Chapter 1

INTRODUCTION

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1.1 Fundamentals

1.1.1 Overview of UWB

Ultra wideband (UWB) communication systems can be broadly classified as any communication system whose instantaneous bandwidth is many times greater than the minimum required to deliver particular information. This excess bandwidth is the defining characteristic of UWB. Understanding how this characteristic affects system performance and design is critical to making informed engineering design decisions regarding UWB implementation.

The very first wireless transmission, via the Marconi Spark Gap Emitter, was essentially a UWB signal created by the random conductance of a spark. The instantaneous bandwidth of spark gap transmissions vastly exceeded their information rate. Users of these systems quickly discovered some of the most important wireless system design requirements: providing a method to allow a specific user to recover a particular data stream, and allowing all the users to efficiently share the common spectral resource. The UWB technology of the time did not offer a practical answer to either requirement. These problems were solved during the evolution into carrier-based communications systems with regulatory bodies, such as the Federal Communications Commission (FCC) in the United States. The FCC is responsible for carving the spectrum into narrow slices, which are then licensed to various users.

This regulatory structure effectively outlawed UWB systems and relegated UWB to purely experimental work for a very long time.

Within the past 40 years, advances in analog and digital electronics and UWB signal theory have enabled system designers to propose some practical UWB communications systems. Over the past decade, many individuals and corporations began asking the FCC for permission to operate unlicensed UWB systems concurrent with existing narrowband signals. In 2002, the FCC decided to change the rules to allow UWB system operation in a broad range of frequencies.[1] In the proceedings of the FCC UWB rule-making process [14], one can find a vast array of claims relating to the expected utility and performance of UWB systems, some of them quite fantastic. Testing by the FCC, FAA, and DARPA has uniformly shown that UWB still conforms to Maxwell's Equations and the laws of physics.

UWB has several features that differentiate it from conventional narrowband systems:

1. Large instantaneous bandwidth enables fine time resolution for network time distribution, precision location capability, or use as a radar.
2. Short duration pulses are able to provide robust performance in dense multipath environments by exploiting more resolvable paths.
3. Low power spectral density allows coexistence with existing users and has a Low Probability of Intercept (LPI).
4. Data rate may be traded for power spectral density and multipath performance.

What makes UWB systems unique is their large instantaneous bandwidth and the potential for very simple implementations. Additionally, the wide bandwidth and potential for low-cost digital design enable a single system to operate in different modes as a communications device, radar, or locator. Taken together, these properties give UWB systems a clear technical advantage over other more conventional approaches in high multipath environments at low to medium data rates.

Currently, numerous companies and government agencies are investigating the potential of UWB to deliver on its promises. A wide range of UWB applications have been demonstrated [15, 16] but much more work needs to be done. Designers are still faced with the same two problems that Marconi faced more than 200 years ago: How does a particular user recover a particular data stream, and how do all the users efficiently share the common spectral resource? Additionally, now that wireless communications have progressed beyond the point where just making it work at all was sufficient, a designer must face a third and perhaps more important question: Can a UWB system be built with a sufficient performance or cost advantage over conventional approaches to justify the effort and investment?

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[1] The FCC defines UWB as a signal with either a *fractional bandwidth* of 20% of the center frequency or 500 MHz (when the center frequency is above 6 GHz) [14]. The formula proposed by the FCC commission for calculating the fractional bandwidth is $2(f_H - f_L)/(f_H + f_L)$ where f_H represents the upper frequency of the -10 dB emission limit and f_L represents the lower frequency limit of the -10 dB emission limit.

1.1.2 A Brief History of UWB Signals

Impulse UWB Signals

The modern era in UWB started in the early 1960s from work in time domain electromagnetics and was led by Harmuth at Catholic University of America, Ross and Robins at Sperry Rand Corporation, and van Etten at the United States Air Force (USAF) Rome Air Development Center [2,3]. Harmuth's work culminated in a series of books and articles between 1969 and 1990 [23–32]. Harmuth, Ross, and Robbins all referred to their systems as baseband radio. During the same period, engineers at Lawrence Livermore, Los Alamos National Laboratories (LLNL and LANL), and elsewhere performed some of the original research on pulse transmitters, receivers, and antennas.

A major breakthrough in UWB communications occurred as a result of the development of the sampling oscilloscope by both Tektronix and Hewlett-Packard in the 1960s. These sampling circuits not only provided a method to display and integrate UWB signals, but also provided simple circuits necessary for subnanosecond, baseband pulse generation [3, 17]. In the late 1960s, Cook and Bernfeld published a book [11] that summarized Sperry Rand Corporation's developments in pulse compression, matched filtering, and correlation techniques. The invention of a sensitive baseband pulse receiver by Robbins in 1972, as a replacement for the sampling oscilloscope, led to the first patented design of a UWB communications system by Ross at the Sperry Rand Corporation [45].

In parallel with the developments in the United States, extensive research into UWB was conducted in the former Soviet Union. In 1957 Astanin developed an X-band 0.5 ns duration transmitter for waveguide study at the A. Mozjaisky Military Air Force Academy, while Kobzarev et al. conducted indoor tests of UWB radars at the Radioelectronics Institute of the USSR Academy of Science [4]. As in the United States, development accelerated with the advent of sampling oscilloscopes.

By the early 1970s, the basic designs for UWB radar and communication systems evolved with advances in electronic component technology. The first ground-penetrating radar based on UWB was commercialized in 1974 by Morey at the Geophysical Survey Systems Corporation. In 1994, McEwan at LLNL developed the Micropower Impulse Radar (MIR), which provided a compact, inexpensive, low power UWB system for the first time [35].

Around 1989, the Department of Defense created the nomenclature ultra wideband to describe communication via the transmission and reception of impulses. The U.S. government has been and continues to be a major backer of UWB research. The FCC effort to authorize the use of UWB systems [14] spurred a great amount of interest and fear of UWB technology. In response to the uncertainty of how UWB systems and existing services could operate together, several UWB interference studies were sponsored by the U.S. government.

In 1993, Robert Scholtz at the University of Southern California wrote a landmark paper that presented a multiple access technique for UWB communication systems [38]. Scholtz's technique allocates each user a unique spreading code that determines specific instances in time when the user is allowed to transmit. With a viable multiple access scheme, UWB became capable of supporting not only radar and point-to-point communications but wireless networks as well.

With the advent of UWB as a viable candidate for wireless networks, a number of researchers in the late 1990s and early 2000s began detailed investigations into UWB propagation. These propagation studies, and the channel models developed from the measurement results, culminated in a number of notable publications by Cassioli, Win, Scholtz, Foerster, and Molisch [8, 12, 13, 18, 19, 36, 39, 40, 43, 44]. Additionally, the DARPA-funded Networking in Extreme Environments (NETEX) project began detailed investigations into indoor/outdoor UWB propagation modeling, characterization of the response of building materials to UWB impulses, and characterization of the antenna response to UWB signals.

