1

Introduction to UWB Signals and Systems

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The word 'ultra-wideband' (UWB) commonly refers to signals or systems that either have a large relative, or a large absolute bandwidth. Such a large bandwidth offers specific advantages with respect to signal robustness, information content and/or implementation simplicity, but lead to fundamental differences from conventional, narrowband systems. The past years have seen a confluence of technological and political/economic circumstances that enabled practical use of UWB systems; consequently, interest in UWB has grown dramatically. This book gives a detailed investigation of an important part of this development, namely UWB antennas and propagation. The current chapter is intended to place this part in the bigger picture by relating it to the issues of system design, applications and regulatory rules.

1.1 History of UWB

UWB communications has drawn great attention since about 2000, and thus has the mantle of an 'emerging' technology. It is described in popular magazines by monikers such as 'one of ten technologies that will change your world'. However, this should not detract from the fact that its origins go back more than a century. Actually, electromagnetic communications started with UWB. In the late 1800s, the easiest way of generating an electromagnetic signal was to generate a short pulse: a spark-gap generator was used, e.g., by Hertz in his famous experiments, and by Marconi for the first electromagnetic data communications [1]. Thus, the first practical UWB systems are really more than 100 years old. Also, theoretical research into the propagation of UWB radiation stems back more than a century. It was the great theoretician, Sommerfeld, who first analysed the diffraction of a short pulse by a half-plane – one of the fundamental problems of UWB propagation [2].

However, after 1910, the general interest turned to narrowband communications. Part of the reason was the fact that the spectral efficiency of the signals generated by the spark-gap transmitters was low – the signals that were generated had a low bit rate, but occupied a large bandwidth. In other words, those signals

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had a large spreading factor. At that time, it was not known how to exploit such signal spreading; it was simply seen as a deficiency. On the other hand, narrowband communications, which allowed frequency division multiplexing, offered an easy way of transmitting multiple signals in a finite bandwidth. Thus, UWB research fell dormant.

It was revived in the 1960s in a different context, namely military radar, where spectral efficiency was not a major consideration. Rather, the point was to improve the spatial resolution; in other words, improve the accuracy with which the runtime from the radar transmitter to a specific object, and back to the receiver, can be determined. It follows from elementary Fourier considerations that this can be done the better, the shorter the transmitted radar pulses are. Increased interest in this work coincided with the invention of the sampling oscilloscope, which allowed the experimental analysis of short-duration signals in the time domain. A key component for UWB radar systems was the design of high-power, short-pulse generators, which was investigated by the military in both the USA and the Soviet Union.

Ultra-wideband communications started to receive renewed interest in the 1970s [3]. At this time, it was called ‘baseband’ or ‘carrier-free’ communications. Around 1973, it was recognised that short pulses, which spread the signal over a large spectrum, are not significantly affected by existing narrowband interferers, and do not interfere with them, either. However, the problem of multiple-access interference (MAI) of unsynchronised users remained, so that in the 1970s and 1980s, UWB communications continued to be mostly investigated in the military sector, where spectral efficiency was of minor importance. The MAI problem was solved by the introduction of time-hopping impulse radio (TH-IR) in the early 1990s, where the pioneering work of Win and Scholtz [4], [5], [6] showed that impulse radio could sustain a large number of users by assigning pseudorandom transmission times to the pulses from the different users. This insight, coupled with advances in electronics device design, spawned the interest of commercial wireless companies into UWB.

Another key obstacle to commercial use of UWB was political in nature. Frequency regulators all over the world assign narrow frequency bands to specific services and/or operators. UWB systems violate those frequency assignments, as they emit radiation over a large frequency range, including the bands that have already been assigned to other services. Proponents of UWB tried to convince the frequency regulator in the USA, the FCC (Federal Communications Commission), that the emissions from UWB devices would not interfere with those other services. After a lengthy hearing process, the FCC issued a ruling in 2002 that allowed intentional UWB emissions in the frequency range between 3.1 and 10.6 GHz, subject to certain restrictions for the emission power spectrum [7] (for more details, see Section 1.4).

If the introduction of time-hopping impulse radio had created a storm of commercial UWB activities, the FCC ruling turned it into a hurricane. Within two years, more than 200 companies were working on the topic. Recognising this trend early on, the IEEE (Institute of Electric and Electronics Engineers) established a working group (IEEE 802.15.3a) with the task of standardising a physical layer for high-throughput wireless communications based on UWB. High-data rate applications showed the greatest initial promise, largely due to the immediately visible commercial potential. While the process within the IEEE stalled, it gave rise to two industry alliances (Multiband-OFDM Alliance/WiMedia, and the UWB Forum) that were shipping products by 2005. Ironically, neither of those alliances uses impulse radio, but rather more ‘mature’ technologies, namely OFDM (orthogonal frequency division multiplexing) and DS-CDMA (direct-sequence code division multiple access), respectively (see Section 1.5). UWB is also beneficial for the transmission of data with low rates, using as little energy as possible – the principles of impulse radio are especially suitable in this context. As the goals are greatly different from the high-data rate applications, also a different standardisation group was charged with developing a common specification for such devices, the IEEE 802.15.4a group (see Section 1.5).

Since 2000, the scientific research in UWB communications has gone in a number of different directions. The theoretical performance of time-hopping impulse radio was the first topic that drew widespread interest. The most fundamental problems were solved in [6], [8]; more detailed aspects of multiple access and narrowband interference were treated in [9], [10], [11], [12], [13], [14]. Issues of equalisation and Rake reception are analysed in [15], [16], channel estimation and synchronisation [17], [18], transmitted-reference and differential schemes [19], [20], [21], [22], [23]. Spectral shaping and the design of hopping sequences are the topic of [24], [25], [26], [27]. Practical implementation issues, both for impulse radio, and for alternative implementations, are discussed, e.g., in [28], [29], [30]. The combination of UWB with MIMO (multiple-input multiple-output), i.e., the use of multiple antenna elements at both link ends, is the topic of [31], [32], [33].[1]

It is also interesting to see how the research into UWB antennas and propagation evolved over the years. UWB antennas are more than 100 years old [34]. Some of the very first antennas were biconical antennas and spherical dipoles, which have very good wideband characteristics. They were rediscovered in the 1930s by Carter, who also added broadband transitions from the feed to the radiating elements. It is noteworthy that UWB antenna research never experienced the slump of UWB communications, but rather stayed a popular and important area throughout the past 70 years. A main factor in this development was TV broadcasting: the assigned TV bands extend over a large frequency range, and since it is desirable that a single antenna can transmit/receive all available stations, it implied that the antenna had to be very broadband as well. As UWB communications emerged as a commercially viable option in the 1990s, the development of smaller antennas became a new requirement. Slot antennas and printed antennas have proven to be especially useful in that context.

