is crucial to select the appropriate modulation according to purpose. Possible choices for UWB are binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), PAM, OOK, PPM, pulse interval modulation (PIM), and pulse shape modulation (PSM) [2]. Among these options, BPSK is the most popular in UWB applications due to its smooth power spectrum and low BER. However, accurate phase detection of the modulated signal in BPSK requires complex channel estimation algorithms at the receiver. Compared with BPSK, OOK and PPM only require the knowledge of the presence or absence of energy and therefore channel estimation is not necessary for noncoherent reception. However, it is also possible to employ coherent receivers for these modulations for improved performance. Noise levels over the wireless channel also influence the choice of modulation. Higher-order modulation ensures high data rate at the cost of poor BER over noisy channels. Therefore, lower order modulation for low data rate applications is desirable under poor channel conditions. Transmission over multiple frequency bands or over multiple carriers, and various multiple accessing options such as time hopping (TH) and direct sequence (DS) could also be considered under the umbrella of UWB modulations. These issues will be covered in Chapter 4, "UWB Modulation Options," where several modulation options will be compared.

Similar to modulation options, there are also various ways to control the UWB spectrum shape by pulse shaping. As mentioned in the previous section, for appropriate spectrum overlay, the local regulators impose spectral masks that strictly constrain the transmission power of a UWB signal. Spectral masks are often not uniform, that is, there are stronger restrictions in some parts of the spectrum compared with others. The spectrum of a transmitted signal is influenced by the modulation format, the multiple access scheme, and most critically by the spectral shape of the underlying UWB pulse. The choice of the pulse shape is thus a key design decision in UWB systems. Chapter 5, "Ultra Wideband Pulse Shaper Design," will discuss the UWB pulse design issues.

Another important challenge in UWB wireless systems is the design of antennas. Most difficult issues include broadband response of impedance matching, gain, phase, radiation patterns, and polarization. Therefore, Chapter 6, "Antenna Issues," discusses antenna design in UWB systems along with the effects of antenna design on the transmission of UWB signals. Also, antenna design and pulse shaping issues are related in this chapter, and special considerations are given for UWB antenna design by taking pulse sources into account.

Many of the current applications of UWB require power efficient, low cost, and small-sized UWB transceivers. Therefore, practical and low complexity implementation of transceivers is of vital importance for the successful penetration of the UWB technology. UWB transceiver requirements and related trade-offs regarding practical designs will be discussed in Chapter 7, "Ultra Wideband Receiver Architectures." Different receiver structures will be discussed and these various approaches will be compared in terms of their ability to exploit *a priori* information (side information). The robustness of these various receivers depending on the availability and accuracy of the side information will also be investigated.

In order to be able to develop efficient and high performance transceiver algorithms and to design reliable radio systems, accurate and realistic modeling of the radio channel is needed. Unfortunately, the mechanisms that govern radio propagation in a wireless communication channel are complex and diverse. Consequently, channel modeling has been a subject of intense research for a long time. UWB channel modeling presents many differences compared with the well-known narrowband channel models. Therefore, Chapter 8, "Ultra Wideband Channel Modeling and its Impact on System Design," will provide an overview of the UWB propagation channel modeling work and its impact on the UWB communication system design. Establishment of the fundamental concepts and background for modeling the UWB multipath propagation channel, discussion of the two commonly used channel sounding techniques, description of the UWB statistical-based channel modeling work, and discussion of the impact of UWB channel on the system design are some of the important aspects that will be discussed in this chapter.

Exploiting the radio channel properties for improving the transceiver performance has a rich and long history in the wireless communication literature. Multiple antenna systems is one of these techniques that has been used for different purposes including diversity combining, interference cancellation, and data rate increase. Multi-input multi-output (MIMO) antenna systems is a major topic that has received significant interest in the wireless community over recent years. MIMO, which is often interpreted as an add-on technology, can be incorporated in any type of wireless technology, one of which is UWB. Therefore, in Chapter 9, "MIMO and UWB," the potential benefits of MIMO and UWB in terms of range extension, data rate improvement, interference rejection, and potential technological simplifications are introduced. Also, in the same chapter, a literature review on UWB multiantenna techniques, subdivided in spatial multiplexing, spatial diversity, beam-forming, and related topics, is provided. Complementing the channel models of Chapter 8, spatial UWB channel measurements and modeling will be highlighted to provide a solid basis for algorithmic design of MIMO and UWB transceivers.