Recently there has been a rapid expansion of the number of companies and government agencies involved with UWB, growing from a handful in the mid 1990s that included Multispectral Solutions, Time Domain, Aether Wire, Fantasma Networks, LLNL and a few others, to the plethora of players we have today. The FCC, NTIA (National Telecommunications and Information Adminstration), FAA, and DARPA, as well as the previously mentioned companies, spent many years investigating the effect of UWB emissions on existing narrowband systems. The results of those studies were used to inform the FCC on how UWB systems could be allowed to operate. In 2003, the first FCC certified commercial system was installed [37], and in April 2003 the first FCC-compliant commercial UWB chipsets were announced by Time Domain Corporation.

1.1.3 Types of UWB Signals

There are two common forms of UWB: one based on sending very short duration pulses to convey information and another approach using multiple simultaneous carriers. Each approach has its relative technical merits and demerits. Because Impulse UWB (I-UWB) is generally less understood than Multicarrier (MC-UWB), this book primarily focuses on impulse modulation approaches. The most common form of multicarrier modulation, Orthogonal Frequency Division Multiplexing (OFDM), has become the leading modulation for high data rate systems, and much information on this modulation type is available in recent technical literature.

Pure impulse radio, unlike classic communications, does not use a modulated sinusoidal carrier to convey information. Instead, the transmit signal is a series of baseband pulses. Because the pulses are extremely short (commonly in the nanosecond range or shorter), the transmit signal bandwidth is on the order of gigahertz. Note that the fractional bandwidth is greater than 20%, as shown in Figure 1.1. The unmodulated transmit signal as seen by the receiver, in the absence of channel effects, can be represented as

$$s\left(t\right) = \sum_{i=-\infty}^{\infty} A_i\left(t\right) p\left(t - iT_f\right) \tag{1.1}$$

where $A_i(t)$ is the amplitude of the pulse equal to $\pm\sqrt{E_p}$, where E_p is the energy per pulse, $p(t)$ is the received pulse shape with normalized energy, and T_f is the frame

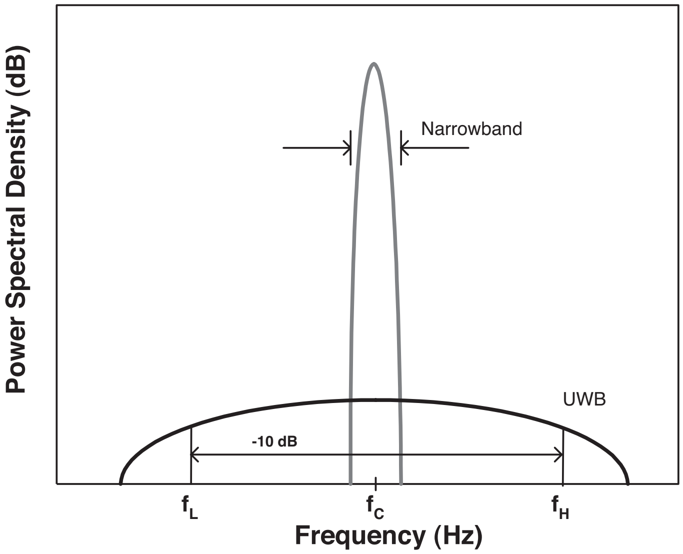


Figure 1.1: Comparison of the Fractional Bandwidth of a Narrowband and Ultra Wideband Communication System.

repetition time. (A UWB frame is defined as the time interval in which one pulse is transmitted.) We also define T_p to be the duration of the pulse. Note that the pulse repetition rate $R_f = \frac{1}{T_f}$ is not necessarily equal to the inverse of the pulse width. In other words, the duty cycle of the transmitted signal is almost always less than 1. In this work we will refer to $s(t)$ as the transmit signal to avoid confusion with the received signal $r(t)$ that includes channel and antenna effects. Most practical systems will use some form of pulse-shaping to control the spectral content of each pulse to conform to regulatory limits.

Multicarrier UWB Signals

Multicarrier communications were first used in the late 1950s and early 1960s for higher data rate HF military communications. Since that time, OFDM has emerged as a special case of multicarrier modulation using densely spaced subcarriers and overlapping spectra, and was patented in the United States in 1970 [9]. However, the technique did not become practical until several innovations occurred. First, the OFDM signal needs precisely overlapping but noninterfering carriers, and achieving this precision requires the use of a real-time Fourier transform [41], which became feasible with improvements in Very Large-Scale Integration (VLSI). Throughout the 1980s and 1990s, other practical issues in OFDM implementation were addressed, such as oscillator stability in the transmitter and receiver, linearity of the power amplifiers, and compensation of channel effects. Doppler spreading caused by rapid time variations of the channel can cause interference between the carriers and held back the development of OFDM until Cimini developed coded multicarrier modulation [10].

OFDM is now used in Asymmetric Digital Subscriber Line (ADSL) services, Digital Audio Broadcast (DAB), Digital Terrestrial Television Broadcast (DVB) in Europe, Integrated Services Digital Broadcasting (ISDB) in Japan, IEEE 802.11a/g, 802.16a, and Power Line Networking (HomePlug). Because OFDM is suitable for high data rate systems, it is also being considered for the fourth generation (4G) wireless services, IEEE 802.11n (high speed 802.11) and IEEE 802.20 (MAN) [34].

MC-UWB is very different from I-UWB. In multicarrier UWB, the complex baseband model transmitted signal has the form

$$s\left(t\right)=\sum_{i=1}^{N}d_{i}\left(t\right)e^{j2\pi i\left(T/T_{s}\right)} \tag{1.2}$$

where N is the number of carriers, $T_s = NT_b$ is the symbol duration, and $d_i(t)$ is the symbol stream modulating the i^{th} carrier. Figure 1.2 illustrates a comparison of the spectrum of I-UWB and MC-UWB transmissions.

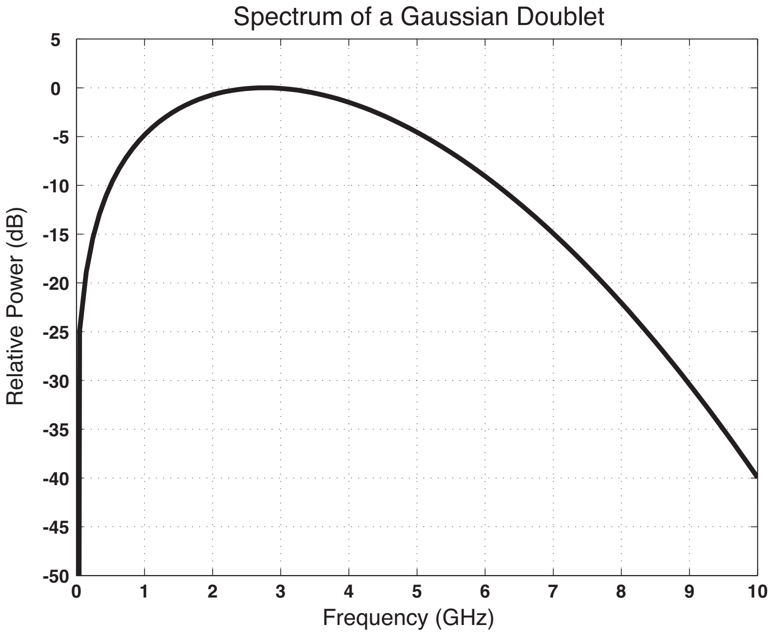
Relative Merits of Impulse Versus Multicarrier

The relative merits and demerits of I-UWB and MC-UWB are controversial issues and have been debated extensively in the standards bodies. One particularly important issue is minimizing interference transmitted by, and received by, the UWB system. MC-UWB is particularly well-suited for avoiding interference because its carrier frequencies can be precisely chosen to avoid narrowband interference to or from narrowband systems. Additionally, MC-UWB provides more flexibility and scalability, but requires an extra layer of control in the physical layer. For both forms of UWB, spread spectrum techniques can be applied to reduce the impact of interference on the UWB system.