UWB propagation research, on the other hand, has a more chequered history. Theoretical investigations of the interaction of short pulses with variously shaped objects have abounded since the classical studies of Sommerfeld mentioned above [35]. Practical propagation studies, however, seem to have been limited to radar measurements; as those were typically classified. The development of statistical UWB channel models, which are essential for the development of communications systems, started only recently: the first measurement-based statistical channel model that took UWB aspects explicitly into account was [36], which is valid in the low frequency range (<1 GHz). The IEEE 802.15.3a group established a channel model for residential and office environments [37] in the 3–10 GHz range, based on two measurement campaigns. This model was widely used both by industrial and academic research from 2003 to 2005. More measurement campaigns were performed after 2003, and another standardised model, the IEEE 802.15.4a model, published in 2005, included a larger variety of environments and took more propagation effects into account [38]. However, while considerable progress has been made in understanding UWB channels, as described in Part III of this book, a lot remains to be done; see also [39].

1.2 Motivation

UWB systems can be characterised either by a large relative bandwidth, or a large absolute bandwidth. Each of these has specific advantages, as well as challenges, which we will discuss in the remainder of this section.

1.2.1 Large Absolute Bandwidth

By 'large absolute bandwidth', we usually refer to systems with more than 500 MHz bandwidth, in accordance with the FCC definition of UWB radiation [7]. Such a large bandwidth offers the possibility of very large spreading factors: in other words, the ratio of the signal bandwidth to the symbol rate is

[1] The list of references given here is far from complete, and is just intended to exemplify the trends in UWB communications.

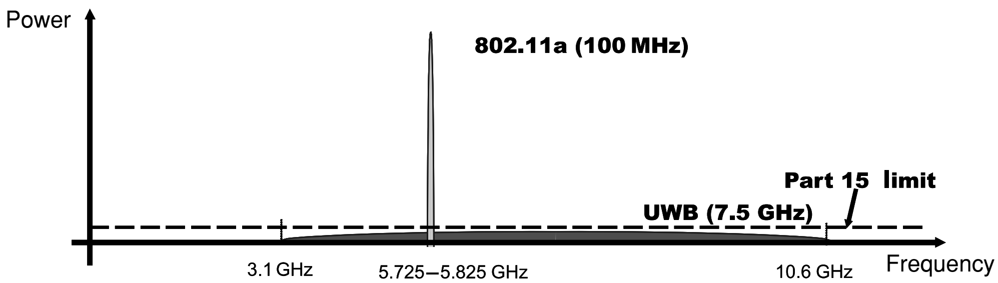

Figure 1.1 Interference between a UWB system and a narrowband (IEEE 802.11a) local area network

very large. For a typical sensor network application with 5 ksymbol/s throughput, a spreading factor of 10^5 to 10^6 is achieved for transmission bandwidths of 500 MHz and 5 GHz, respectively. Spreading over such a large bandwidth means that the power spectral density of the radiation, i.e., the power per unit bandwidth, is very low. A victim legacy (narrowband) receiver will only see the noise power within its own system bandwidth, i.e., a small part of the total transmit power, see Figure 1.1. This implies that the interference to legacy (narrowband) systems is very small. Furthermore, a UWB receiver can suppress narrowband interference by a factor that is approximately equal to the spreading factor. These principles are well understood from the general theory of spread spectrum systems. The distinctive feature of UWB is that it goes to extremes in terms of the spreading factor, and thus brings the power spectral density to such low levels that it does not disturb legacy systems at all under most operating conditions. Ideally, the radiation just increases the noise level seen by the victim receiver by a negligible amount. As an additional advantage, such radiation is almost undetectable for unauthorised listeners. It must be kept in mind that the spreading factor is a function of both the transmission bandwidth and the data rate. Consequently, UWB systems with high data rates (>100 Mbit/s) do not exhibit such a large spreading factor as that in the above example, and are thus more sensitive to interference.

Another important advantage of using a large absolute bandwidth is a high resilience to fading. In conventional narrowband systems, the received signal strength undergoes fluctuations, caused by multipath components (MPCs), i.e., echoes from different scatterers, which interfere with each other constructively or destructively, depending on the exact location of transmitter, receiver and scatterers [40]. The amplitude statistics of the total received signal is typically complex Gaussian, because a large number of (unresolvable) MPCs add up at the receiver. A UWB transceiver receives a signal with a large absolute bandwidth, and can thus resolve many of those MPCs. By separately processing the different MPCs, the receiver can make sure that all those components add up in an optimum way, giving rise to a smaller probability of deep fades. In other words, the many resolvable MPCs provide a high degree of delay diversity. As an additional effect, we will observe in Section 1.3 that the number of actual MPCs that constitute a resolvable multipath component is rather small; for this reason, the fading statistics of each resolvable multipath component does not have a complex Gaussian distribution anymore, but shows a lower probability of deep fades. Due to this, and the delay diversity, UWB systems with large absolute bandwidth need hardly any fading margin for compensating small-scale fading [41], yielding a significant advantages over conventional narrowband systems, see Figure 1.2.

