

Preface

Recent advances in wireless communication technologies have had a transformative impact on society and have directly contributed to several economic and social aspects of daily life. Increasingly, the untethered exchange of information between devices is becoming a prime requirement for further progress, which is placing an ever greater demand on wireless bandwidth. The ultra wideband (UWB) system marks a major milestone in this progress. Since 2002, when the FCC allowed the unlicensed use of low-power, UWB radio signals in the 3.1–10.6 GHz frequency band, there has been significant synergistic advance in this technology at the circuits, architectural and communication systems levels. This technology allows for devices to communicate wirelessly, while coexisting with other users by ensuring that its power density is sufficiently low so that it is perceived as noise to other users.

UWB is expected to address existing needs for high data rate short-range communication applications between devices, such as computers and peripherals or consumer electronic devices. In the long term, it makes available spectrum to experiment with new signaling formats such as those based on very short pulses of radio-frequency (RF) energy. As such it represents an opportunity to design fundamentally different wireless systems which rely on the bandwidth of the signals to enhance the data rate or which use the available bandwidth for diverse applications such as ranging and biomedical instrumentation.

This book offers its readers a comprehensive overview of the state of the art of the physical implementation of ultra wideband transceivers. It addresses system level aspects, architectural design issues, circuit level implementation challenges as well as emerging challenges in the field. The material assumes the reader has a basic familiarity with wireless communication systems and RF integrated circuit design.

The editors thank the chapter authors for their excellent contributions and help in coordinating this book into a cohesive treatment of the subject. Many thanks go to the Springer editorial staff, in particular Katelyn Stanne and Carl Harris. We also

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Chapter 2

High-Rate UWB System Design Considerations

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Abstract The ability to optimally exploit the 7.5 GHz of newly created unlicensed spectrum for UWB technology depends on addressing a number of challenging system design issues. This chapter provides an overview of many of these issues and some technical trade-offs and comparisons with different system designs. Some of the challenges include dealing with multipath propagation, energy capture, narrow-band interference, rapid synchronization, and varying regulatory rules throughout the world, just to name a few.

2.1 Introduction

According to the rules set forth by the FCC on February 14, 2002, ultrawideband (UWB) systems are defined as systems that occupy more than 20% of a center

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- a. J. Foerster, Document 02490r1P802-15_SG3a-Channel-Modeling-Subcommittee-Report-Final, December 2002 (see <http://iee802.org/15/>), © 2002 IEEE
- b. J. Decuir, Dave Leeper, “MB-OFDM Proposal Update”, IEEE 802.15.3, 15-05-0648-00-003a-mb-ofdm-update.pdf, Nov. 2005, © 2005 IEEE
- c. J. Foerster, “The effects of multipath interference on the performance of UWB systems in an indoor wireless channel”, IEEE VTC, Volume 2, May 2001, Page(s):1176–1180. © 2001 IEEE
- d. J. Foerster, “The Performance of a Direct-Sequence Spread Ultra-wideband System in the Presence of Multipath, Narrowband Interference, and Multiuser Interference,” IEEE UWBST Conference Proceedings, May, 2002, © 2002 IEEE
- e. V. Somayazulu, J. R. Foerster, and S. Roy, “Design challenges for very high data rate UWB systems”, Conf. Record of the Thirty-Sixth Asilomar Conf. on Signals, Systems and Computers, vol. 1, pp. 717–721, 2002, © 2002 IEEE
- f. J. Foerster, “Interference modeling of pulse-based UWB waveforms on narrowband systems”, IEEE VTC, May 2002 Page(s):1931–1935 vol.4, © 2002 IEEE
- g. S. Somayazulu, “Detect and Avoid (DAA) Mechanisms for UWB Interference Mitigation”, Invited Paper, page 513–518., IEEE UWBST Conference proceedings, Sept. 2006, © 2006 IEEE

frequency or more than 500 MHz bandwidth. For communications systems, the available spectrum is 7.5 GHz, from 3.1 to 10.6 GHz, with slight differences in the spectral mask for indoor and handheld devices. So, from a high-level perspective, this looks like a tremendous opportunity if one can figure out how to best, and in a cost effective manner, exploit this newly available bandwidth. In order to optimally exploit this available bandwidth, it is important to understand the various system design and implementation trade-offs when it comes to dealing with multipath, energy capture, narrowband interference, implementation complexities, and different regulatory constraints. This chapter primarily investigates the potential for UWB technology to be used for very high-throughput, short-range applications like high-speed cable replacement (wireless USB), video distribution within the room, and fast image downloads from a camera to a wireless kiosk, for example. However, there are also a number of other uses of the technology that are currently being developed. These include low-rate, low-power sensors; inventory tracking and cataloging devices; building material analysis; and radar and position location-based applications, just to name a few. Many of these functions would also be beneficial to high-rate devices as well, but are not covered here. The ability for a single UWB physical layer solution to exploit high-rate, low-power, and accurate positioning capabilities of the technology could result in some interesting future capabilities.

This chapter is organized as follows. First, a brief introduction to UWB technology and the trends which have led to the development of the first industry standard is presented in Section 2.2. Section 2.3 covers a number of system design considerations and trade-offs to be taken into account when developing a high-rate UWB system, including issues related to multipath, energy capture, processing gain and spectral flatness, multi-user access, implementation, link budgets, initial acquisition, and narrowband interference. Section 2.4 provides an update on the current regulatory status for UWB both inside and outside the United States and introduces a relatively new concept of “detect and avoid” (DAA) which will likely be needed in order to more efficiently share the available spectrum with other users. Finally, future possibilities including a link with cognitive radios and conclusions are provided in Sections 2.5 and 2.6, respectively.

2.2 Brief History

2.2.1 *The Link to Early Wireless*

UWB technology is as old as radio itself. The earliest transmitters of Bose¹ and Marconi,² circa 1895, used spark gap technology that generated radio waves across a multi-GHz spectrum in a largely uncontrolled manner.

¹ *IEEE Transactions of Microwave Theory and Techniques*, December, 1997, Vol. 45, No. 12, pp. 2267–2273.

² *IEEE History Center*, URL http://www.ieee.org/organizations/history_center/milestones_photos/swiss_marconi.html.

Over the next 25 years, radio technologists sought methods to allow more systems to share spectrum on a non-interfering basis. Motorized spark generators and LC tank circuits limited the bandwidth of spark-based signals and helped control center frequencies. With DeForest's invention of the vacuum tube triode, circa 1906,³ it became possible to transmit very narrowband signals at a frequency of one's choosing. As a result, spark technology largely vanished by the 1920s.

Thanks to vacuum tube technology, it also became possible to regulate wireless on a spectrum-allocation basis. In the United States, the Federal Communications Commission was chartered to do just that by the Communications Act of 1934.

For over 70 years, reserving portions of the spectrum for specific purposes has been an effective way to limit interference. But that approach suffers from the disadvantage that at any given time, large portions of the radio spectrum often go unused by anyone. Over the years, the FCC has used various sharing mechanisms to mitigate this inefficiency, including such concepts as primary, secondary, coequal, and other licensing constructs. UWB is just the latest attempt by the FCC to improve spectrum use.