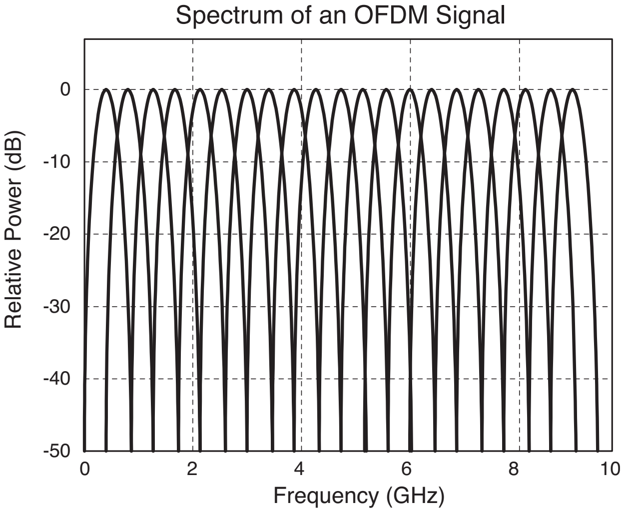
I-UWB signals require fast switching times for the transmitter and receiver and highly precise synchronization. Transient properties become important in the design of the radio and antenna. The high instantaneous power during the brief interval of the pulse helps to overcome interference to UWB systems, but increases the possibility of interference from UWB to narrowband systems. The RF front-end of an I-UWB system may resemble a digital circuit, thus circumventing many of the problems associated with mixed-signal integrated circuits. Simple I-UWB systems can be very inexpensive to construct.

On the other hand, implementing a MC-UWB front-end can be challenging due to the continuous variations in power over a very wide bandwidth. This is particularly challenging for the power amplifier. In the case of OFDM, high-speed FFT processing is necessary, requiring significant processing power.

Another issue in the implementation of a UWB system is the general detection theory assumption that the system operates in an AWGN noise environment. Unfortunately, this is not always true for any real communication system and especially for UWB systems. There can be other signals that are within the UWB passband



(a) Spectrum of a Gaussian Monocycle-Based Impulse UWB Signal



(b) Spectrum of an OFDM-based MC-UWB Signal

Figure 1.2: Comparison of Impulse and Multicarrier UWB Spectrums.

that do not have Gaussian noise statistics. These narrowband signals force a system to operate at higher transmit power or find a way to excise the in-band interference.

1.1.4 Regulatory, Legal, and Other Controversial Issues

On September 1, 1998, the FCC issued a Notice of Inquiry pertaining to the revision of Part 15 rules to allow the unlicensed use of UWB devices [14]. The FCC was motivated by the potential for a host of new applications for UWB technology: high-precision radar, through-wall imaging, medical imaging, remote sensors, and secure voice and data communications. Investigating the potential use of UWB devices presented a very different mode of operation for the FCC. Instead of dividing the spectrum into distinct bands that were then allocated to specific users/services, UWB devices would be allowed to operate overlaid with existing services. Essentially, the UWB device would be allowed to interfere with existing services, ideally at a low enough power level that existing services would not experience performance degradation. The operation of UWB devices in tandem with existing users is a significantly different approach to spectral efficiency than achieving the highest possible data rates in a channel with precisely defined bandwidths. In fact, many have questioned whether the operation of UWB devices is “efficient” in the strict sense of the word, or if it is instead an exercise in interference tolerance.

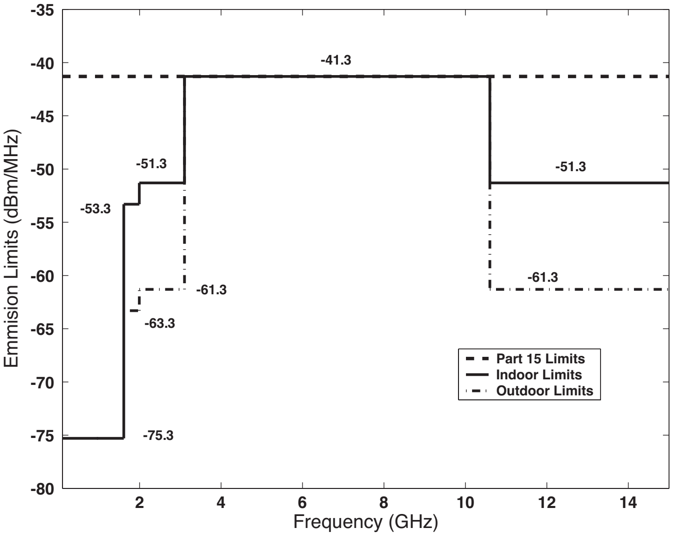
By May 2000, the FCC had received more than 1,000 documents from more than 150 different organizations in response to their Notice of Inquiry, to assist the FCC in developing an appropriate set of specifications. Specifically, the FCC was concerned about the potential interference from UWB transmissions on Global Positioning System (GPS) signals and commercial/military avionics signals. On February 14, 2002, the FCC issued a First Report and Order [14], which classified UWB operation into three separate categories:

1. Communication and Measurement Systems
2. Vehicular Radar Systems
3. Imaging Systems, including Ground Penetrating Radar, Through-Wall Imaging and Surveillance Systems, and Medical Imaging.

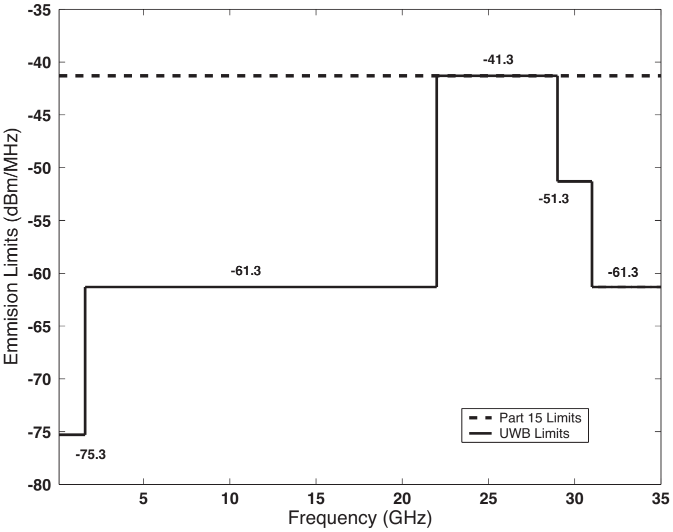
Each category was allocated a specific spectral mask, as shown in Figure 1.3. Table 1.1 summarizes the various UWB operational categories and their allocated bandwidths, along with restrictions on organizations that are allowed to operate in that particular mode.

