

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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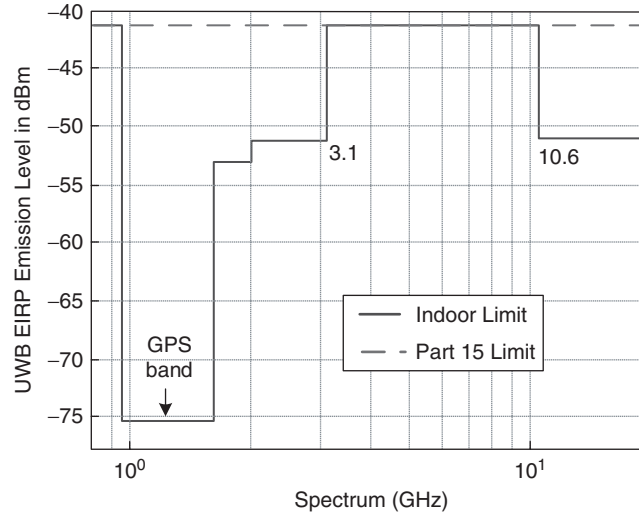


Figure 1.1 UWB spectral mask for indoor communication systems.

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

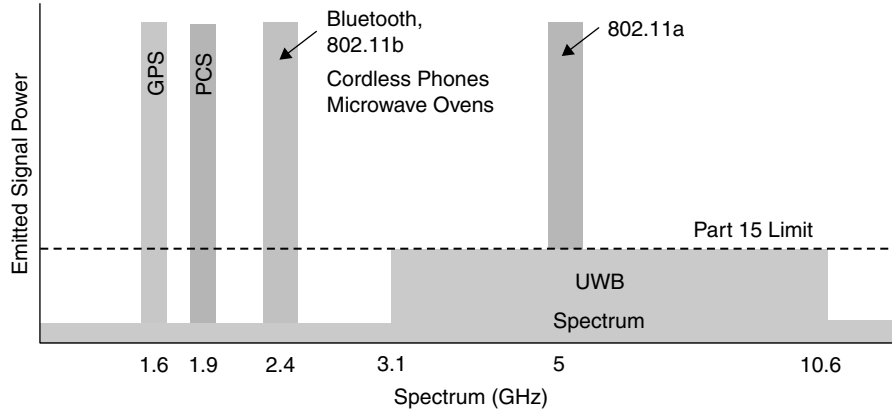


Figure 1.2 Spectrum of UWB and existing narrowband systems.

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],

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

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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Shannon's equation we can see that UWB system has a great potential for high-speed wireless communications.

Conveying information with ultrashort-duration waveforms, UWB signals have low susceptibility to multipath interference. Multipath interference occurs when a modulated signal arrives at a receiver from different paths. Combining signals at the receiver can result in distortion of the signal received. The ultrashort duration of UWB waveforms gives rise to a fine resolution of reflected pulses at the receiver. As a result, UWB transmissions can resolve many paths, and are thus rich in multipath diversity.

The low complexity and low cost of UWB systems arises from the carrier-free nature of the signal transmission. Specifically, due to its ultrawide bandwidth, the UWB signal may span a frequency commonly used as a carrier frequency. This eliminates the need for an additional radio-frequency (RF) mixing stage as required in conventional radio technology. Such an omission of up/down-conversion processes and RF components allows the entire UWB transceiver to be integrated with a single CMOS implementation. Single-chip CMOS integration of a UWB transceiver contributes directly to low cost, small size, and low power.

The ultrashort duration of UWB waveforms gives rise to the potential ability to provide high-precision ranging and localization. Together with good material penetration properties, UWB signals offer opportunities for short-range radar applications such as rescue and anticrime operations as well as in surveying and in the mining industry.

1.3 UWB APPLICATIONS

UWB technology can enable a wide variety of applications in wireless communications, networking, radar imaging, and localization systems. For wireless communications the use of UWB technology under the FCC guidelines [FCC02] offers significant potential for the deployment of two basic communications systems:

- High-data-rate short-range communications: high-data-rate wireless personal area networks
- Low-data-rate and location tracking: sensor, positioning, and identification networks

The high-data-rate WPANs can be defined as networks with a medium density of active devices per room (5 to 10) transmitting at data rates ranging from 100 to 500 Mbps within a distance of 20 m. The ultrawide bandwidth of UWB enables various WPAN applications, such as high-speed wireless universal serial bus (WUSB) connectivity for personal computers (PCs) and PC peripherals, high-quality real-time video and audio transmission, file exchange among storage systems, and cable replacement for home entertainment systems.