2.2.2 Ultrawideband Reemerges

In the mid-1960s, interest in pulse-based broad-spectrum radio waveforms reemerged, growing largely out of radar technology. Most of the work was carried out under classified U.S. Government programs. However, beginning in 1994, much of the work became non-classified, and a group of pioneers began exploring commercial as well as government/defense applications of pulse-based UWB.⁴ In 1998, working with those pioneers, farsighted engineers at the FCC Office of Engineering and Technology launched a formal FCC Notice of Inquiry, ET Docket No. 98-153, proposing the use of UWB systems on an unlicensed basis.⁵

The Notice of Inquiry was controversial, to say the least. The FCC was proposing to allow unlicensed operation across broad swaths of the radio spectrum, most of which had already been licensed to others. Rather than relying on now-traditional frequency segregation to avoid interference, the FCC proposed an average power spectral density limit of -41.3 dBm/MHz. This was and is the same limit already assigned in Part 15 of the FCC rules⁶ to devices such as hair dryers, electric drills, laptop computers, and other *unintentional* radiators. Despite these low emission

³ Wikipedia, URL http://en.wikipedia.org/wiki/Vacuum_tube.

⁴ Fontana, Robert, "A Brief History of UWB Communications", www.multispectral.com, see link "UWB History", "Papers on UWB" and other links.

⁵ http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/fedreg/63/50184.pdf.

⁶ <http://www.fcc.gov/oet/info/rules/>.

limits, the wide spectrum made it possible to transmit hundreds of megabits, or even gigabits per second over short distances with very low power.

After more than 900 filed comments on ET 98-153, the FCC released a formal Report and Order in April of 2002⁷ specifying the rules under which UWB systems could operate. Among those rules is a frequency mask (see Table 2.1) specifying the maximum power spectral density for UWB transmitters as a function of frequency. Interest focused quickly on the 3–5 GHz portion of the spectrum where propagation losses were lowest, CMOS silicon performance was best, and interference with WLAN UNII systems (5150–5350 MHz) could be avoided.

2.2.3 Ultrawideband and Standards: Challenges and Eventual Path(s) to Convergence

With UWB approved for use in the United States, IEEE Task Group 802.15.3a began working on an alternate physical layer (PHY) technology to support the 802.15.3 Personal Area Network (PAN) protocol. A list of requirements for the PHY was developed,⁸ among them was the requirement to support at least 110 Mbps at a distance of 10 m. Among the applications foreseen were high-speed “synch-and-go” and “download-and-go” file transfers among PCs, laptops, digital cameras, portable media players, cellphones, and other portable devices. Also foreseen were high-definition video streaming from portable devices to nearby displays. Virtually, all the 26 proposals appearing before the IEEE group were focused on UWB because of its high-rate and low-power possibilities.

Most of the initial UWB proposals were traditional impulse-based designs. That is, the signals consisted of a stream of short-duration (approximately 1 μ s) pulses. Depending on the proposal, these pulses were modulated by polarity, amplitude, time position, or other characteristics. Impulse-based proposals offered simple, efficient transmitter designs with pulses formed by pin diodes or other

Table 2.1 FCC spectral mask for indoor devices

Frequency (MHz)	Max EIRP (dBm)
960–1,610	–75.3
1,610–1,990	–53.3
1,990–3,100	–51.3
3,100–10,600	–41.3
Above 10,600	–51.3

⁷ FCC 02-48, “Revision of Part 15 of the Commission’s Rules Regarding Ultra-Wideband Transmission Systems”, Adopted February 14, 2002, Released April 22, 2002.

⁸ Siwiak, Kai, “SG3a Technical Requirements”, IEEE P802.15-02/104r14, September 2002.

devices – a modern-day equivalent of the old spark systems. Furthermore, some of these proposals used simple 1-bit ADCs in the receiver with chip rates proportional to the data bandwidth being transmitted. One of the proposals, later known as Direct-Sequence UWB (DS-UWB), combined a high-chip-rate impulse-based approach with orthogonal coding.

A second cluster of UWB proposals sought to strike a balance between the reduced implementation complexity of lower instantaneous occupied bandwidth and the performance advantages of increased overall bandwidth, based on the “sweet spot” of CMOS process technology in the near future. These proposals also foresaw a future need to allow finer control over the transmitted UWB spectrum, so emissions could be suppressed over selected frequencies in order to protect other narrow-band systems or to adapt to local regulations in countries outside the United States. One such approach, called “Multiband UWB” was based on pulses with longer duration (3–5 μs), resulting in occupied bandwidths of approximately 500 MHz, as shown in Fig. 2.1. By “hopping” the center frequencies of three or four segments, most of the 3–5 GHz spectrum could be occupied, allowing an average transmitted power of approximately $-41.3 \text{ dBm/MHz} + 10 \log_{10}(1700 \text{ MHz}) = -9 \text{ dBm}$. To obtain finer control over the transmit spectrum, one or more of these bands could be dropped.

Multiband UWB turned out to be short lived. A third proposal, dubbed *Multiband OFDM* (MB-OFDM),⁹ combined multiband hopping with OFDM. This turned out to be a superior solution, offering the best combination of implementation complexity and performance, and the various multiband UWB proponents converged to this proposal. After multiple rounds of comments and updates, the MB-OFDM proposal became what is today WiMedia/ECMA-368. The details of this specification are given in the following sections.

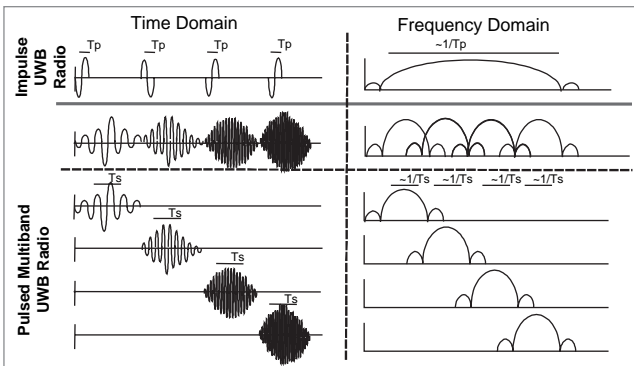


Fig. 2.1 A pulsed multiband UWB concept

⁹ IEEE P802.15-03/268r1, October, 2003.

Another proposal, described above as Direct Sequence Ultrawideband¹⁰ (DS-UWB), also survived down-selection in the IEEE process. DS-UWB is based on traditional, narrow pulses that can themselves occupy 1.5 GHz bandwidth or more. Two modes were described for DS-UWB – one using BPSK modulation and variable length spreading codes to obtain various data rates, and another employing orthogonal modulation with 4-BOK (binary orthogonal keying) sequences of different length. These modes were defined for use both in the lower frequency band from 3–5 GHz, and in a band of twice the width above 6 GHz. It is interesting to note that for the BPSK modes with data rates of 110 Mbps and higher, the DS-UWB proposal is actually to be regarded as an impulse radio system [IEEE P802.15-04/137r4, Table 2.7].

MB-OFDM and DS-UWB each had technical pros and cons and attracted their adherents in the IEEE 802.15.3a Task Group, but neither was able to achieve the 75% majority of voters needed for confirmation. As a result, in January 2006, the Task Group voted to recommend termination of the effort. However, adherents of both approaches had already been pursuing alternate paths to industry alliance, resulting in the WiMedia Alliance (MB-OFDM) and the UWB Forum (DS-UWB). Products using both technologies were planned for 2006. In January 2006, the MB-OFDM approach was accepted by the European standards organization ECMA as ECMA-368, and in March 2006, the Bluetooth Special Interest Group chose the WiMedia/ECMA-368 standard as the technology to be used in the next-generation, higher speed version of Bluetooth.

2.3 System Design Considerations

2.3.1 UWB Channel Models

In order to implement an efficient UWB system for high-rate communications, it's critical to understand the characteristics of the propagation channel. Intel and other companies performed several channel measurements spanning the frequency spectrum from 2 to 8 GHz (see [2, 3, 3] and related references) which were contributed to the development of a channel model in the IEEE 802.15.3a study group. An example channel realization is shown in Fig. 2.2, which points out two important characteristics of a very wideband, indoor channel. First, as can be seen in the figure, the multipath spans several nanoseconds in time which could result in inter-symbol interference (ISI) if UWB pulses are closely spaced in time, even when the separation distance is relatively short (less than 10 m). This ISI would need to be mitigated through proper waveform design, signal processing, and equalization algorithms at the cost of additional complexity. Second, the very wide bandwidth of the transmitted pulse permits resolution of several multipath components, which has its pros and cons. On the one hand, the multipath

¹⁰ IEEE P802.15-04/137r4, January, 2005.