The FCCs ruling, however, did not specifically address precision location for asset tracking or inventory control. These applications, known as location-aware communication systems, are a hybrid of radar and data communications that use UWB pulses to track the 2-D and 3-D position of an item to accuracies within a few tens of centimeters [15], as well as transmitting information about the item, such as its contents, to a centralized database system.

Note that the FCC has only specified a spectral mask and has not restricted users to any particular modulation scheme. As discussed previously, a number of

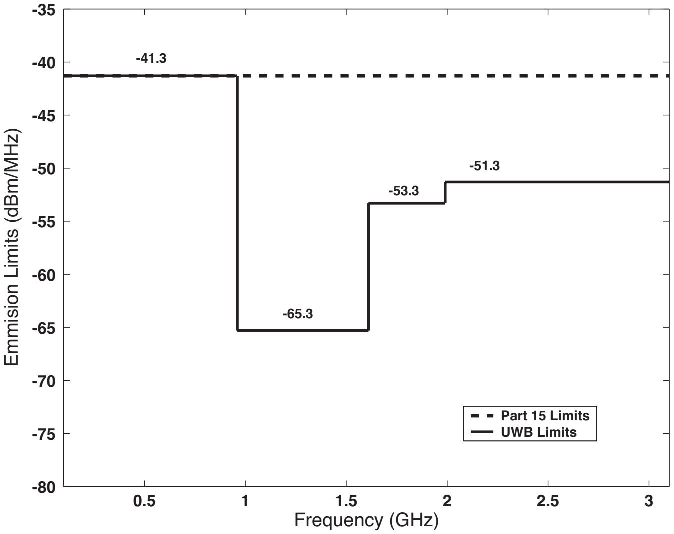


(a) Indoor UWB Communication Systems

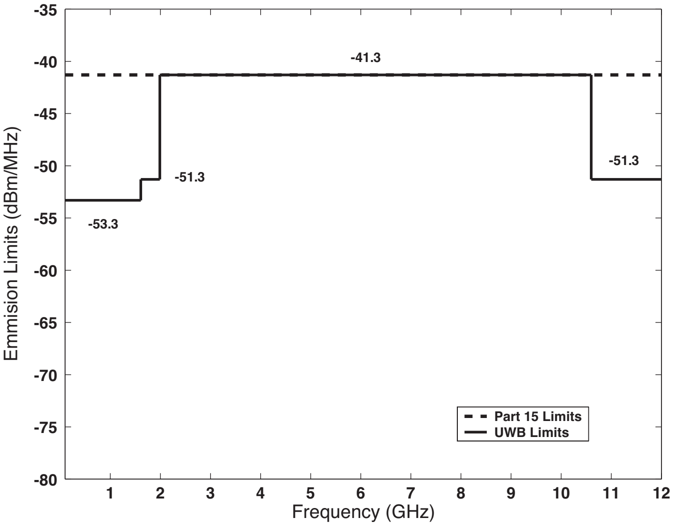


(b) Vehicular Radar

Figure 1.3: FCC Allocated Spectral Mask for Various UWB Applications (continued).

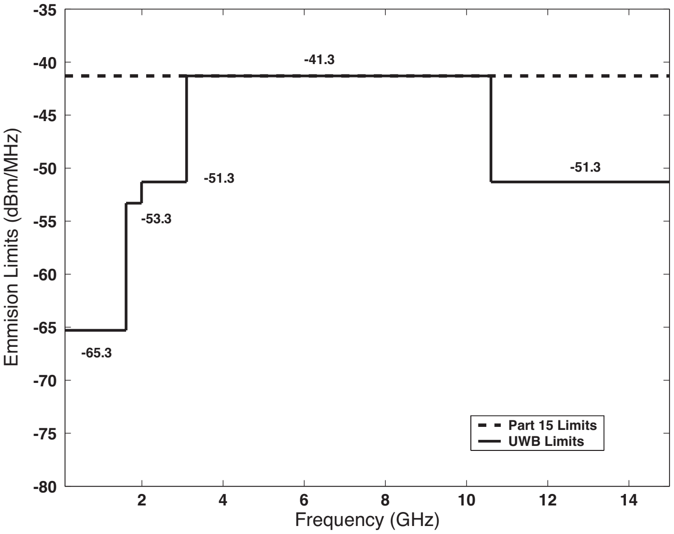


(c) Imaging (Low Frequency)



(d) Imaging (Mid Frequency)

Figure 1.3: (cont.) FCC Allocated Spectral Mask for Various UWB Applications



(e) Imaging (High Frequency)

Figure 1.3: (cont.) FCC Allocated Spectral Mask for Various UWB Applications.

Table 1.1: Summary of FCC Restrictions on UWB Operation (continued).

Application	**Frequency Band for Operation at Part 15 Limits**	**User Restrictions**
Communications and Measurement Systems (sensors)	3.1–10.6 GHz (different emission limits for indoor and outdoor systems)	None
Vehicular Radar for collision avoidance, airbag activation, and suspension system control	24–29 GHz	None
Ground Penetrating Radar to see or detect buried objects	3.1–10.6 GHz and below 960 MHz	Law enforcement, fire and rescue, research institutions, mining, construction

Table 1.1: (cont.) Summary of FCC Restrictions on UWB Operation.

Application	**Frequency Band for Operation at Part 15 Limits**	**User Restrictions**
Wall Imaging Systems to detect objects contained in walls	3.1–10.6 GHz and below 960 MHz	Law enforcement, fire and rescue, mining, construction
Through-wall Imaging Systems to detect location or movement of objects located on the other side of a wall	1.99–10.6 GHz and below 960 MHz	Law enforcement, fire and rescue
Medical Systems for imaging inside people and animals	3.1–10.6 GHz	Medical personnel
Surveillance Systems for intrusion detection	1.99–10.6 GHz	Law enforcement, fire and rescue, public utilities, and industry

organizations are promoting multicarrier techniques, such as OFDM, as a potential alternative to I-UWB for high data rate communications.

Beyond the United States, other countries have been using a similar approach toward licensing UWB technology. In both Europe and Japan, initial studies have been completed, and regulations are expected to be issued in the near future that are expected to harmonize with the FCC mask.