Finally, a large absolute bandwidth also leads to a great improvement of the accuracy of ranging and geolocation. Most ranging systems try to determine the flight time of the radiation between transmitter and receiver. It follows from elementary Fourier considerations that the accuracy of the ranging improves the bandwidth of the ranging signal. Thus, even without sophisticated high-resolution algorithms for the

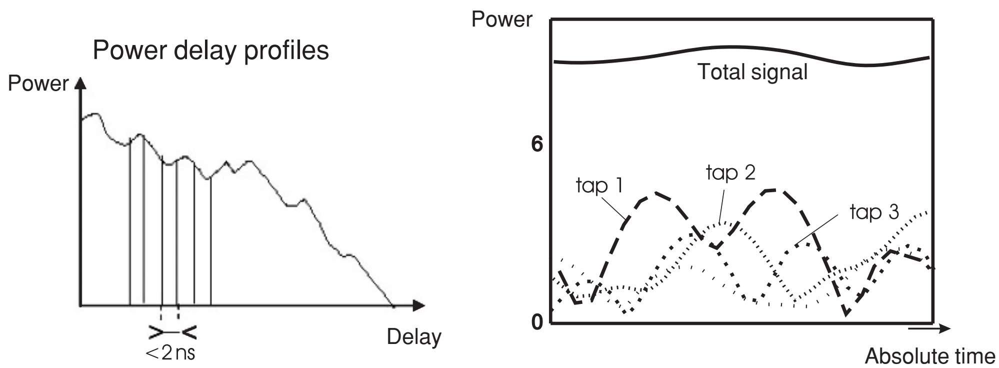

Figure 1.2 Delay diversity in a UWB system

determination of the time-of-arrival of the first path, a UWB system can achieve centimetre accuracy for ranging [42]. Of course, this inherent accuracy can be augmented by additional information, like direction-of-arrival, and/or receive power.

While the large absolute bandwidth gives a number of advantages, it also gives rise to a number of challenges. From a hardware point of view, the accuracy of the local oscillators and/or timing circuits has to be very high. When the absolute bandwidth is 1 GHz, a timing jitter of 1 ns can obviously have catastrophic consequences. Another consequence of the high delay resolution is that a large number of components need to be received and processed. For example, the number of fingers in a Rake receiver that is required to collect 90 % of the available energy can easily reach several tens or even hundreds [43]. Finally, the fine delay resolution can also have drawbacks for ranging: the first, (quasi-) line-of-sight component that needs to be detected by the ranging algorithms can contain little energy, and can thus have a poor signal-to-noise ratio (SNR).

1.2.2 Large Relative Bandwidth

Again, following the FCC definition, we consider systems with a relative bandwidth of larger than 20 % as ultra-wideband. Such a large bandwidth can greatly enhance the signal robustness for data transmission, and can have even more important advantages for radar and ranging. Intuitively, the different frequency components of the signal 'see' different propagation conditions. Thus, there is a high probability that at least some of them can penetrate obstacles or otherwise make their way from transmitter to receiver. This advantage is especially striking in a baseband system, where frequencies from (typically) a few tens of Megahertz, to up to 1 Gigahertz are being used. The low-frequency components can more easily penetrate walls and ground, while the high-frequency components give strongly reflected signals. Consequently, the signal is more robust to shadowing effects (in contrast to the large-absolute-bandwidth systems, which are more robust to interference between MPCs). The good wall and floor penetration is also very useful for radar and geolocation systems.

In many practical cases, large-relative-bandwidth systems are pure baseband systems, i.e., systems where baseband pulses are directly applied to the transmitting antennas (note, though, that no DC components can be transmitted). Such systems have also advantages from an implementation point of view. In particular, they obviate the necessity for RF components such as local oscillators, mixers, etc.

On the other hand, a large relative bandwidth can also lead to considerable complications in the system design. Most devices such as antennas, amplifiers, etc., have inherent narrowband characteristics that are caused by both practical restrictions, and by fundamental principles.

For radar applications, as well as disaster communications systems, a large relative bandwidth is the most important argument for using UWB. For other communications systems, a large absolute bandwidth is typically more important.

1.3 UWB Signals and Systems

The investigation of UWB antennas and propagation is intimately related to the design of UWB transceivers and signal processing. On one hand, it is impossible to design good and efficient systems if we do not know the effective channel (including antennas) that we are designing the system for. On the other hand, we have to know the system design in order to know how antenna design and propagation channel impact the system performance.

In the past years, four methods have emerged for signalling with ultra-wide bandwidths: impulse radio, DS-CDMA, OFDM and frequency hopping.[2] We will also introduce these four signalling schemes in the following sections and also the issues of signalling for geolocation and radar.

1.3.1 Impulse Radio

Impulse radio has many attractive properties, like enabling to build extremely simple transmitters. However, an important problem that plagued impulse radio (baseband transmission) for a long time was the spectral efficiency: it seemed that only a small number of users could be 'on air' simultaneously. Consider the case where one pulse per symbol is transmitted. Since the UWB transceivers are unsynchronised, so-called 'catastrophic collisions' can occur, where pulses from several transmitters arrive at the receiver simultaneously. The signal-to-interference ratio then becomes very bad, leading to a high bit error rate (BER). Win and Scholtz showed that this problem could be avoided by time-hopping impulse radio (TH-IR) [6]. Each data bit is represented by *several* short pulses; the duration of the pulses determines essentially the bandwidth of the system. The transmitted pulse sequence is different for each user, according to a so-called time-hopping (TH) code. Thus, even if one pulse within a symbol collides with a signal component from another user, other pulses in the sequence will not, see Figure 1.3. In other words, collisions can still occur, but they are not catastrophic anymore. TH-IR achieves a multiple-access interference suppression that is equal to the number of pulses in the system. The possible positions of the pulses within a symbol follow certain rules: the symbol duration is subdivided into N_f 'frames' of equal length. Within each frame the pulse can occupy an almost arbitrary position (determined by the time-hopping code). Typically, the frame is subdivided into 'chips', whose length is equal to a pulse duration. The (digital) time-hopping code now determines which of the possible positions the pulse actually occupies.

When all the transmitted pulses have the same polarity, as shown in Figure 1.3, the signal spectrum shows a number of lines. This is highly undesirable, as most spectrum regulators prescribe a maximum power spectral *density* that has to be satisfied, e.g., in each 1-MHz sub-band. Thus, the transmit power of a signal with spectral lines has to be backed off such that the spectral lines satisfy the spectral mask – this

[2] A fifth technique, chirping, in which the carrier frequency is linearly changed during transmission, is explicitly forbidden by some frequency regulators, and will not be considered further here.