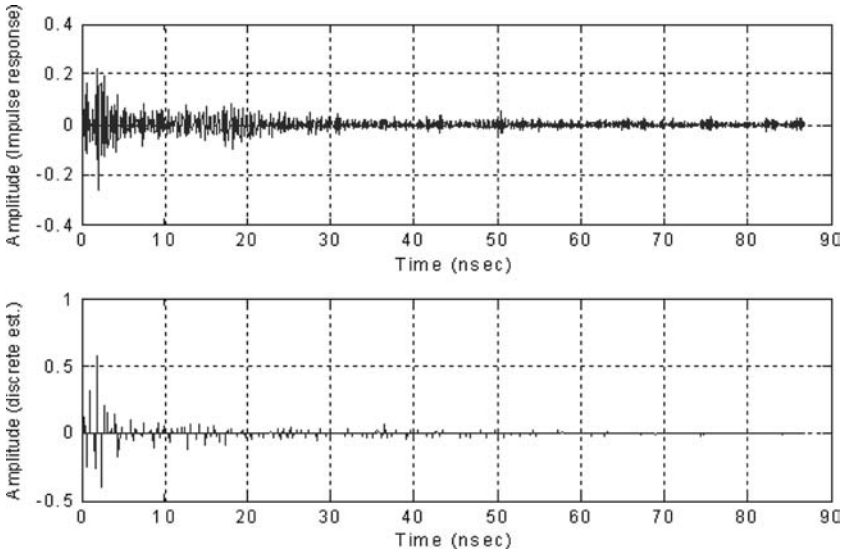


Fig. 2.2 Example indoor channel realization from measurements in a condo

arrivals will undergo less amplitude fluctuations (fading) since there will be fewer reflections that cause destructive/constructive interference within the resolution time of the received impulse. On the other hand, the average total received energy is distributed between a large number of multipath arrivals. In order to take advantage of that energy, unique systems and receivers need to be designed with multipath energy capture in mind. For a traditional impulse based UWB waveform, this may consist of a rake receiver with multiple arms, one for each resolvable multipath component. However, as the bandwidth of the UWB waveform increases, the complexity of the rake receiver could become limiting in order to capture the same energy. As a result, careful bandwidth selection of the UWB waveform can help balance the receiver complexity for capturing multipath energy while still benefiting from the reduced fading of the short duration of the pulses.

For proper system design, and to understand and quantify the impact of multipath propagation, it is important to have a reliable channel model that captures the important characteristics of the channel. Towards this end, a number of popular indoor channel models were evaluated in the IEEE to determine which model best fits the important characteristics that were measured and documented in [1]. The analysis and the results of this channel modeling work are contained in the IEEE 802.15.3a channel modeling sub-committee final report [3] and are briefly summarized here for completeness. Three indoor channel models were considered: the tap-delay line Rayleigh fading model [4], the Saleh-Valenzuela (S-V) model [5], and the Δ -K model described in [6]. Each channel model was parameterized in order to best fit the important channel characteristics, which included the mean excess delay, mean RMS delay, and mean number of significant paths defined as paths within 10 dB

of the peak path power. The results found that the S–V model was able to best fit the measurements and observed characteristics of the channel. In particular, the channel measurements showed a clustering of the multipath arrivals, which is also found in [7] and captured by the S–V model. In addition, the amplitude statistics of the measurements was found to best fit the log-normal distribution rather than the Rayleigh, which was part of the original S–V model. We have since compared the amplitude distribution to the Nakagami distribution and found that both the log-normal and Nakagami distributions fit the data equally well. So, the S–V model was modified slightly in order to take the log-normal fading distribution into account. The final proposed model is described in [3], and the reader is encouraged to visit these references for more detail.

Since completion of the work of the IEEE 802.15.3a channel modeling subcommittee, a number of additional measurements and models have been investigated which give even greater insight into the UWB propagation channel. An excellent tutorial of the latest theory and modeling of UWB channels is provided in [8], which also provides a thorough list of references addressing further UWB propagation characteristics including angular dispersion needed for MIMO implementations, temporal variation, and considerations for low-rate and localization applications.

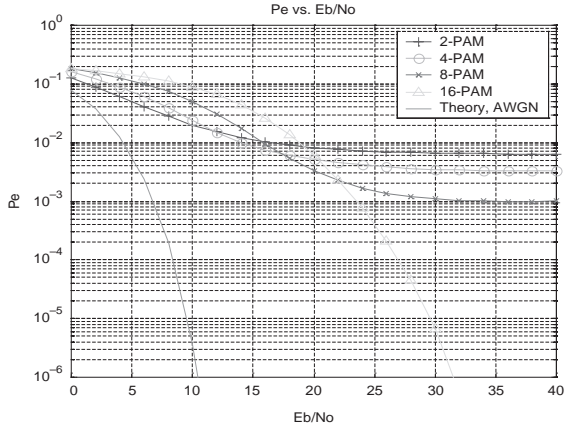
2.3.2 *Multipath Energy Capture and ISI*

2.3.2.1 **Impulse Radios’ Design Impact in Multipath Channels**

There are different ways to design a UWB impulse radio system in order to mitigate the impact of multipath and ISI. For example, if the impulses are sufficiently far apart in time (further than the maximum delay spread of the channel), then the ISI is reduced. The throughput is also significantly reduced, but this could be recovered to some extent by using higher order modulation on the impulses (of course, at the expense of range and increased linearity requirements of the RF front end). In order to illustrate this, the following results compare various impulse M -PAM systems based on the same throughput (see [9] for additional details). As M increases, the pulse repetition period increases for a given throughput. Figure 2.3 shows the performance of a UWB system without a rake receiver (i.e., $L_p = 1$). For simplicity, a so-called Δ -K model [10] is used to generate the following results which uses a two-state Markov model for the path arrival probabilities and is based on a number of previously reported indoor channel measurements for narrowband channels, but suffices here for explanation.

In this case, the 2-PAM system experiences considerable ISI, which causes it to have an error floor at high SNR regions. As the modulation level is increased, the error floor is lowered due to the reduced ISI. The various cross-over points between the M -PAM systems occur as the benefits of reduced ISI for the higher order

Fig. 2.3 Performance of M -PAM in a multipath channel with no RAKE



modulation help to overcome the greater E_b/N_0 required by these same modulation schemes in an AWGN channel.

Figure 2.4 shows the performance of the M -PAM systems with a maximal ratio combining RAKE (MRC-RAKE). Interestingly, the ISI seems to have less of an effect when an MRC-RAKE is used. This is due to the effective diversity that is obtained by capturing the multiple paths (i.e., the ISI experienced on each path is different and therefore results in averaging the overall ISI caused by the channel at the output of the RAKE). Averaging the results over more channel realizations could show the existence of an error floor, but the general observation that the effect of ISI is lessened by the use of a rake receiver should still hold.