1.2 What Makes UWB Unique?

1.2.1 Time Domain Design

UWB has a very unique set of design requirements, and attempting to apply the principles for traditional narrowband or even broadband communications to the design of I-UWB systems can be misleading. Analysis of I-UWB systems often means examining the impulse response of the system as opposed to the steady state response, particularly when examining the antenna response. Time domain effects can include frequency dependant pulse distortion imparted by RF components or the wireless channel, pulse dispersion produced by the antenna, or timing jitter generated by non-ideal oscillators. For traditional communication systems, these transient effects are only a small fraction of the symbol duration and may often be ignored. In I-UWB systems, these effects directly impact the performance of the overall communication system. For example, timing jitter will lead to imperfect correlation at the receiver or potential loss of data and system synchronization for modulation schemes where data is transmitted in the precise position of a pulse.

1.2.2 Impact of the Antenna

One of the challenges of the implementation of UWB systems is the development of a suitable antenna that would enhance the advantages promised by a pulsed communication system. I-UWB requires antennas that can cover multi-octave bandwidths in order to transmit pulses on the order of a nanosecond in duration with minimal distortion. Because data may be contained in the shape or precise timing of the pulse, a clean impulse response (that is, minimal pulse distortion) can be considered as a primary requirement for a good I-UWB antenna.

While it may be more intuitive for communication engineers to think of the performance of an antenna in terms of its frequency domain characteristics, the response of an antenna to a I-UWB pulse stream can best be described in terms of its temporal characteristics. An ideal UWB antenna needs to be relatively efficient across the entire frequency band with a Voltage Standing Wave Ratio (VSWR) of at most 2:1. To prevent distorting the pulse, an ideal UWB antenna should produce radiation fields with constant magnitude and a phase shift that varies linearly with frequency [5]. An antenna that meets these characteristics will radiate a signal which is only a time derivative of the input signal.

In reality, due to size and cost constraints, practical UWB antennas may not meet the previous requirements. It must also be noted that the antenna induced distortion can change with elevation and azimuth angle. Thus, we assume that such effects will ultimately be included in the assumed channel model. Chapter 3, "Channel Modeling," and Chapter 4, "Antennas," detail channel modeling and antenna effects, respectively.

1.2.3 Propagation and Channel Models

To perform systems-level engineering, UWB propagation characteristics must be considered. UWB differs from conventional communications in that the signal may be overlaid on top of interference. This interference must be considered in the link budget and, in fact, can often be the primary reason for performance limitations. Another issue is the introduction of large numbers of multipath signals that were not resolvable in narrowband communication systems. Measurements of typical UWB channels have revealed dense, multipath-rich environments, allowing for RAKE receivers that can harvest a tremendous amount of energy. Additionally, UWB propagation is highly dependent on the effect the antenna has on the shape and duration of the transmitted pulse.

UWB propagation measurements and modeling are the subjects of ongoing debate in the engineering community; as such, this book does not claim to resolve that debate. Rather, it discusses the basic concepts behind several UWB channel models and some of the differences between narrowband and UWB signal propagation.

1.2.4 Transmitter and Receiver Design

RF design for UWB systems is distinct from traditional narrowband or broadband systems in several ways. The extremely wide bandwidth of a UWB necessitates RF components that have flat frequency responses. Significant deviation, or ripple, in the frequency response of RF components as well as the nonlinearities present in all RF devices will introduce distortion to the UWB signal. UWB transmitted signals also have a very high peak-to-average power ratio (PAPR). As RF components are peak power limited, it becomes important to ensure that all RF devices have a power handling capacity at least as great as the peak power in the UWB signal.

Furthermore, the coexistence of UWB and existing services means that narrowband interfering signals will be detected by the receiver. These narrowband signals can either corrupt the pulse or saturate the RF front-end, decreasing the receiver's dynamic range and effectively limiting the range of the UWB system. Introducing notch filters at the receiver is a potential solution; pulse-shaping techniques, such as those described in [22], provide an alternative method for mitigating narrowband interferers without distorting the UWB waveform.

Most UWB receiver techniques require highly accurate synchronization with the transmitter as well as stable oscillators to maintain synchronization. With certain I-UWB modulation schemes, data may be conveyed by the precise position or timing of the pulse, and a loss of precise synchronization could result in a loss of data.

1.2.5 Difficulties in Using DSP Technology

Designing an I-UWB transmitter to broadcast short pulses is much simpler than designing a receiver to demodulate those pulses. For instance, assuming a pulse width of 250 picoseconds and 2 samples/pulse requires a sampling rate of 8 Gigasamples per second. Assuming 6 bits per sample, the receiver must process a data stream of 48 Gbps; at 8 bits per sample, the data stream increases to 64 Gbps. At the time of this writing, only the most technologically advanced FPGAs and ASICs are capable of handling such a huge amount of data.

Another problem is the limitations inherent in practical Analog to Digital Converters (ADCs). Most mass-produced commercial grade ADCs have analog input bandwidths[2] less than 1 GHz. Regardless of the sampling clock frequency, the ADC can only sample signals that fall within its input bandwidth. The highest performance commercially available ADCs can have input bandwidths, which extend into several GHz and have a maximum sampling clock frequency in the low GHz range. It is quite obvious, therefore, that in order to sample a UWB signal which lies in the 3.1–10.6 GHz range, the ADC must, at the very least, have an analog input bandwidth equal to or greater than the highest frequency component of the input signal (that is, an input bandwith of 10.6 GHz). The use of high-performance (and high-cost) FPGAs, DSPs, and ADCs are, however, an anathema to engineers who have heralded UWB as a low-cost, simple communication system.

1.2.6 Networking Issues

A primary driving application of UWB is a high rate Wireless Personal Area Network (WPAN) confined to a small coverage area (less than 10 m radius). The network should be a self-organized, dynamic, ad hoc network, which means the network

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[2] Analog Input Bandwidth is defined as the frequency at which the sampled output of the ADC falls 3 dB below the full-scale input amplitude.

is formed without advanced planning and that users can join or leave at any time. Network security is also an important issue. Even though UWB signals may have a Low Probability of Intercept (LPI), it is still important to provide authentication, confidentiality, integrity, and availability. Variable modes of operation should allow for both long-range, low data rate communications and short-range, high-speed connections for multimedia or large data transfers.

UWB communications presents some unique challenges for a wireless network's Medium Access Control (MAC). As discussed in Chapter 9, "Networking," as the signal bandwidth becomes significantly greater than the data rate, a hybrid CDMA and Time Division Multiple Access (TDMA)-based MAC becomes a more optimal approach than a traditional TDMA MAC. This hybrid technique provides greater flexability and adaptability—an important advantage for UWB networks that may need to meet a variety of Quality of Service (QoS) requirements. Furthermore, the unique nature of I-UWB communications means that several additional features should be built into the MAC layer. Ranging information will assist in the formation of piconets by excluding users that fall outside a predetermined radius of operation. The need for strict synchronization between transmitter and receiver and the ability to generate accurate channel estimates must also be addressed by the MAC. Implementing a decentralized MAC provides the ability to incorporate UWB into consumer electronics and mobile phones that can operate over ad-hoc networks. Finally, different modes of operation, such as high data rate, long-range, or distributed sensor networks, each have somewhat different design constraints, suggesting that multiple approaches to the MAC design may be necessary to develop an optimal MAC layer for a particular application.