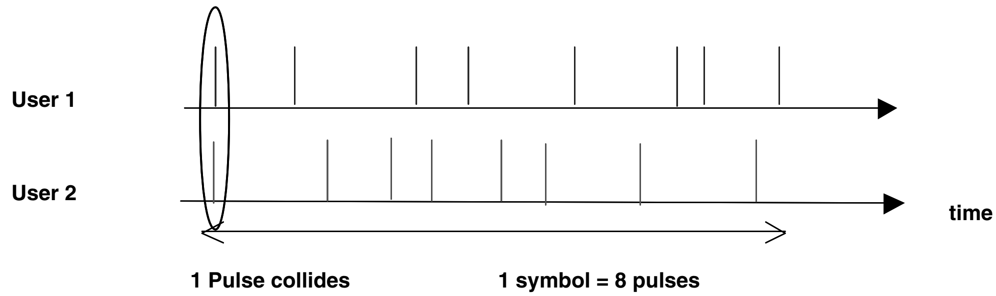

Figure 1.3 Principle of time-hopping impulse radio for the suppression of catastrophic collisions

leads to a considerable loss in SNR. This problem was solved in [24] (see also [25]) by choosing the polarity of the transmit pulses in a pseudorandom way; this process can be undone at the receiver.

The modulation of this sequence of pulses can be pulse-position modulation (PPM), as suggested in [6], or pulse amplitude modulation (PAM) such as BPSK (binary phase shift keying) [40]. PPM has the advantage that the detector can be much simpler – it only needs to determine whether there is more energy at time t_0, or at time $t_0 + \delta$. It allows the use of noncoherent receivers (energy detectors), as well as the use of coherent receivers. For noncoherent receivers, it is required that δ is larger than the delay spread of the channel. BPSK can only be used in conjunction with coherent receivers, however, it gives better performance than PPM since it is an antipodal modulation format. The transmit signal for BPSK modulation reads

$$s_{\mathrm{tr}}(t) = \sum_{j=-\infty}^{\infty} d_j b_{\lfloor j/N_f \rfloor} w_{\mathrm{tr}}\left(t - jT_f - c_j T_c\right) = \sum_{k=-\infty}^{\infty} b_k w_{\mathrm{seq}}(t - kT_s), \tag{1.1}$$

where $w_{\mathrm{tr}}(t)$ is the transmitted unit-energy pulse, T_f is the average pulse repetition time, N_f is the number of frames (and therefore also the number of pulses) representing one information symbol of length T_s, and b is the transmitted information symbol, i.e., ± 1; $w_{\mathrm{seq}}(t)$ is the transmitted pulse sequence representing one symbol. The TH sequence provides an additional time shift of $c_j T_c$ seconds to the j-th pulse of the signal, where T_c is the chip interval, and c_j are the elements of a pseudorandom sequence, taking on integer values of between 0 and $N_c - 1$. To prevent pulses from overlapping, the chip interval is selected to satisfy $T_c \leq T_f/N_c$. The polarity randomisation is achieved by having each pulse multiplied by a (pseudo) random variable, d_j, that can take on the values of $+1$ or -1 with equal probability. The sequences d_j and c_j are assumed to be known at transmitter and receiver.

Coherent reception requires the use of Rake receivers in order to collect the energy of the available resolvable MPCs. The Rake can be implemented as a bank of correlators, where correlation is done with the transmit waveform, and the sampling time of each finger is matched to the delay of one resolvable MPC. Note, however, that for systems with a large absolute bandwidth, the number of resolvable MPCs can become very large. Since the number of fingers in practical Rake receivers is limited, only a subset of the available MPCs can be received [16].

Furthermore, Rake receivers operating with UWB signals can cause distortion of the MPCs. For conventional wireless systems, the impulse response of the channel can be written as

$$h(t, \tau) = \sum_{i=1}^{N} a_i(t) \cdot \chi_i(t, \tau) \otimes \delta(\tau - \tau_i), \tag{1.2}$$

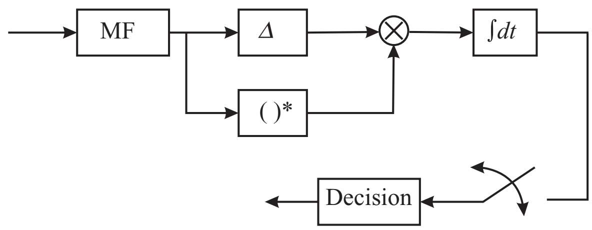

Figure 1.4 Block diagram of a transmitted-reference receiver [49]. Reproduced by permission of © 2004 IEEE.

where N is the number of resolvable MPCs, and the $a_i(t)$ are the complex amplitudes of the resolvable MPCs. For a UWB system, the impulse response must be written as

$$h(t, \tau) = \sum_{i=1}^{N} a_i(t) \cdot \delta(\tau - \tau_i), \tag{1.3}$$

where $\chi_i(t,\tau)$ denotes the (time-varying) distortion of the i-th echo due to the frequency selectivity of the interactions with the environment, the reasons for which will be described in Part III (see also [39]). The distortions can be significant, especially in systems with large relative bandwidth. For optimum reception, a Rake receiver needs to know the functions $\chi_i(t,\tau)$. Alternatively, the receiver must sample at the Nyquist rate and process all the sample values – the number of which can be significantly higher than the number of MPCs. As a further important conclusion, we find that the matched filter has to take the distortions of the waveform, w_{tx}, by the antennas into account. If that is not possible, it is desirable that the antennas distort w_{tx} as little as possible.

Since coherent reception of impulse radio can be challenging, alternative demodulation schemes have been investigated. Noncoherent reception is the simplest approach, and works very well when the delay spread of the channel is small and the signal-to-noise ratio is high. For large delay spreads, the receiver has to integrate the received energy over a long period, which also means that it picks up a lot of noise in the process. Furthermore, the contribution of the noise–noise cross-terms in the squared signal leads to an additional deterioration of the performance. Finally, noncoherent detection is more sensitive to interference.