In order to effectively share the available spectrum between different users, multiple accessing is of fundamental importance in wireless communication systems. Time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA) are the most popular multi-access techniques for wireless systems. As in any communication system, multiple access is a key issue in UWB networks. In an ideal scenario, the system should be designed in such a way that there will be no interference from other users on a desired user. In reality this is not the case, as the systems are trying to provide access to more users so that the spectrum can be exploited more efficiently. As a result, multiple-access interference (such as co-channel interference, adjacent channel interference, and correlation of the other users code with the desired user code) becomes a tricky issue in wireless communications. Chapter 10, "Multiple-access Interference Mitigation in Ultra Wideband systems," covers the issues related to multiple-access IR-UWB, and explains signal processing techniques for combating the effects of interfering users on the detection of information symbols.

Another major interference source, specifically in UWB systems, is narrowband interference. The influence of narrowband technologies on UWB system can be significant, and in the extreme case, these signals may completely jam the UWB receiver. Even though narrowband signals interfere with only a small fraction of the UWB spectrum, due to their relatively high power with respect to the UWB signal, the performance and capacity of UWB systems can be affected considerably [3]. Recent studies show that the BER of UWB receivers is greatly degraded due to the impact of narrowband interference [4–8]. The high processing gain of the UWB signal can cope with the narrowband interferers to some extent. In many cases, however, even the large processing gain alone is not sufficient to suppress the effect of the high power interferers. Therefore, either the UWB system needs to avoid transmission over frequencies of strong narrowband interferers, or UWB receivers need to employ NBI suppression techniques to improve performance, capacity, and range. Narrowband interference issues will be discussed in detail in Chapter 11, "Narrowband Interference Issues in Ultra Wideband Systems."

Several of the above issues affect both impulse radio and multicarrier-based implementations of UWB. There are some specific issues and advantages, however, related to the OFDM based approach that deserved at least one whole chapter, considering also that the multiband OFDM system is currently one of the leading proposals for the IEEE 802.15.3a standard and is supported by more than 100 large companies and universities. For this purpose, Chapter 12, "Orthogonal Frequency Division Multiplexing for Ultra Wideband Communications," discusses in detail the OFDM based UWB approach.

The physical (PHY) and multiple access issues do not constitute the only research and development challenges and opportunities for UWB. Many other aspects are related to networking, adaptation, and crosslayer optimization. UWB networks have the potential to offer high bandwidth rates with low spectral energy, besides other features such as accurate localization and lower probability of jamming and detection. This has led to an increased interest in building UWB-based data networks. For instance, the IEEE TG802.15.3a standards group is in the process of developing an alternative high-speed link layer design conformable with the IEEE 802.15.3 wireless personal area network (WPAN) multiple-access protocol, operating at a few tens of meters and speeds of the order of several hundred megabits per second. UWB based networks are also being considered for wireless sensor networks and military applications. Chapter 13, "UWB Networks and Applications," contains a survey that will cover these issues.

Besides the strong push for high-data-rate UWB networks, there has also been a growing interest towards applying UWB to low-power and low-data-rate networks, such as in sensor networks [9]. The low bit rate applications and network issues of UWB will be discussed in Chapter 14, "Low-bit-rate UWB Networks."

Related to the UWB networking, one of the biggest challenge is to develop efficient routing protocols for mobile ad-hoc networks. The routing protocols in ad-hoc networks in general, and some specific aspects of these for UWB, will be discussed in detail in Chapter 15, "An Overview of Routing Protocols for Mobile Ad-hoc Networks." Power (or energy) aware routing protocols, which are described in this chapter, can be efficiently applied to ad-hoc networks with UWB.

As mentioned in the previous section, one of the great benefits of UWB is the flexibility for adaptive transceiver and network design. The adaptive network design and cross-layer optimization techniques are gaining significant interest in wireless communications. Therefore, Chapter 16, "Adaptive UWB Systems," focuses on adaptivity in UWB systems. In particular, it addresses the problem of how to exploit the UWB adaptability to support wireless links in ad-hoc networks as well as how to dynamically set up wireless communications among devices distributed in a given area, without the support of a centralized infrastructure.

Finally, a case study chapter on the application of UWB on wireless sensors network and for geolocationing is provided in Chapter 17, "UWB Location and Tracking—a Practical Example of an UWB-based Sensor Network." Impulse radio-based UWB technology has a number of inherent properties which are well suited to sensor network applications. In particular, impulse radio-based UWB systems (with potentially low complexity and low-cost designs and with noise-like signals) are resistant to severe multipath and have very good time domain resolution supporting location and tracking applications. In this chapter, an example architecture of a sensor system based on low-power, low-complexity UWB transceivers and a TDMA-based MAC will be provided.

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