1.2.7 Future Directions

At the present time, the FCC is content to allow UWB devices to develop within the limitations of their First Note and Order [14]. As the technology matures, it is possible that the FCC may relax both the transmitted power level and bandwidth restrictions for UWB operation. Such modifications will most likely be a result of detailed investigations that demonstrate the minimal impact that higher power UWB devices will have on the QoS of existing users. In particular, major concerns still exist about the potential interference of UWB emissions to GPS and air traffic control signals.

A potential future application of UWB communications is low power, low data rate distributed sensor communications, similar to the 802.15.4/ZigBee standard. Because the duty cycle of I-UWB pulses is inherently very small, an I-UWB-based extension of the 802.15 standard would help to conserve valuable battery life [15]. Also, the extremely low power spectral density and short time duration of the pulse makes the transmitted signal difficult to detect and intercept, which is a definite advantage for ensuring a secure network.

Another potential application for I-UWB signals is the field of medicine. Microwave and radar monitoring of physiologic functions is an idea that has been around in concept since the 1970s [7, 20], but its development was hampered by the cumbersome and expensive technology of the time. With sufficiently short pulse duration (on the order of 100 picoseconds), an I-UWB radar would be capable of monitoring the movements of internal organs such as the heart or lungs without the need for direct skin contact or constraining the patient in space. Additionally, research is underway that analyzes the backscattered signals from a UWB pulse to detect cancer [6, 21]. Although I-UWB imaging may not provide the resolution of CT (Computed Tomography) or MRI (Magnetic Resonance Imaging) scans, it has the potential to cost-effectively provide critical information and determine, based on those results, whether further diagnostics are required.

1.3 The I-UWB System Model

1.3.1 Overview of the I-UWB System

This section presents the overall system model and notation convention that will be used throughout the book. The basic model for an unmodulated I-UWB pulse train was given in (1.1) and is repeated here

$$s\left(t\right) = \sum_{i=-\infty}^{\infty} A_i\left(t\right) p\left(t - iT_f\right) \tag{1.3}$$

Note that we have assumed that the pulse is not distorted by the channel. Thus, $p(t)$ is the pulse that would be observed by the receiver in a distortionless and noiseless channel with infinite SNR. However, this is not necessarily equal to the pulse generated by the pulser circuitry, nor is it necessarily equal to the pulse launched by the transmitter. This is a unique feature of UWB systems and arises from the fact that the transmit and receive antennas can, and often do, distort the pulse shape.

Thus, in our system model we assume that the antenna-induced distortion is included in the received pulse $p(t)$. Recall also that the antenna-induced distortion can change with elevation and azimuth angles. Thus, we assume that such effects will ultimately be included in the assumed channel model.

1.3.2 Pulse Shapes

By far the most popular pulse shapes discussed in I-UWB communication literature are the Gaussian pulse and its derivatives, as they are easy to describe and work with. A Gaussian pulse is described analytically as

$$p\left(t\right) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{(t-\mu)^2/(2\sigma^2)} \tag{1.4}$$

where σ is the standard deviation of the Gaussian pulse in seconds, and μ is the location in time for the midpoint of the Gaussian pulse in seconds. Note that the pulse width, τ_p, is related to the standard deviation as $\tau_p = 2\pi\sigma$. An example is plotted in Figure 1.4 (a). The first derivative of a Gaussian pulse is also a commonly used analytical pulse shape, due to the fact that a UWB antenna may differentiate the generated pulse (assumed to be Gaussian) with respect to time,[3] leading to the following pulse shape

$$p\left(t\right)=\left(\frac{32k^{6}}{\pi}\right)te^{-(kt)^{2}} \tag{1.5}$$

where k is a constant that determines the pulse width, and we have assumed $\mu = 0$. A third model uses the second derivative of a Gaussian pulse or

$$p\left(t\right)=\left(\frac{32k^{2}}{9\pi}\right)^{\frac{1}{4}}\left(1-2\left(kt\right)^{2}\right)e^{-(kt)^{2}}$$

These three pulse types are plotted in Figure 1.4. The time axis is arbitrary and depends on the values assumed above for k and σ. We should also note that the current FCC rules make UWB transmission most practical in the 3.1–10.6 GHz band. As a result, the preceding pulse shapes may not be useful for commercial systems. Instead, the Gaussian modulated sinusoidal pulse is more practical. Specifically, the pulse shape

$$p\left(t\right)=\left(\frac{8k}{\pi}\right)^{\frac{1}{4}}\frac{1}{\sqrt{1+e^{\frac{2\pi^{2}f_{c}^{2}}{k}}}}e^{-(kt)^{2}}\cos\left(2\pi f_{c}t\right) \tag{1.6}$$

where f_c is the desired center frequency for the pulse. An example plot of this pulse is given in Figure 1.5.

1.3.3 Modulation Schemes

I-UWB systems allow for several modulation schemes, including Pulse Position Modulation (PPM) and Pulse Amplitude Modulation (PAM).[4] A detailed discussion of modulation schemes will be presented in Chapter 5, "Transmitter Design." We introduce them here in order to establish the notation and system model used throughout this book. The transmit signal in the case of amplitude modulation is represented by

$$s\left(t\right)=\sum_{i=-\infty}^{\infty}A_{i}\left(t\right)p\left(t-iT_{f}\right) \tag{1.7}$$

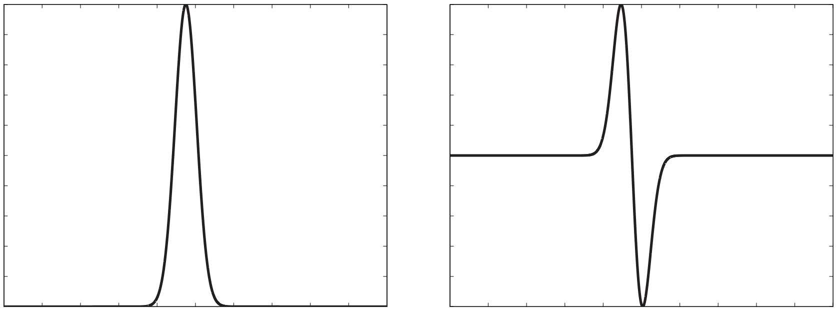
where $A_i = d_i(t)$ now represents the amplitude of the i^{th} pulse, which is dependent on the data $d_i(t)$ and the specific modulation scheme. A pulse position modulation scheme is represented by

$$s\left(t\right)=\sum_{i=-\infty}^{\infty}Ap\left(t-iT_{f}-\delta d_{i}\left(t\right)\right) \tag{1.8}$$

---

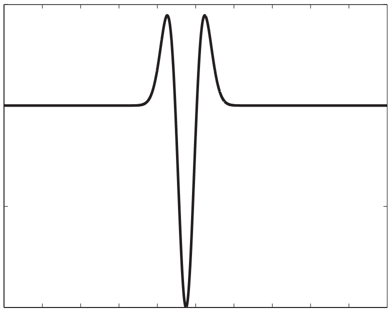
[3] Certain types of antennas, such as the Bicone antenna, can be configured to prevent differentiation of the generated pulse.