Recently, the IEEE 802.15.3 standard task group has established the 802.15.3a study group [TG3a] to define a new physical layer concept for high-data-rate WPAN applications. A major goal of this study group is to standardize UWB wireless radios

for indoor WPAN transmissions. The goal for the IEEE 802.15.3a standard is to provide a higher-speed physical layer for the existing approved 802.15.3 standard for applications that involve imaging and multimedia. The work of the 802.15.3a study group includes standardizing the channel model to be used for UWB system evaluation.

Alternatively, UWB transmission can trade a reduction in data rate for an increase in transmission range. Under the low-rate operation mode, UWB technology could be beneficial and potentially useful in sensor, positioning, and identification networks. A sensor network comprises a large number of nodes spread over a geographical area to be monitored. Depending on the specific application, the sensor nodes can be static or mobile. Key requirements for sensor networks operating in challenging environments include low cost, low powers, and multifunctionality. With its unique properties of low complexity, low cost, and low power, UWB technology is well suited to sensor network applications [Opp04]. Moreover, due to the fine time resolution of UWB signals UWB-based sensing has the potential to improve the resolution of conventional proximity and motion sensors. The low-rate transmission, combined with accurate location tracking capabilities, offers an operational mode known as *low-data-rate and location tracking*.

The IEEE also established the 802.15.4 study group to define a new physical layer concept for low-data-rate applications utilizing UWB technology at the air interface. The study group addressed new applications which require only moderate data throughput but long battery life, such as low-rate wireless personal area networks, sensors, and small networks.

1.4 UWB TRANSMISSION SCHEMES

Although the FCC has regulated the spectrum and transmitter power levels for a UWB, there is currently no standard for a UWB transmission scheme. Various pulse generation techniques have been proposed to use the 7.5-GHz license-free UWB spectrum. Generally, UWB transmission approaches can be categorized into two main approaches: single-band and multiband. Figure 1.3 illustrates UWB signals in the time and frequency domains when single and multiband approaches are employed.

A traditional UWB technology is based on single-band systems employing carrier-free or impulse radio communications [Sch93, Win98, Wel01, Foe02a, Rob03, Bou03]. *Impulse radio* refers to the generation of a series of impulselike waveforms, each of duration in the order of hundreds of picoseconds. Each pulse occupies a bandwidth of several gigahertz that must adhere to the spectral mask requirements. The information is modulated directly into the sequence of pulses. Typically, one pulse carries the information for 1 bit. Data could be modulated using either pulse amplitude modulation (PAM) or pulse position modulation (PPM). Multiple users can be supported using the time-hopping or direct-sequence spreading approaches. This type of transmission does not require the use of additional carrier modulation, as the pulse will propagate well in the radio channel. The technique is therefore a baseband

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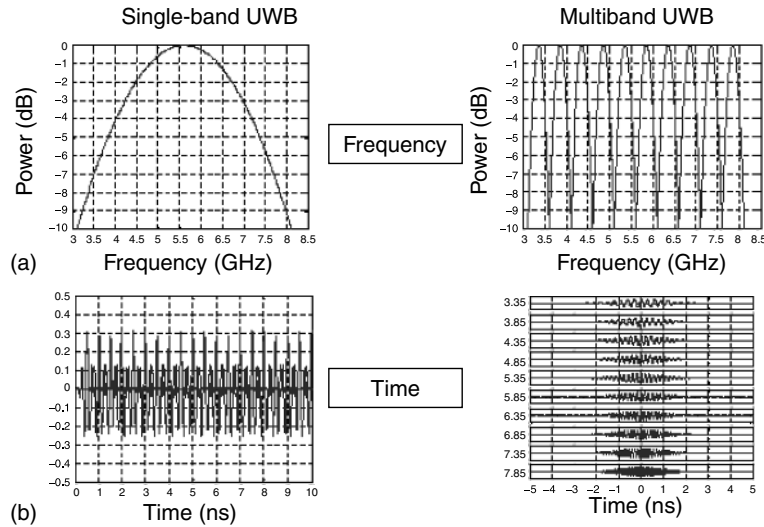


Figure 1.3 UWB transmission approaches: (a) single- and (b) multiband approaches [Dis03].

signal approach. However, the single-band system faces a challenging problem in building RF and analog circuits and in designing a low-complexity receiver that can capture sufficient multipath energy.

To overcome the drawback of single-band approaches, multiband approaches were proposed in [Sab03, Foe03a, Bat03, Bat04]. Instead of using the entire UWB frequency band to transmit information, the multiband technique divides the UWB frequency band from 3.1 to 10.6 GHz into several smaller bands, referred to as *subbands*. Each subband occupies a bandwidth of at least 500 MHz, in compliance with FCC regulations [FCC02]. By interleaving the transmitted symbols across subbands, multiband approaches can maintain the power being transmitted as if a large GHz bandwidth were being utilized. The advantage is that multiband approaches allow information to be processed over a much smaller bandwidth, thereby reducing overall design complexity as well as improving spectral flexibility and worldwide compliance.