Figure 2.5 shows how the performance of the MRC-RAKE changes with the number of combined paths. In order to remove the effects of ISI, the symbol rate is reduced to 5 Mbps in this case. This figure shows that the majority of the energy is

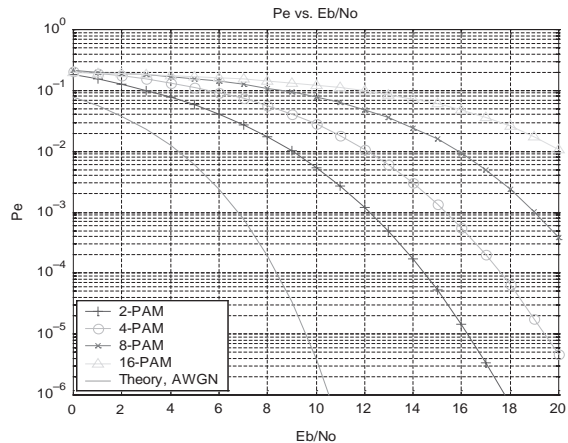
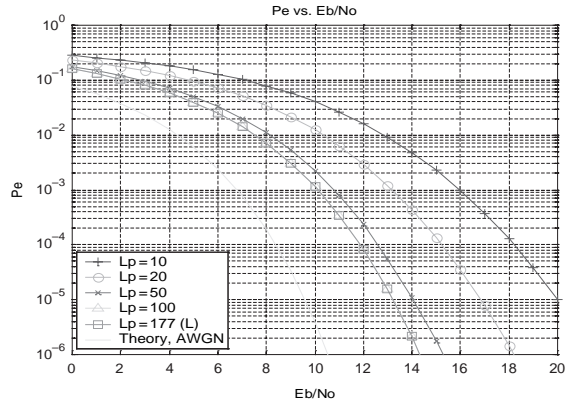


Fig. 2.4 Performance of M -PAM in a multipath channel with an MRC-RAKE

Fig. 2.5 Performance of 2-PAM with an MRC-RAKE and a pulse repetition period of $200\ \mu\text{s}$ (5 Mbps and thus no ISI)

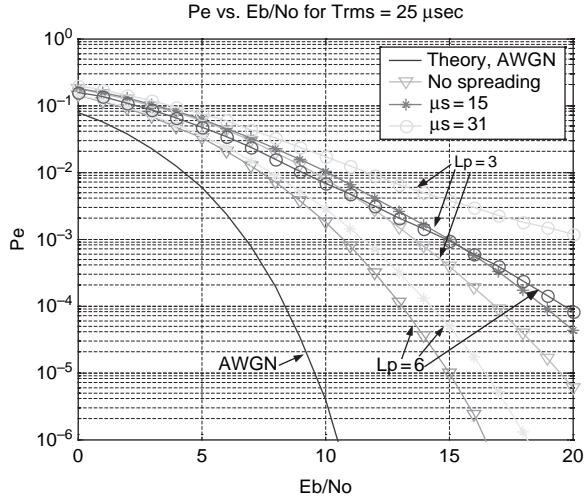


captured with $L_p=50$ where L_p is the number of arms in the rake. Clearly there is a trade-off between receiver complexity and performance, but this figure shows that there are significant gains possible with the use of a RAKE combiner. This type of system design may not be appropriate for high-rate communications since it requires the impulses to be spread apart in time in order to minimize the impact of ISI. However, it might be very appropriate for low-rate designs.

Since rake reception both significantly improves energy capture and mitigates ISI due to the averaging effect of the rake, another impulse system design option is to use a direct sequence (DS) spread spectrum approach, with an impulse radio and a rake receiver. In this case, actual channel measurements are used to generate the following results (see [11] for additional details and analysis). Figure 2.6 shows the performance of the DS UWB system in a multipath channel at a bit rate of 100 Mbps (i.e., for a non-spread system, pulses are separated by $10\ \mu\text{s}$, and for a spread system with N_r chips per bit, pulses are separated by $10/N_r\ \mu\text{s}$). These results show that the performance is actually worse for the DS systems compared to a system with no DS spreading due to the inter-chip interference caused by the multipath and the non-zero autocorrelation of the spreading sequences. This figure also shows that there can be significant benefits for increasing the number of RAKE arms from 3 to 6 for these indoor channels.

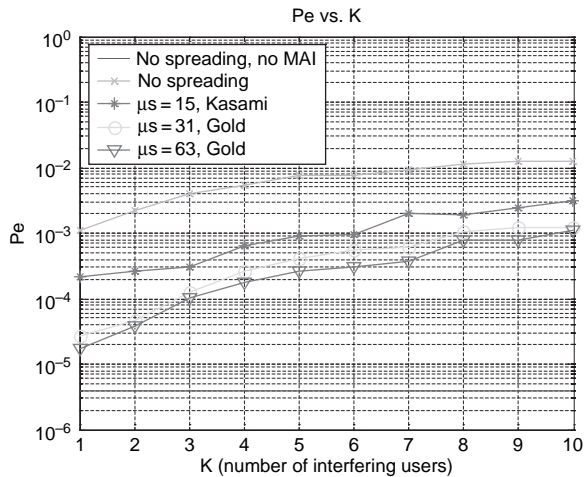
One of the main reasons for using direct sequence spreading is to enable multiple users to share the same spectrum simultaneously [12]. Figure 2.7 shows results with multiple access interference (MAI) and multipath present for a data rate of 16.7 Mbps (corresponding to a bit period of 60, 62, and $63\ \mu\text{s}$ for the length 15, 31, and 63 codes, respectively). In AWGN, there is a clear advantage for using DS spreading and the benefits of the longer codes which have lower cross-correlation values. For the non-spread system, the probability of making an error is dependent on the probability of a collision, which can be relatively high with even a single user present. The correlations of the DS codes alleviate this problem when a direct collision occurs. However, the benefit of spreading is reduced in a multipath

Fig. 2.6 Performance of DS system with $L_p=3$ and 6 RAKE arms, averaged over 50 NLOS channels and 100 Mbps



channel, as shown in Fig. 2.7 due to the inter-chip interference. It is interesting to note that the length 31 code has similar performance compared to length 63 code with multipath and MAI. This is due to the improved cross-correlation properties of the longer code which helps reduce the impact of other users even in the presence of severe multipath. The results clearly show that the performance of a DS system is highly dependent on the auto- and cross-correlation properties of the spreading sequences and highlights the importance of taking into account the propagation model when designing the system. The combination of careful sequence design along with equalization techniques should further improve the systems performance.

Fig. 2.7 Performance of DS system in presence of interfering users and a single multipath channel realization averaged over 1,000 realizations of MAI and $E_b/N_0 = 10$ dB



Finally, it is worth noting other impulse radios, designs which are not covered here. In particular, impulse radios using time-hopping and pulse position modulation (PPM) have been heavily studied in the research literature (see [13] and related references). These systems will have similar design trade-offs when it comes to optimizing performance in a multipath and multiple access environment. In particular, energy capture may also require a rake receiver to capture the energy from the reflections in the channel, and the combination of multipath and multiple access interference would need to be carefully considered when designing the PPM receiver and hopping patterns.

2.3.2.2 MB-OFDM Radio Design for Multipath Channels

Multiband OFDM (MB-OFDM) combines the advantages of multibanding for frequency diversity and implementation complexity, with the well-known robustness of OFDM in dense multipath channels. OFDM systems can mitigate multipath using either a cyclic prefix or a zero pad [14]. In the former, a portion of the OFDM symbol is copied from the end and pre-appended to the beginning of the symbol before transmission. Unfortunately for UWB, the cyclic prefix causes repetitive structure in the signal which shows up as spectral ripple in the OFDM spectrum, as shown in Fig. 2.8. Since the FCC specifies allowed PSD based on the peak spectrum, such ripple is not desirable.