As a compromise between coherent and noncoherent schemes, transmitted-reference (TR) schemes are often used. In TR, we first transmit a reference pulse of known polarity (or position), followed by a data pulse whose polarity (position) is determined by the information bit. At the receiver, we then have to multiply the received signal with a delayed version of itself, see Figure 1.4. This scheme has an SNR that is worse than that of a coherent receiver (due to the occurrence of noise–noise crossterms) and comparable to a noncoherent receiver. It is not sensitive to distortions by antennas and channels, because both the data pulse and the reference pulse undergo the same distortions. Furthermore, it is less sensitive to interference than noncoherent detection.

1.3.2 DS-CDMA

Although UWB has long been associated with impulse radio, it is not the only possibility of spreading a signal over a large bandwidth. More ‘classical’ spreading methods, as discussed, e.g., in [44], can be used as well. In particular, DS-CDMA can be used in a straightforward way to generate UWB signals.

DS-CDMA spreads the signal by multiplying the transmit signal with a second signal that has a very large bandwidth. The bandwidth of this total signal is approximately the same as the bandwidth of the wideband spreading signal. Conventionally, the spreading sequence consists of a sequence of ± 1s. m-sequences (Maximum-length sequences (m-sequences) generated by shift-registers with feedback are the most popular of these sequences, although there are many others. The transmit signal is thus

$$s_{\mathrm{tr}}(t) = \sum_{j=-\infty}^{\infty} d_j b_{\lfloor j/N_f \rfloor} w_{\mathrm{tr}}(t - jT_c) = \sum_{k=-\infty}^{\infty} b_k w_{\mathrm{seq}}(t - kT_s), \tag{1.4}$$

where the symbols have the same meaning as in Equation (1.1).

The difference between a conventional (e.g., cellular) DS-CDMA system and a UWB signal is the chip rate, i.e., $1/T_c$. Consequently, both the theoretical underpinnings and the implementation aspects of DS-CDMA are well understood; this facilitates their use for UWB systems. For example, the high-data-rate UWB system proposed by the UWB Forum industrial group is such a DS-CDMA system.

When comparing Equations (1.4) and (1.1), we find some important similarities: both TH-IR and DS-CDMA transmit a bit by multiplying it with a spreading sequence $w_{\mathrm{seq}}(t)$, and the bandwidth is essentially determined by the duration and shape of a basis pulse, $w_{tx}(t)$. The major difference lies in the nature of the spreading sequence. For the DS-CDMA case, it consists only of binary values, ± 1, while in the impulse radio (IR) case, it consists of many zeroes, with several ± 1's located at pseudorandom positions. As a consequence, DS-CDMA signals can be more difficult to generate: it is not just a matter of generating short pulses at large intervals, but rather it requires the continuous generation of those pulses. Furthermore, DS-CDMA as described above does not allow noncoherent (energy detection) reception since a correlation process is required to recover the original data.

1.3.3 OFDM

OFDM transmits information in parallel on a large number of subcarriers, each of which requires only a relatively small bandwidth. This approach, first suggested for wireless applications by Cimini [45], has become popular for high-data-rate transmission in conventional systems, e.g., the IEEE 802.11a/g wireless standards, and its theory and implementation are now well understood. The block diagram of a typical system is shown in Figure 1.5. The data stream is first serial-to-parallel converted, and then modulated onto subcarriers that are separated by a frequency spacing W/N, where W is the total transmission bandwidth, and N is the number of subcarriers. The modulation process can be done either in the analogue domain (Figure 1.5(a)), or digitally, by performing an inverse fast Fourier transform (IFFT) on the data (Figure 1.5(b)). The latter approach does not need multiple local oscillators, and is thus the one in use today. However, it requires an IFFT and analogue-to-digital converters operating at high speed (clock speed of approximately W).

OFDM transmits each information symbol on one carrier, and thus does not exploit the frequency diversity inherent in a UWB system. This problem can be circumvented by the use of appropriate coding and/or by the use of multicarrier-CDMA, which spreads each modulation symbol over a number of subcarriers [46].

The impact of channels and antennas on UWB-OFDM systems is similar to that on conventional OFDM systems. In either case, the receiver determines the distortion (attenuation and phase shift) on each subcarrier, and compensates for it. The choice of subcarrier spacing depends mostly on the channel characteristics, especially the *maximum excess delay*, and not on the total system bandwidth. Rather, the total number of tones increases approximately linearly with the total bandwidth. Furthermore, the FFT

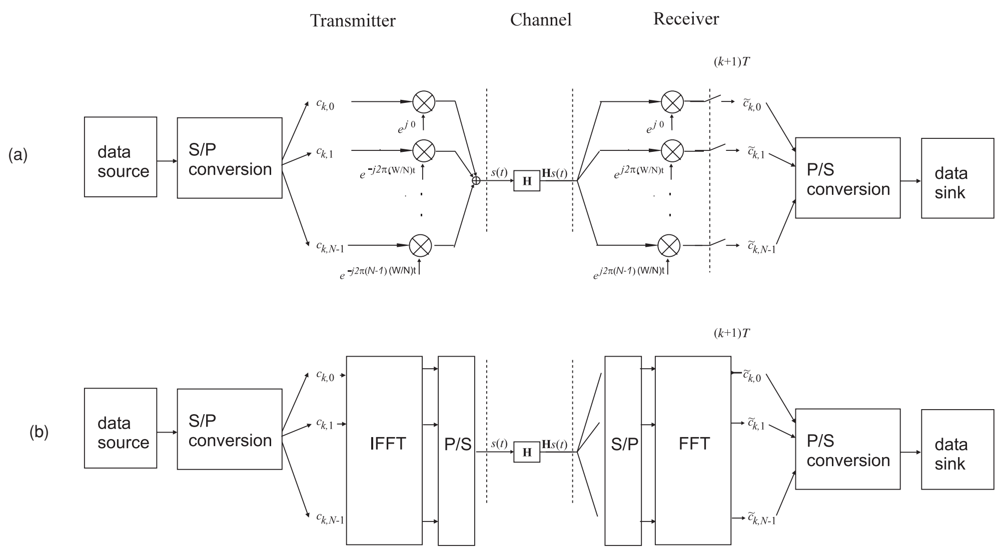

Figure 1.5 Principle of OFDM: analogue implementation (a) and digital implementation (b). Source [40], reproduced by permission of © 2005 John Wiley & Sons, Ltd.

has to operate with a clock speed that is approximately equal to the bandwidth. For these reason, OFDM becomes impractical for bandwidths above 500 MHz (at least with the technology available at the time of writing, 2006).