[4] Pulse Amplitude Modulation (PAM) is also referred to as Pulse Position Modulation (PPM), or BPSK in the literature. We have chosen to use the generic PAM, as it allows for a more general discussion of UWB modulation. PPM thus becomes a specal case of PAM (2-PAM).



(a) Gaussian Pulse

(b) First Derivative of a Gaussian Pulse



(c) Second Derivative of a Gaussian Pulse

Figure 1.4: Example UWB Pulses.

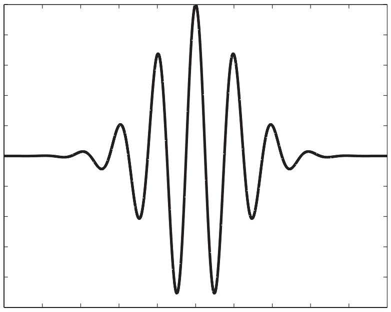


Figure 1.5: Example of a Sinusoidal Gaussian Pulse.

where $d_i(t)$ is the time modulation based on the information and δ is the base time increment.

As an example, let $d_i(t)$ be an antipodal binary bit stream consisting of +1’s and −1’s. The transmitted PAM signal will consist of a stream of positive and negative pulses (Figure 1.6a). The transmitted PPM signal will consist of pulses that are shifted either slightly before or slightly after their ideal positions in a regularly spaced pulse train (Figure 1.6b).

A key characteristic of UWB systems is their low power spectral density. The desire for low power spectral density (PSD) impacts the system model in two distinct ways. First, the pulse rate is often higher than the data rate. In other words, to obtain sufficient energy per symbol while maintaining sufficiently low PSD, multiple pulses will be associated with a single symbol. In this case the received signal is represented by

$$s\left(t\right) = \sum_{i=-\infty}^{\infty} A_{\left\lfloor \frac{i1}{N_s} \right\rfloor} p\left(t - iT_f\right) \tag{1.9}$$

where N_s is the number of pulses per symbol, and the symbol rate is $R_s = \frac{R_p}{N_s}$. For PPM systems where multiple pulses per symbol are used, the received signal is represented as

$$s\left(t\right) = \sum_{i=-\infty}^{\infty} Ap\left(t - iT_f - \delta d_{\left\lfloor \frac{i}{N_s} \right\rfloor}\right) \tag{1.10}$$

The received signal is then modeled as

$$r\left(t\right) = s\left(t\right) * h\left(t\right) + n\left(t\right) \tag{1.11}$$

where $h(t)$ represents the channel that possibly distorts the transmit signal and is assumed to have unit average energy and represents the convolution operation. That is, we scale out all gross attenuation effects and include them in the noise power. The noise is assumed to be Additive White Gaussian Noise (AWGN) with power $\sigma^2 = \frac{1}{SNR}$, where SNR is the average signal-to-noise ratio.[5] In the case where the channel is modeled using a Finite Impulse Response (FIR) filter approach (Chapter 3), the channel is modeled as

$$h\left(t\right) = \sum_{i=1}^{N_p} \beta_i \delta\left(t - \tau_i\right) \tag{1.12}$$

where β_i is the amplitude and sign of the i^{th} path, τ_i is the relative delay of the i^{th} path, $\delta(t)$ is an impulse function, and N_p is the number of paths. Note that in general we will model these parameters as random variables, as discussed in Chapter 3.

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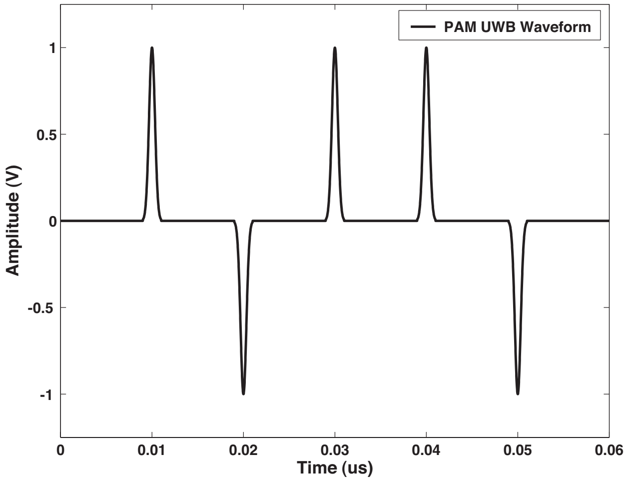
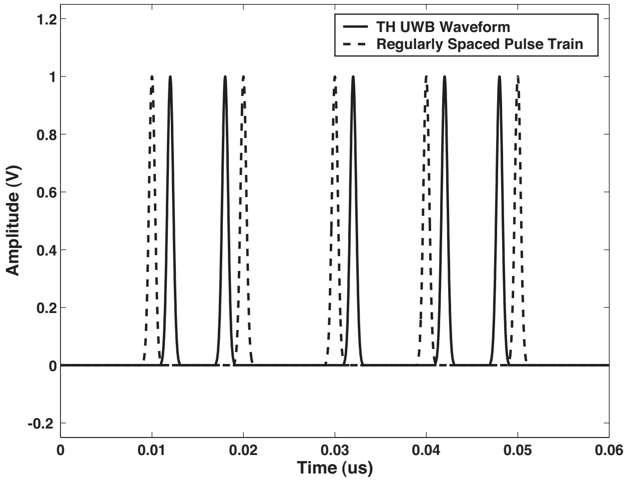
[5] Unfortunately, narrowband interferers located within the bandwidth of the I-UWB signal invalidate the AWGN assumption. For the sake of simplicity, however, we will adhere to the assumption of AWGN in order to provide a means to enable some selected comparison of I-UWB with traditional narrowband communcation systems.



(a) Antipodal Pulse Amplitude Modulation: Positive Pulses Represent a +1 and Negative Pulses Represent a −1.



(b) Time Hop Modulation: Pulses Transmitted After Their Ideal Position Represent a +1 and Pulses Transmitted Prior to Their Ideal Position Represent a −1.

Figure 1.6: Example of Modulated UWB Signals Using the Data Sequence $\{1\ -1\ 1\ 1\ -1\}$.

1.3.4 Multiple Access Schemes

When a system has multiple users, we represent the transmit signal for user k as $s_k(t)$. The total received signal is given by

$$r(t) = \sum_{i=1}^{K} s^{(k)}(t) * h^{(k)}(t) + n(t) \tag{1.13}$$

where $h^{(k)}(t)$ is the channel impulse response between the k^{th} user and the receiver, K is the total number of users considered, and $n(t)$ is AWGN.