However, the spectral ripple can be eliminated by using a zero-padded prefix [14]. The zero padding at the transmitter requires a receiver using overlap-add FFT

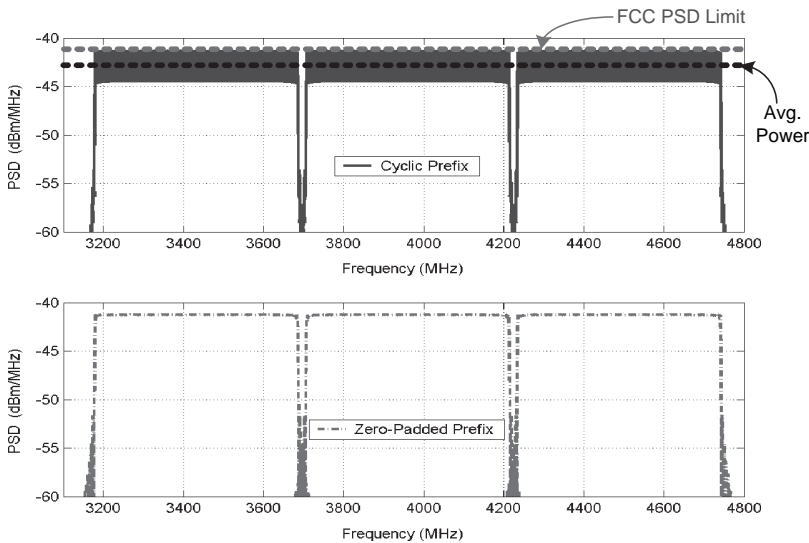


Fig. 2.8 Spectral flatness comparison between OFDM with a cyclic prefix vs. zero padding

processing – this implies that the effect of the zero padding can be regarded as similar to employing a noisy cyclic prefix. This typically results in a small SNR loss in performance when compared with the cyclic prefix OFDM case, but the reduced spectral ripple for the zero-padded signal permits enough of an increase in average TX power to compensate for this loss.

In general, the design of the MB-OFDM signal follows that of a conventional OFDM system, with the major difference being the frequency hopping induced by the time-frequency codes (TFC). The choices for the numerical values of the OFDM symbol duration follow from the multipath channel characteristics – considering the delay spread over all the different environments, a zero pad of $\sim 60 \mu\text{s}$ was found to yield a good compromise. Based on this, keeping the overhead of the zero pad at roughly 25% led to an OFDM symbol length of $\sim 240 \mu\text{s}$ (for a total length of $\sim 300 \mu\text{s}$). This OFDM symbol length implies a sub-carrier spacing of $\sim 4 \text{ MHz}$, and given a minimum occupied bandwidth of 500 MHz, leads to a 128 point FFT/IFFT being necessary. An additional guard interval of about $9.5 \mu\text{s}$ is inserted between the successive OFDM symbols, in order to simplify the design of the frequency-hopping circuits. The precise values for these parameters lead to a total duration of $312.5 \mu\text{s}$ on each frequency band ($242.4 \mu\text{s}$ OFDM symbol, $60.6 \mu\text{s}$ zero pad, and $9.5 \mu\text{s}$ additional guard interval).

The WiMedia MB-OFDM symbol is formed from a 128 point FFT, which means that potentially there are 128 sub-carriers with a spacing of 4.125 MHz in the OFDM symbol, of which only 122 are actually used, for both data and reference signals. A time frequency code (TFC) is used to modulate each successive OFDM symbol on multiple frequency bands, each band being 500 MHz wide as required by the FCC part 15.500 rules. Thus, if we represent each OFDM symbol as $Z(t)$, then the transmitted RF signal would be written in terms of the complex baseband signal as

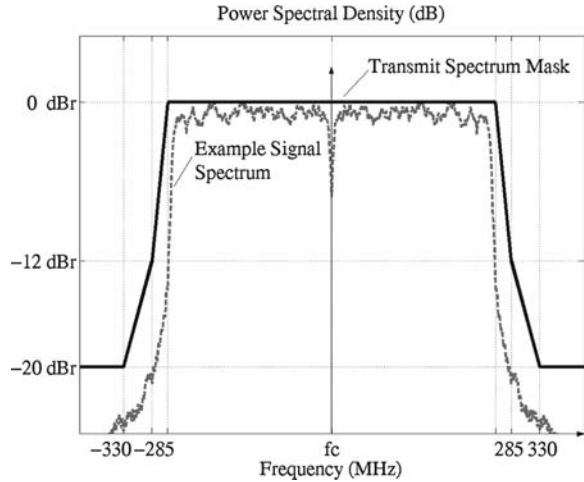
$$s_{\text{RF}} = \text{Re} \left\{ \sum_{n=0}^{N-1} Z_n(t - T_{\text{SYM}}) \exp(j2\pi f_c(q(n))t) \right\}$$

where $\text{Re}(\cdot)$ represents the real part of the signal, N is the number of symbols in the packet, $f_c(m)$ is the centre frequency for the m th frequency band, $q(n)$ is a function that maps the n th symbol to the appropriate frequency band, and $Z_n(t)$ is the complex baseband signal representation for the n th symbol.

Modulation is applied to each of the OFDM sub-carriers using traditional techniques such as BPSK, QPSK, or 16-QAM. This allows the signal to carry multiple bits per symbol and permits the system to change the bit rate while holding the OFDM symbol rate constant. An example signal spectrum is shown in Fig. 2.9 (see ECMA-368 standard).

The MB-OFDM signal, especially for rates up to 200 Mbps, offers considerable protection against Rayleigh fading on the individual sub-carriers as well as MAI through a combination of time, frequency, and FEC code diversity techniques. At higher data rates, however, with the diversity gain weakening, an additional

Fig. 2.9 Example spectral plot of the MB-OFDM waveform in a single band



technique is used for frequency selective fading mitigation. This is called dual carrier modulation (DCM), in which four-coded and interleaved bits are mapped onto modulated symbols on a pair of widely separated sub-carriers. This orthogonal mapping is derived from a modification of the 2×2 Hadamard matrix. It can be equivalently represented as mapping four interleaved bits onto two 16-point symbols using two fixed but different mappings as shown in Fig. 2.10. The two resulting 16-point symbols are mapped onto two different tones separated by 50 ton, as shown in Fig. 2.10.

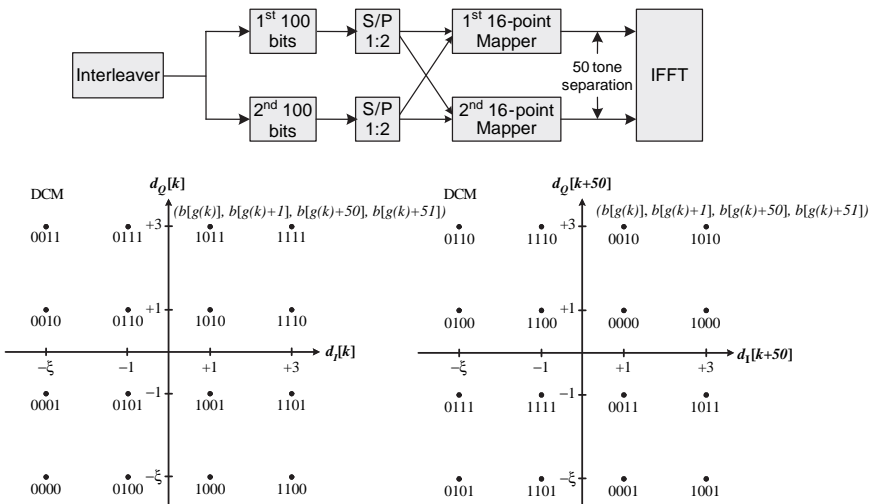


Fig. 2.10 Dual carrier modulation (DCM) block diagram and signal mapping

This technique has the advantage of having the same 4 bits of information on 2 tones that are separated by at least 200 MHz. The assumption here is that the probability that there is a deep fade on both tones is small. And if there is a deep fade on one of the 2 tones, the 4 bits of information can be recovered using a simple detection scheme. This approach offers a large degree of frequency diversity and enhanced performance for the higher data rates where the FEC code is weak (320–480 Mbps).