1.3.4 Frequency Hopping

Fast frequency hopping changes the carrier frequency several times during the transmission of one symbol; in other words, the transmission of each separate symbol is spread over a large bandwidth. *Slow frequency hopping* transmits one or several symbols on each frequency. Frequency hopping has a multiple-access capability. Different users are distinguished by different hopping sequences, so that they transmit on different frequencies at any given time.

For more details, we have to distinguish between the case of synchronised and unsynchronised users. In the synchronised case, all users can use the same hopping pattern, but with different offsets, see Figure 1.6(a). In the unsynchronised case (Figure 1.6(b)), we have no control over the relative timing between the different users. Thus, the hopping sequences must make sure that there is little multiple-access interference for all possible timeshifts between the users; otherwise, catastrophic collisions between users could occur. The situation is analogous to TH-IR, where we need to find time-hopping sequences that avoid catastrophic collisions.

Frequency hopping can be used either as a multiple-access scheme of its own, or it can be combined with other schemes. In the latter case, we divide the available frequency band into sub-bands, and transmit (e.g., with OFDM) in different sub-bands at different times. This approach simplifies implementation, as the sampling and A/D conversion now has to be done only with a rate corresponding to the width of the sub-band instead of the full bandwidth. The UWB channel is thus converted into a number of narrowband channels, because most propagation effects in a 500-MHz channel are the same as those in conventional

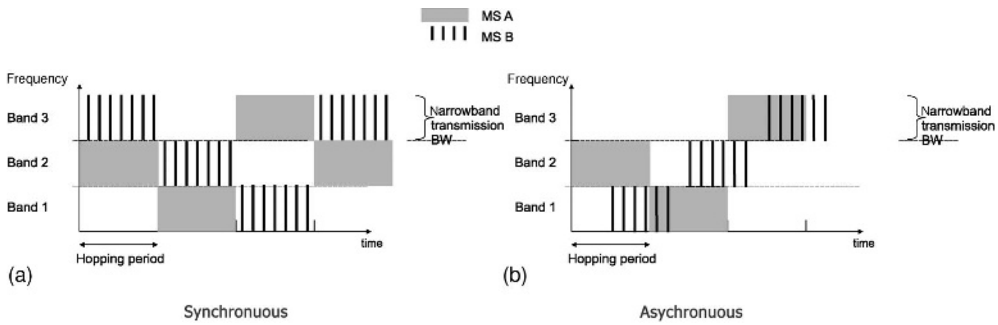

Figure 1.6 Frequency hopping multiple access with synchronous (a) and asynchronous users (b). Source [40], reproduced by permission of © 2005 John Wiley & Sons, Ltd.

(wireless) channels. However, the different sub-bands undergo different attenuations. In a similar manner to conventional OFDM systems, it is also essential that coding/interleaving across different frequency bands is performed.

1.3.5 RADAR

While conventional radar systems work with modulated carriers with a bandwidth of no more than 10 %, UWB radars transmit short, high-powered pulses. The product of the speed of light with the pulse duration should be less than the physical dimensions of the observed objects; it is also often smaller than the dimensions of the used antennas. As a consequence, the signal shape of the signal is distorted by transmission from the antennas, by reflection from the observed objects and by reception at the receive antenna. This situation is similar to the distortion of each separate MPC as discussed in Section 1.3.1. Thus, again, the received signal has an unknown shape, and matched filtering, the mainstay of conventional radar detection theory, cannot be applied [47].

It is also important to recognise that the pulse shape distortions at the antenna depend on the direction of the radiation. As a consequence, the compensation for antenna signal distortion depends on the direction of arrival. When radars with synthetic aperture arrays are used, many of the well-known high-resolution direction-finding algorithms do not work anymore, since they depend on the narrowband signal assumption.

Quite generally, new signal-processing algorithms need to be developed to extract all the available information about target shape, distance and movement from the received signals. The correct modelling of the distortion of the pulses caused by the antenna and object is the *conditio sine qua non* for those algorithms.

1.3.6 Geolocation

For sensor networks and similar applications, ranging and geolocation has become an important function.[3] While (active) ranging shows some similarities to radar, it also has some important differences. A ranging

[3] By ‘ranging’ we mean the determination of the distance between two devices. By ‘geolocation’, we mean the determination of the absolute position of a device in space. Geolocation of a device can be achieved if the range of

system tries to determine the time-of-arrival of the *first* MPC in the transmission from another active device. Together with knowledge of the absolute time when the transmitter sent out the signal, this allows us to determine the runtime of the signal between the two devices.[4] A major challenge in geolocation is the determination of the first arriving MPC in the presence of other MPCs as well as noise. This is made more difficult by the fact that – due to the very high delay resolution – the first resolvable MPC carries less energy than in conventional systems, especially in non-line-of-sight situations. The actual propagation conditions, especially the attenuation of the (quasi-) line-of-sight, have thus an important influence on the accuracy of UWB ranging.

1.4 Frequency Regulation

When designing a UWB system, the first step is to decide the frequency range over which it should operate. The transmit signals have to satisfy the frequency regulations in the country in which the device operates. Until the turn of the century, frequency regulators the world over prohibited the intentional emission of broadband radiation (and put strict limits on unintentional radiation), because it can interfere with existing, narrowband communications systems. It was pointed out by UWB advocates that UWB systems minimise this interference by spreading the power over a very large bandwidth. After lengthy deliberations, the FCC issued its 'report and order' in 2002, which allowed the emission of intentional UWB emissions [7], subject to restrictions on the emitted power spectral density.[5]

The 'frequency masks' depend on the application and the environment in which the devices are operated. For indoor communications, a power spectral density of −41.3 dBm/MHz is allowed in the frequency band between 3.1 and 10.6 GHz. Outside of that band, no intentional emissions are allowed, and the admissible power spectral density for spurious emissions provides special protection for GPS and cellular services (see Figure 1.7). Similarly, outdoor communications between mobile devices is allowed in the 3.1–10.6 GHz range, though the mask for spurious emissions is different. For wall-imaging systems and ground-penetrating radar, the operation is admissible either in the 3.1–10.6 GHz range, or below 960 MHz; for through-wall and surveillance systems, the frequency ranges from 1.99–10.6 GHz, and below 960 MHz are allowed. Furthermore, a number of military UWB systems seem to operate in that range, though exact figures are not publicly available. The frequency range from 24–29 GHz is allowed for vehicular radar systems.