In multiuser systems there are many forms of multiple access that will be discussed in Chapter 5. The signal model for TDMA-based (or random access methods) will not differ from that presented here. However, CDMA systems will require additional notation. When pseudorandom amplitude modulation is used to distinguish users, we represent the signal from the k^{th} user as

$$s^{(k)}(t) = \sum_{i=-\infty}^{\infty} A_i^{(k)} p(t - iT_f) \tag{1.14}$$

where $A_i^{(k)} = c_i d^{(k)}_{\lfloor \frac{i}{N_s} \rfloor}$ and c_i is the pseudorandom code value for the i^{th} pulse. This value can repeat every symbol (short codes) so that $c_i = c_{i+N_s}$, or it can repeat at some much longer interval (long codes).

Pseudorandom codes can also be applied to PPM schemes, and are often referred to as time hopping or pseudorandom dithering. In this case the transmit signal of the k^{th} user is

$$s^{(k)}(t) = \sum_{i=-\infty}^{\infty} Ap\left(t - iT_f - c_i^{(k)} T_c - \delta d_{\lfloor i/N_s \rfloor}\right) \tag{1.15}$$

where the time hopping is accomplished with the sequence $c_i^{(k)}$, and T_c is the fundamental hopping granularity.

1.3.5 Receiver Decision Statistic

The receiver estimates the most likely transmitted data symbol by using a decision statistic that is a function of the received signal

$$\widehat{d} = f(Z) \tag{1.16}$$

where Z represents the output of the receiver, and the function $f(Z)$ depends on the modulation scheme and receiver structure, as discussed in Chapter 6, "Receiver Design Principles," and Chapter 7, "On the Coexistence of UWB and Narrowband Radio Systems." Additionally, in diversity systems with multiple receiver branches (such as multiple antenna structures or a RAKE receiver) the decision statistic Z will be the sum of several statistics

$$Z = \sum_{i=1}^{L} Z_i \tag{1.17}$$

where L is the number of diversity branches, either in time or space, and z_i is the statistic calculated per diversity branch.

1.4 The MC-UWB System Model

1.4.1 Overview of the MC-UWB System

In the past several years, MC-UWB (also called frequency domain UWB) has received a significant amount of attention. The transmit MC-UWB signal $s(t)$ has the following complex baseband form

$$s\left(t\right) = A\sum_{r}\sum_{n=1}^{N} b_n^r p\left(t - rT_p\right) e^{\left(j2\pi n f_0 \left(t - rT_p\right)\right)} \tag{1.18}$$

where N is the number of subcarriers, b_n^r is the symbol that is transmitted in the r^{th} transmission interval over the n^{th} subcarrier, and A is a constant that controls the transmitted power spectral density and determines the energy per bit. The fundamental frequency is $f_0 = \frac{1}{T_p}$.

1.4.2 OFDM UWB

OFDM is a special case of multicarrier transmission that permits subcarriers to overlap in frequency without mutual interference and hence spectral efficiency is increased. Multiple users can be supported by allocating each user a group of subcarriers. OFDM-UWB is a novel system that has been proposed as a physical layer for high bit rate, short-range communication networks. Reliable communication systems achieve high throughput by transmitting multiple data streams in parallel on separate carrier frequencies. Unlike narrowband OFDM, the OFDM-UWB spectrum can have gaps between subcarriers. OFDM-UWB is one proposed physical layer standard for 802.15.3a Wireless Personal Area Networks.

OFDM-UWB uses a frequency coded pulse train as a shaping signal. The frequency coded pulse train is defined by

$$p\left(t\right) = \sum_{n=1}^{N} s\left(t - nT\right) e^{\left(-j2\pi c(n) \frac{1}{T_c}\right)} \tag{1.19}$$

where $s\left(t\right)$ is an elementary pulse with unit energy and duration $T_s < T$, and $p\left(t\right)$ has duration $T_p = NT$. Each pulse is modulated with a frequency $f_n = \frac{c(n)}{T_c}$ where $c\left(n\right)$ is a permutation of the integers $\{1, 2, \ldots, N\}$. As shown in Chapter 6, the set $p_k\left(t\right) = p\left(t\right) e^{\left(j2\pi k f_0 t\right)}$ is orthogonal for $k = 1, 2, \ldots, N$.

1.5 Overview of the Book

This book is designed to be an interdisciplinary study of UWB communication systems. The development of channel models for UWB communication systems requires extensive data on propagation of UWB signals. Both experimental and simulation techniques can be used to examine the propagation of UWB signals in indoor and indoor/outdoor environments. In Chapter 2, "Channel Measurement and Simulation," time domain and frequency domain measurement methods for UWB channel sounding and their advantages and disadvantages are discussed. The electromagnetic simulation of UWB signal propagation in indoor environments is also addressed in Chapter 2. In Chapter 3, channel models and UWB link budgets are developed based on data collected from extensive UWB propagation measurements.

A critical component of UWB propagation, the antenna, is covered in Chapter 4. This chapter presents a detailed parametric study of time and frequency domain characteristics of both the antenna and scattering structures that must be considered in the performance estimates of UWB links. Additionally, mathematical modeling is presented that allows the antenna effects to be theoretically integrated into the UWB channel models.

As discussed previously in this chapter, transmitter and receiver design presents a unique challenge for UWB systems, particularly with the emphasis on low power, low cost devices. Chapter 5, "Transmitter Design," describes several widely used signal generation and modulation/signaling schemes unique to both I-UWB and MC-UWB. Chapter 6 provides a comprehensive review of a wide variety of UWB receiver architectures, with an emphasis on different mechanisms for optimally demodulating the received UWB signal.

UWB signals will encounter interference from many sources, primarily from relatively narrowband systems. In addition, UWB signals will also affect a large number of narrowband radios; of critical importance is the potential interference with GPS, E-911, and navigation bands. In Chapter 7, we assess, via analysis and simulations, the interference caused by UWB signals, as well as the impact of narrowband interference on a UWB receiver.

Simulation of UWB communication systems is unique in that it emphasizes the transient nature of UWB systems, and it is the focus of Chapter 8, "Simulation." This chapter covers several subjects important to efficient and accurate simulation of UWB communication systems, including challenges introduced by the simulation of UWB, architectural approaches to simulating UWB communication systems, and simulation models for UWB communication systems components.

Chapter 9, "Networking," addresses networking issues for networks of directly connected UWB nodes and larger ad hoc networks where network formation and multihop routing is required. In Chapter 9, we will examine several design issues related to UWB networks, including data link layer design, architectures of multihop ad hoc networks, and corresponding routing schemes, as well as related issues such as performance and Quality of Service (QoS) management.

Chapter 10, "Applications and Case Studies," explores the wide range of applications that can exploit the unique properties of I-UWB. Practical examples will be discussed from among some of the first commercial UWB products that feature several of the diverse set of UWB applications, including precision location, radar, imaging, distributed sensors, and high-speed communication. Appendix A of Chapter 10 provides a brief overview of the IEEE 802.15.3a preliminary standard that describes the MAC and PHY layers[6] of a wireless personal area network (WPAN).

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[6] At the time of publication, the PHY layer has not been fully determined; two alternative candidates remain.

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