2.3.3 Processing Gain and Spectral Flatness

Processing gain is a measure of the increase in signal-to-noise ratio achieved by integration of the spread spectrum code word over the duration of the data symbol period. In continuous chip systems, the processing gain is related to the number of chips per symbol. This definition is difficult to apply to an UWB based system; instead, we use an alternate definition of processing gain as the ratio of the UWB bandwidth to the symbol rate.

$$PG = BW_{UWB} / R$$

The reason we utilize this definition has to do with the fact that in UWB, transmitter power is typically allocated on a per MHz basis. For example, in the United States, the FCC has set the power spectral density (PSD) for UWB to be -41.3 dBm/MHz. This means that the larger the occupied bandwidth the more available transmitter power. To calculate the total average transmitted power, we integrate the power over the UWB bandwidth. Then, the total power that will be allocated to each data symbol is the average power times the processing. As a result, the slower the data symbol rate, the more energy allocated to each bit when calculating E_b/N_0 .

Implied in the way that transmitter power is allocated to UWB is the need for spectral flatness to achieve the maximum transmit power. For example, the FCC has indicated that the spectral peak must not exceed the -41.3 dB/MHz limit. The total transmitted power will be determined by the average PSD but the maximum value in the spectrum can not exceed regulatory limits. Hence, keeping the spectral peak-to-average ratio as small as possible is the key to maximizing the total transmit power. OFDM achieves spectral flatness by transmitting a spectral series of RF tones, where each RF tone's amplitude is controlled to facilitate a flat spectrum.

2.3.4 Multi-User Access

Multi-user access in the WPAN environment is determined by how many uncoordinated simultaneous operating piconets (SOP) can be accommodated in the same vicinity at the same time. In IEEE802.15.3a and in ECMA-368, it was desired to accommodate an SOP of at least four.

Multiband OFDM makes use of several mechanisms to facilitate multi-user access via a combination of frequency channels, hopping codes, and spreading codes. All this comes under the general heading of a time-frequency coding.

The time-frequency codes are generated by first subdividing the UWB band into fourteen 500 MHz wide sub-bands, band 1 through band 14. These 14 sub-bands are collected into band groups as shown in Fig. 2.11 below.

Figure 2.12 shows an example time-frequency code using the frequencies in band group 1. This particular code sequentially steps through the available bands.

Other codes can be generated as shown in Table 2.2. Each time-frequency code gives some degree of separation between multi-users simultaneously using band group 1. In addition, codes 5, 6, and 7 are used for frequency division multiple access, giving complete separation for up to three users.¹¹

The use of these codes decreases the overall probability of two transmissions interfering with each other. Still, under a heavily loaded scenario, it is possible for interference from other users to occur. In these cases, we rely on the OFDM processing gain and on the forward error correction to allow successful transmission of the data. In addition, decoding techniques which apply erasures to interfered symbols can also help mitigate the impact of strong interferers.

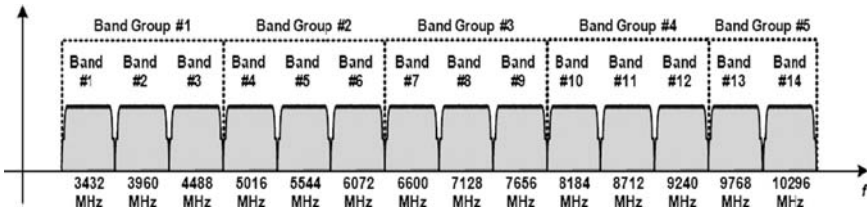


Fig. 2.11 MB-OFDM band plan

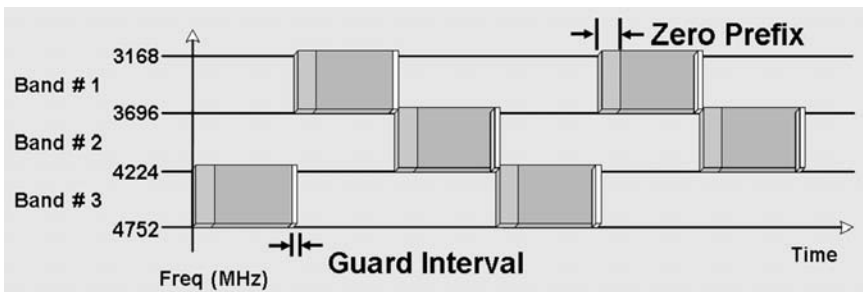


Fig. 2.12 Time-frequency coding

¹¹ TFI = time-frequency interleaving; FFI = fixed-frequency interleaving.

Table 2.2 Time-frequency codes

TFC number	Type	BAND_ID					
1	TFI	1	2	3	1	2	3
2	TFI	1	3	2	1	3	2
3	TFI	1	1	2	2	3	3
4	TFI	1	1	3	3	2	2
5	FFI	1	1	1	1	1	1
6	FFI	2	2	2	2	2	2
7	FFI	3	3	3	3	3	3

2.3.5 Implementation Issues

2.3.5.1 Antenna Dispersion and Aperture

Antenna aperture relates to the concept of a propagating sphere of radiated energy emanating from an isotropic radiator, as shown in Fig. 2.13.

We can model the antenna as a patch of fixed area ingesting energy off the surface of an energy sphere. As the surface area of the sphere expands with radius distance, the percentage amount of power in the antenna patch area proportionally decreases. Since the surface area is proportional to the square of the radius ($S = 4\pi \cdot r^2$), the amount of available power decreases inversely to the radius squared, or in decibels, as $20 \times \log 10(r)$ where r is the sphere radius.

The antenna patch square itself is modeled as being proportional to its center frequency on each side; that is, the dimensions of the antenna patch can be modeled as being some fraction of a wavelength on each side, which then gives an antenna patch area that is proportional to the operating wavelength squared multiplied by some scaling constant. This is called the antenna effective aperture. (Fig. 2.14).

$$A_{\text{aperture}} = \kappa_y \kappa_x \lambda_c^2$$

Since the wavelength is inversely proportional to frequency, as the center frequency increases the effective aperture decreases (our conceptual patch antenna gets

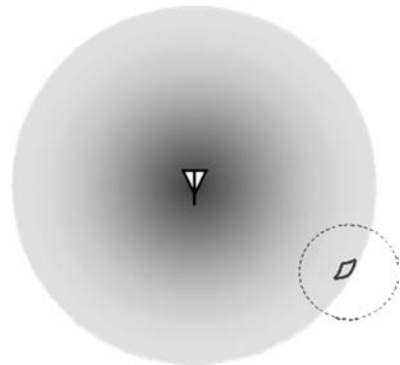
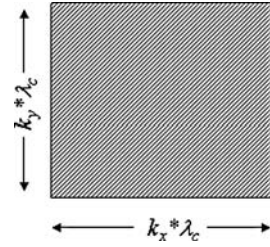


Fig. 2.13 An antenna aperture superimposed on the isotropic radiator sphere

Fig. 2.14 An antenna aperture is proportional to the operating wavelength



smaller). In terms of decibels, the decrease in ingested signal power is proportional to $-20 \times \log(F_c)$, where F_c is the center operating frequency.