Recently, a multiband OFDM approach that utilizes a combination multiband approach and orthogonal frequency-division multiplexing (OFDM) technique was proposed [Bat03]. The OFDM technique is efficient at collecting multipath energy in highly dispersive channels, as is the case for most UWB channels [Bat04]. Moreover, OFDM allows each subband to be divided into a set of orthogonal narrowband channels (with a much longer symbol period duration). The major difference between multiband and traditional OFDM schemes is that multiband OFDM symbols are not sent continually on a single frequency band; instead, they are interleaved over different subbands across both time and frequency. Multiple access to the multiband approach is enabled by the use of suitably designed frequency-hopping sequences over the set

of subbands. A frequency synthesizer can be utilized to perform frequency hopping. By using proper time–frequency codes, a multiband system provides both frequency diversity and multiple access capability [Bat04]. The multiband OFDM approach has been a leading proposal for the IEEE 802.15.3a WPAN standard [TG3a] and has been approved as the UWB standard by the European Computer Manufacturers Association (ECMA) [ECM05].

There are many trade-offs in the UWB approaches described above. The single-band approach benefits from a coding gain achieved through the use of time-hopping or direct-sequence spreading, exploits Shannon's principles to a greater degree than does the multiband approach, has greater precision for position location, and realizes better spectrum efficiency. However, it has less flexibility with regard to foreign spectral regulation and may be too broadband if foreign governments choose to limit their UWB spectral allocations to smaller ranges than authorized by the FCC. On the other hand, the multiband approach has as its main advantage the ability for finer-grained control of the transmitter PSD so as to maximize the average power transmitted while meeting the spectral mask. It allows for peaceful coexistence with flexible spectral coverage and is easier to adopt to different worldwide regulatory environments. Moreover, processing over a smaller bandwidth eases the requirement on analog-to-digital converter sampling rates and, consequently, facilitates greater digital processing. Furthermore, in the UWB multiband OFDM approach, due to the increased length of the OFDM symbol period, the modulation method can successfully reduce the effects of intersymbol interference (ISI). Nevertheless, this robust multipath tolerance comes at the price of increased transceiver complexity, the need to combat intercarrier interference (ICI), and tighter linear constraint on amplifying circuit elements.

1.5 CHALLENGES FOR UWB

Although UWB technology has several attractive properties that make it a promising technology for future short-range wireless communications and many other applications, some challenges must be overcome to fulfill these expectations.

The transmitter power level of UWB signals is strictly limited in order for UWB devices to coexist peacefully with other wireless systems. Such strict power limitation poses significant challenges when designing UWB systems. One major challenge is to achieve the performance desired at an adequate transmission range using limited transmitter power. Another challenge is to design UWB waveforms that efficiently utilize the bandwidth and power allowed by the FCC spectral mask. Moreover, to ensure that the transmitter power level satisfies the spectral mask, adequate characterization and optimization of transmission techniques (e.g., adaptive power control, duty cycle optimization) may be required.

The ultrashort duration of UWB pulses leads to a large number of resolvable multipath components at the receiver. In particular, the UWB signal received contains many delayed and scaled replicas of the pulses transmitted. Additionally, each resolvable pulse undergoes different channel fading, which makes multipath energy

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capture a challenging problem in UWB system design. For example, if a RAKE receiver [Proa1] is used to collect the multipath energy, a large number of fingers is needed to achieve the performance desired.

Design challenges also exist in the areas of modulation and coding techniques that are suitable for UWB systems. Originally, UWB radio was used for military applications, where multiuser transmission and achieving high multiuser capacity are not major concerns. However, these issues become very important in commercial applications, such as high-speed wireless home networks. Effective coding and modulation schemes are thus necessary to improve UWB multiuser capacity as well as system performance.

One design challenge is the impact of narrowband interference on UWB receivers. Specifically, the UWB frequency band overlaps with that of IEEE 802.11a wireless local area networks (WLANs). The signals from 802.11a devices represent in-band interference for the UWB receiver front end.

Other design challenges include scalable system architectures and spectrum flexibility. UWB potential applications include both high-rate applications (e.g., images and video) and lower-rate applications (e.g., computer peripheral support). Thus, the UWB transceiver must be able to support a wide range of data rates. Furthermore, the unlicensed nature of the UWB spectrum makes it essential for UWB devices to coexist with devices that share the same spectrum. However, it is challenging to design UWB systems with spectrum flexibility that allows UWB devices to coexist effectively with other wireless technologies and to meet potentially different regulatory requirements in different regions of the world.