In the autumn of 2005, the Japanese and European frequency regulators issued first drafts of rulings. These would indicate that operation is allowed in the frequency range between 3.1 and 4.8 GHz, as well as between 7–10 GHz, i.e., omitting the band around 5 GHz. For the 3.1–4.8 GHz range, a 'detect-and-avoid' mechanism is required, i.e., a UWB device must determine whether there are narrowband (victim) receivers in the surroundings, and avoid emissions in the frequency range of those victim devices. Further details are unknown at the time of this writing.

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this device to a number of other devices with known positions can be determined. Direction-of-arrival information can be used to make this process more accurate.

[4] A variety of techniques can be used to exchange knowledge about the absolute transmission time of the signal, e.g., timestamps on the transmitted signal, or 'ping-pong' schemes, where device A sends a signal, device B receives it, and after a certain time replies with a signal of its own. After determining the arrival time of this signal, device A knows the total roundtrip time of a signal between the two devices.

[5] The ruling also restricts: (i) the admissible peak power; (ii) the location of deployment (fixed installations of transmitters are prohibited outside of buildings); and (iii) the applications for which the products can be used (e.g., UWB transmitters in toys are prohibited).

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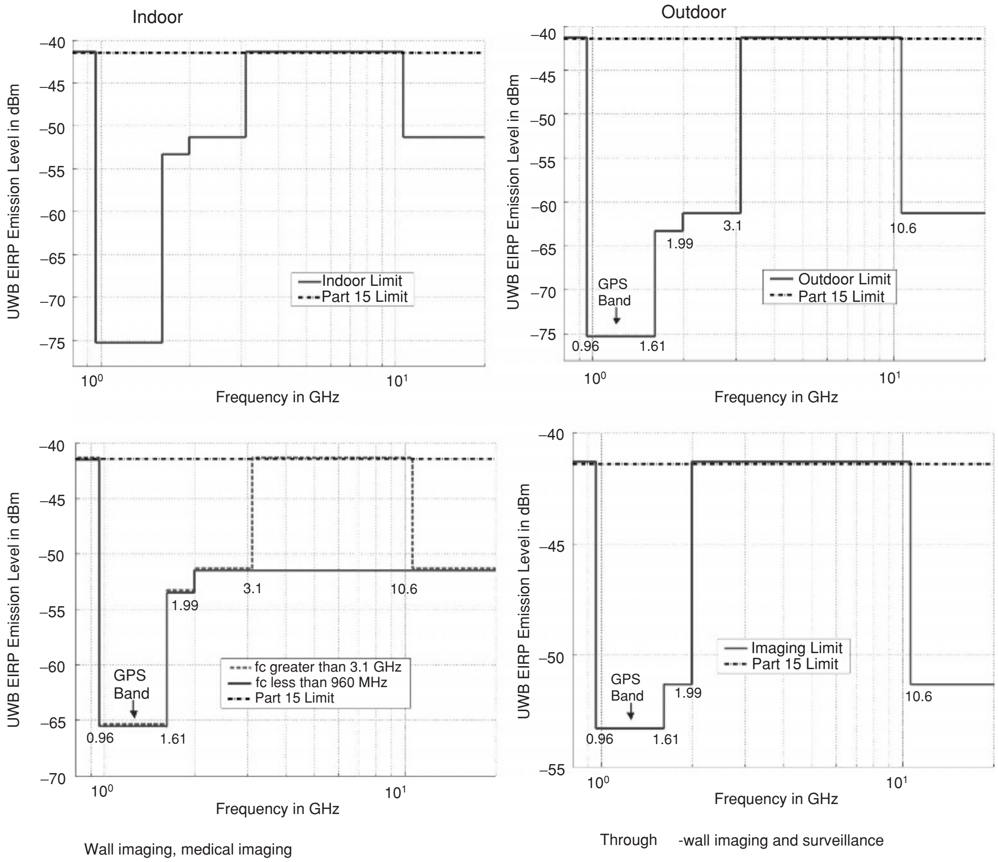

Figure 1.7 FCC masks for different environments [7]

Further restrictions in the useful frequency range arise from the current technological possibilities. Semiconductor devices are available that cover the whole spectrum assigned to UWB. However, complementary metal oxide semiconductor (CMOS) technology, which is by far the most appealing process for high-volume commercial applications, is currently only available for frequencies up to about 5 GHz.

1.5 Applications, Operating Scenarios and Standardisation

For the antennas and propagation researcher, it is important to understand the application and the deployment and operating scenario for which a UWB device is used. The usage of the systems determines their location (which has a big impact on propagation conditions), and on their size (which determines, e.g., the admissible size of the antennas).

One of the most popular applications of UWB is data transmission with a very high rate (more than 100 Mbit/s). Given the large bandwidth of UWB, such high rates can be easily achieved, but the spreading factor is small. The combination of small spreading factor and low admissible power spectral density limits the range of such systems to some 10 m. Networks that cover such a short range are often called *personal area networks* (PANs). High-data-rate PANs are used especially for consumer electronics and personal computing applications. Examples include the transmission of HDTV (high definition television) streams from a set-top box or a DVD player to the TV requires high data rates and wireless USB (universal serial bus), which aims to transmit data at 480 Mbit/s between different components of a computer. For these applications, UWB is in a competition with wireless local area networks (WLANs) based on multiple-antenna technology, such as the emerging 802.11n standard, which also aims to achieve high data rates. UWB has the advantage of possibly lower costs and higher data rates, while the WLANs can achieve longer ranges. In order to further increase the data rate, the combination of UWB with multiple antennas is currently being deliberated. This has important consequences for the antenna research (the design of suitable antenna arrays becomes an issue), signal processing (the appropriate processing of the data from the multiple antennas is different from the narrowband case) and propagation (the directional information of the MPCs at the two link ends is relevant).