The impact that antenna aperture has on UWB can be assessed by considering the wide operating frequency of UWB: from 3.1 to 10.6 GHz in the United States. Optimizing the antenna for this wide bandwidth can be problematic. An antenna optimized for the low end of the UWB band (i.e., low VSWR, etc.) will have good aperture characteristics at low frequencies but poor VSWR and efficiency at high frequencies, and visa versa for an antenna optimized for the high end of the UWB band. In general, the philosophy followed is to apply the $20 \times \log 10(F)$ aperture shrinkage to the operating center frequency in an attempt to capture the varied performance characteristics in some summary manner. However, systems need to be able to adapt to non-flat antenna patterns due to the very wide occupied bandwidth and expected variability in patterns resulting from different antenna designs as well as different m factors.

2.3.5.2 Analog Front- End Challenges

OFDM-Based Transceivers

Figure 2.15 shows a generic analog front end (AFE) for an OFDM-based UWB transceiver. In this section, we describe challenges associated with the key elements of the AFE, emphasizing those attributes that are unique to UWB. Based on analysis and simulation, nominal values are offered for some parameters, but the reader should understand that based on designer choices, these values may differ substantially across different implementations.

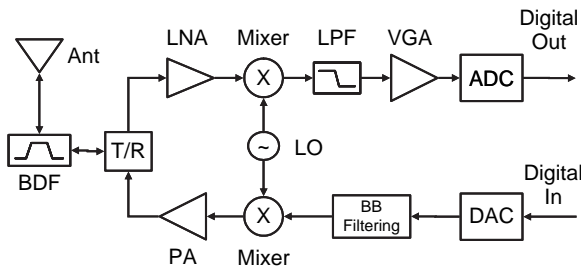


Fig. 2.15 OFDM-based receiver block diagram

A UWB antenna (Ant) must be broadbanded, covering anywhere from a single 500 MHz segment to a span of multiple GHz with low loss and near omnidirectional coverage. Still better is an antenna that also offers some rejection for frequencies where other devices are known in advance to be active, such as IEEE 802.11a or 802.11n devices. Early results have been encouraging,¹² and UWB antenna design remains an area of active research.

Band definition filters (BDF) and transmit/receive switches (T/R) must be designed with very low insertion loss since every dB of loss ahead of the low-noise amplifier (LNA) contributes directly to the overall noise figure of the receiver.¹³ In some designs, the front-end filtering may be split between two filters, with one ahead of the LNA as shown, and another just after the LNA. This may allow a filter with lower insertion loss to be placed ahead of the LNA. Nominal insertion losses for BDFs vary from 0.5 to 1.5 dB.

The LNA must offer very low noise figure since here too, every dB of noise figure adds directly to overall receiver-chain noise figure. The designer must balance the need for high gain against the increased noise figure that typically comes with higher gain. Some designs implement the LNA function in two or more stages, allowing for an initial stage with modest gain and very low noise figure. Subsequent stages and the remainder of the receiver chain can then have relaxed requirements on noise figure. Overall receiver chain noise figures vary with implementation, but a nominal value of 6–7 dB has been assumed in analyses and simulations.

Besides low noise figure, an LNA section must offer good linearity since non-linearities will generate new spectral content that can damage many tones in an OFDM-based system. Depending on its design, pulse-based system may be somewhat less sensitive to non-linear distortion. As an example, in OFDM-based systems, nominal values for input third-order distortion (IIP3) are –10 to –15 dBm in an LNA that offers a nominal 25 dB of gain.

In an ECMA-368 OFDM-based UWB system, the mixer and local oscillator (LO) have additional challenges not found in traditional AFE designs. Specifically, the LO must “hop” among the different sub-band center frequencies and stabilize in as little as 9 μ s. Furthermore, in a direct-conversion design like that in Figure 2.15, DC-offset in the mixer is likely to be different for each sub-band, requiring special compensation measures in either the analog circuitry or in the digital computations that follow the analog-to-digital converter (ADC). As with any LO, phase noise is of concern, although with sub-carriers located 4.125 MHz apart, phase noise is not as critical as it is in OFDM-based systems like IEEE 802.11a/g/n, where sub-carriers are spaced much more closely.

As in traditional designs, the variable gain amplifier (VGA) readies the signal for optimal use of the dynamic range of the analog-to-digital converter (ADC). In

¹² Suh, Seong-Youp et al. “A UWB Antenna with a Stop-Band Notch in the 5 GHz WLAN Band”, *IEEE Applied Computational Electromagnetics Society*, April, 2005”.

¹³ Sklar, Bernard, *Digital Communications (Second Edition)*, Prentice Hall, Upper Saddle River, New Jersey, 2001, 270ff.

an ECMA-368 receiver, the ADC sampling rate is at least 528 MHz, and in some designs may reach 1056 MHz. At these speeds, the ADC can consume considerable power. However, bit precision in this ADC is typically 5 or 6 bits, which helps hold down power consumption. As usual, there is a trade-off between total dynamic range and quantizing noise. One study has shown that for a 6-bit ADC, the optimum dynamic range is approximately 3.5σ , where σ is the root-mean-square voltage at the input to the ADC.¹⁴

On the transmit side, the digital-to-analog converter (DAC) is typically 6–8 bits precision. The baseband filtering section (BB Filtering) may vary widely among implementations. In its simplest form it is a zero-order “hold” filter, although such a choice can suppress the energy in the outer tones of the UWB spectrum. Many implementers will choose to use some form of interpolation in order to flatten the resulting spectrum and reduce sidelobe energy. This also eases the constraints on baseband filtering that precedes the up-conversion mixer. The power amplifier performs a traditional role, but in an ECMA-368 transmitter, the maximum radiated power is only about 100 mW, making the design for linearity somewhat easier than in larger power amplifiers. OFDM signal levels occasionally do reach large peak levels, but based on simulations, “clipping” the signal at 7–9 dB above rms value causes little degradation to the system performance.

Pulse-Based Transceivers

Pulse-based UWB *receiver* AFE designs look similar to those of other receivers, consisting of the same antenna, BDF, LNA, Mixer, LPF, VGA, and ADC chain.¹⁵ Some of the challenges, such as low-noise figure designs are similar to those in OFDM-based counterparts. Some other attributes, like LNA and mixer linearity, may be less critical in a pulse-based design. The largest differences from OFDM-based designs appear after the ADC, where rake filters and decision feedback equalizers are used.¹⁶

Pulse-based UWB *transmitter* AFE designs may look quite different from traditional ones. While mixers, power amplifiers, and filters may still be present, the preceding baseband digital circuitry is quite different, consisting in some cases of hybrid digital and analog circuitry for pulse formation. Many of the implementation details are still proprietary or experimental.

¹⁴ Stein, Bart, *Selecting Resolution and Dynamic Range in an OFDM UWB System*, IEEE P802.15-04/0007r0, January, 2004.

¹⁵ McCorkle, John, “Ultra Wide Bandwidth (WUB): Gigabit Wireless Communications for Battery Operated Consumer Applications”, *2005 Symposium on VLSI Circuits Digest of Technical Papers*, June 16, 2005, pp. 6–9.

¹⁶ Parhar, Ambuj et al., “Analysis of Equalization for DS-UWB Systems”, ICU 2005 International Conference on Ultra-Wideband, Session 6, September 6, 2005.

2.3.5.3 Digital Processing Challenges

The primary challenges of baseband digital signal processing in a UWB transceiver arise from the extremely large bandwidths and associated sampling rates, as well as the need to process very high data rates. Partly related to this is also the challenge of combating the effects of the highly frequency selective dense multipath channel. Different approaches to UWB system design have been already described previously, and here we shall summarize some of the key features of the baseband digital processing in the transceivers for these systems.