In 2002, the IEEE established a standardisation body, the working group 802.15.3a, to write the specifications for high-data-rate PANs. Soon, two major proposals emerged, one based on DS-CDMA (Section 1.3.2), the other on a combination of frequency hopping (Section 1.3.4) and OFDM (Section 1.3.3). Both of those proposals use only the frequency range between 3.1 and 5 GHz. Although the IEEE group has been deadlocked since 2003, both of the proposals are the basis of industry consortia that started to ship products in 2005: the WiMedia consortium, which merged with the MBOA (Multiband OFDM Alliance) consortium, and uses the OFDM-based physical layer specifications; and the UWB Forum, which adopted the DS-CDMA system. The ultimate winner will emerge from a battle in the marketplace; the outcome will also have an impact on the requirements for antennas for a considerable percentage of the UWB market, as discussed in Sections 1.3.2 and 1.3.3.

Another important application area is sensor networks. Data from various sensors are to be sent to a central server, or to be exchanged between different sensors. The volume of data is typically small, so that average data rates of a few kbit/s or less are common. Size restrictions can be stringent, because the transceiver has to be collocated with the sensors. Also the requirements for energy consumption can be very stringent, since the devices are often battery operated [48]. The location of the devices can vary greatly, and include positions where propagation conditions are very unfavourable. Thus, the propagation conditions for such applications can differ significantly from both high-rate UWB devices, and from classical cellular and WLAN applications. Low-data-rate systems are also envisaged for emergency communications, e.g., between people within a collapsed building and rescue workers. In this case, the signal robustness that stems from a large relative bandwidth and the possibility of floor and wall penetration is especially important. Consequently, these systems tend to operate at lower bandwidths. Low-rate systems are currently being standardised by the IEEE 802.15.4a group. In contrast to the deadlocked 802.15.3a group, the 802.15.4a group is expected to produce a standard in 2006, based on an impulse radio approach.

Even at low data rates, the range that can be covered by a single UWB link is rather limited – 30 to 100 m seem to be the maximum. Longer ranges can be achieved by relaying the messages between different nodes, until they arrive at their destination. The appropriate design of the routing and optimisation of the energy spent at each node are some recent research topics that have drawn attention in the academic community. However, from an antenna and propagation point of view, it is sufficient to consider a single link.

Body area networks (BANs) consist of a number of nodes and units placed on the human body or in close proximity such as on everyday clothing. A major drawback of current wired BANs is the inconvenience for the user. While smart (prewired) textiles have been proposed, they imply the need

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for a special garment to be worn, which may conflict with the user's personal preferences. Wireless body-centric network presents the apparent solution.

In sensor networks, geolocation of the nodes can be of great importance. This is a major argument for UWB, which allows a much more precise location of the devices than narrowband schemes. This has an important impact on propagation research, as discussed in Section 1.3.6. When direction-of-arrival information is used to increase the accuracy of the location estimation, antenna arrays are also important system components.

UWB radars have developed into an important market niche, used mainly for two purposes: (i) high-performance radars that have smaller 'dead zones', and (ii) radars for close ranges that can penetrate walls and ground. The second application is useful for surveillance, urban warfare and landmine detection. Most of the applications in this area are classified, as they serve military or law-enforcement purposes. A commercial application is the vehicular collision avoidance radar. Such a radar typically operates in the microwave range (24–29, or around 60 GHz). Propagation conditions are usually straightforward (line-of-sight); antenna research concentrates on antennas that can be easily integrated into the chassis of cars. Another promising application is biological imaging, e.g., for cancer detection.

Naturally, the above enumeration of applications is not complete, and it can be anticipated that in the future, even more ways to use UWB will be discovered.

1.6 System Outlook

In an area as active as UWB, one question arises naturally: where is it going? From a commercial point of view, the initial hype has somewhat abated: statements like 'UWB is the ultimate solution to all problems in wireless' (a quote from a trade journal in 2002) nowadays sound absurd not only to researchers, but also to all people working in the area. At the same time, many more concrete visions for the application of UWB techniques have been developed, as discussed in Section 1.5. It has also been recognised that there is no single solution for all the different applications. The techniques required by a high-data-rate, short-range system attached to a DVD player are completely different from the ones required by a battery-powered sensor node. There is always a trade-off between cost, power consumption, data rate and range, and different applications require different solutions. The more the market develops, the more diverse products will be established.

In order to create all-CMOS devices (where both the digital signal processing and the radiofrequency electronics can be manufactured in this most cost-effective technology), restrictions on the admissible frequency range have to be accepted. At the moment, 5 GHz represents the upper frequency range that can be achieved with that technology. This brings the chip manufacturers on a collision course with frequency regulators in Asia and Europe, who want to move UWB devices to the 7–10 GHz range.

In terms of antenna research, the main goal is a reduction of the antenna size, while still keeping the antenna efficiency at reasonable levels and keeping the manufacturing costs low. Due to the rules of frequency regulators, it is desirable that antennas have the same radiation pattern at all frequencies. Furthermore, the antenna aperture (and not the antenna gain) should be as independent of frequency as possible. Due to the increasing role of antenna arrays both for direction finding and for increasing the capacity of the systems, the design of suitable arrays is becoming increasingly important.

From a propagation point of view, there are still many theoretical as well as practical open issues. Our understanding of the frequency dependence of different propagation processes such as diffuse scattering, and how to include it in deterministic channel prediction tools, is still incomplete. The set up and evaluation of directionally resolved measurement campaigns is also an area of active research. But most importantly, almost all existing propagation channel models are based on a single measurement campaign, and many of the parameters that are used in those models have no statistical reliability. Thus, extensive measurement campaigns will be a key part of future propagation research.

This completes the introductory chapter on UWB, where we discussed its history, various forms of realising a UWB transceiver, as well as regulatory and standardisation aspects. We move now to the four technical parts of this book, dealing with various issues related to UWB antennas and UWB signal propagation.

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