For a pulse-based UWB system, the most demanding processing is at the “front end” since the receiver will typically sample the UWB pulses at the Nyquist rate – this also corresponds to chip rate sampling for a DS-UWB system. Thus, for example, a 1.5 GHz bandwidth UWB system will have a 1.5 Gsps complex input sample stream from the ADCs. Typically, the ADC will need to have some excess dynamic range to contend with in-band narrowband interferers and so a 2–3 bit ADC would be employed. Based on studies of the typical indoor UWB channel models, especially the NLOS channels, a rake receiver with up to 16 arms may be needed to capture adequate energy from the multipath in order to maintain a good link budget margin [see *IEEE802.15-03/388r2*]. Further, for good performance at the higher data rates with either impulse or DS-based UWB systems, a symbol rate equalizer is needed in order to suppress the ISI.

The multiband OFDM UWB system represents a very efficient realization of the multiband approach to UWB system design. The “dwell” time on each band is increased through use of a 242.4 μ s long OFDM symbol, which offers good energy capture, and the zero pad plus overlap-add FFT processing offers an efficient equalizer implementation. The WiMedia MB-OFDM transceiver reduces the ADC sample rate requirements compared with impulse-based UWB systems – a 528 MHz complex input sample stream is required. However, in most cases, a little higher dynamic range is required in the ADC and DAC, and 6 bits of precision is typically employed. The signal processing blocks in the baseband chain are similar to those in conventional OFDM modems – including functions such as timing synchronization, channel estimation, pilot symbol tracking, soft-bit mapping, etc. The FFT engine needs to perform a 128 point FFT every 312.5 μ s. The other major signal processing block is the Viterbi decoder, which is required to decode the rate 1/3, constraint length $K=7$ convolutional code at a peak source data rate of 480 Mbps (when the code is punctured to rate $3/4$).

2.3.6 Link Budget

Link budgets for UWB radios seem to cause undue confusion with system engineers trying to convert from peak power to average power, taking into account processing gain, etc. Actually, to calculate E_b/N_0 – in an AWGN environment due to the receiver front-end noise – we basically only need to know four things: the transmit spectrum bandwidth, the bit rate, the path loss, and the receiver noise figure

(assuming isotropic antennas). An example link budget used by IEEE802.15.3a [3] is shown in Table 2.3.

From a simplistic point of view, E_b is determined by integrating the regulatory limited PSD over the wavelet noise bandwidth, scaling by the path loss and dividing by the bit rate. The noise density N_0 is then determined by the noise figure of the receiver. An example link budget is shown in Table 2.3 for a generic UWB system using the table defined in [3].

Table 2.3 only yields average expected performance of the system, while more accurate performance and reliability needs to be validated with detailed simulations in realistic channels to determine how much additional margin is sufficient. The range at which the ECMA-368 multiband OFDM system, operating in band group 1, achieves a PER of 8% with a link success probability of 90% in example channels with multipath and shadowing is listed in Table 2.4 for various AWGN and multipath channel environments as defined by the IEEE802.15.3a committee in document [3] (see IEEE document 15-05-0648-00-003a-mb-ofdm-updates.pdf from November, 2005).

2.3.7 Initial Acquisition

Modern UWB systems are designed for high data rate packet-based wireless communications. Fast timing acquisition and synchronization is an especially important requirement for these systems since the preamble overhead (which is normally transmitted using a rate among the lowest data rates supported) needs to be minimized in order that overall throughput does not suffer. For example, for a 1,024 byte packet being transmitted at 100 Mbps, a 10 μ s PHY preamble amounts to an overhead of approximately 11%. At 500 Mbps, the same length for the PHY preamble amounts to about a 38% overhead, while at 1 Gbps, the preamble will result in a 54% overhead. This is a simplistic calculation, and certainly the PHY layer preamble requirements can be affected by other aspects of the overall system design; however, the point remains that short preamble length/fast acquisition is an important factor in high data rate system design.

For a pulse-based UWB system design, the approach to timing synchronization can be based on using a serial search strategy with an analog or digital correlator, or using a digital matched filter. The serial-search-based approach trades lower implementation complexity for a longer average acquisition time due to the necessity of dwelling for a fixed integration time at any given timing epoch. The matched filter approach relies on a greater implementation complexity to obtain a faster acquisition time. The UWB channel characteristics have a significant impact on the acquisition time because the dispersion in the signal energy among the multiple reflections that define the dense multipath channel causes the per path signal energy to be a small fraction of the total energy in the transmitted UWB pulse. In [15], the effect of the multipath channel profile on impulse-based UWB and multiband UWB pulse timing acquisition was studied. As shown in Fig. 2.16, the multiband pulse system

Table 2.3 Example link budget calculation

Parameter: Mode 1 DEV	Value	Value	Value
Throughput (R_b)	100 Mb/s	200 Mb/s	500 Mb/s
Average Tx power (P_T) (~ 1.5 GHz bandwidth)	-10 dBm	-10 dBm	-10 dBm
Tx antenna gain (G_T)	0 dBi	0 dBi	0 dBi
$f'_c = \sqrt{f_{\min} f_{\max}}$: geometric center frequency of waveform (f_{\min} and f_{\max} are the -10 dB edges)	3,850 MHz $f_{\min} = 3.1$ GHz; $f_{\max} = 4.8$ GHz	3,850 MHz $f_{\min} = 3.1$ GHz; $f_{\max} = 4.8$ GHz	3,850 MHz $f_{\min} = 3.1$ GHz; $f_{\max} = 4.8$ GHz
Path loss at 1 m ($L_1 = 20 \log_{10}(4\pi f'_c/c)$) $c = 3 \times 10^8$ m/s	44.2 dB	44.2 dB	44.2 dB
Path loss at d m ($L_2 = 20 \log_{10}(d)$)	20 dB ($d=10$ m)	12 dB ($d=4$ m)	6 dB ($d=2$ m)
Rx antenna gain (G_R)	0 dBi	0 dBi	0 dBi
Rx power ($P_R = P_T + G_T + G_R - L_1 - L_2$)	-74.2 dBm	-66.2 dBm	-60.2 dBm
Average noise power per bit ($N = -174 + 10 \times \log_{10}(R_b)$)	-94 dBm	-91 dBm	-87 dBm
Rx Noise Figure (N_F)	7 dB	7 dB	7 dB
Average noise power per bit ($P_N = N + N_F$)	-87 dBm	-84 dBm	-80 dBm
Required E_b/N_0 (S) (assuming strong coding)	4.0 dB	5.0 dB	6.0 dB
Implementation loss (I)	3.0 dB	3.0 dB	3.0 dB
Link margin available for multipath and shadowing ($M = P_R - P_N - S - I$)	5.8 dB	9.8 dB	10.8 dB

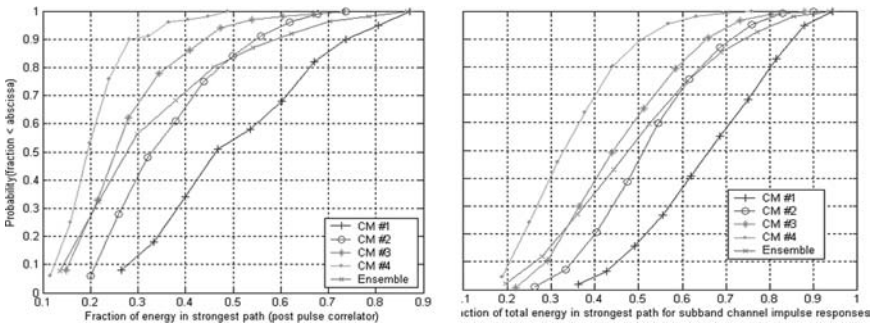
Table 2.4 Range to achieve a PER fo 8% with 90% link success probability for band group 1 devices

Rate(Mb/s)	AWGN(M)	CM1(M)	CM2(M)	CM3(M)	CM4(M)
110	21.5	12.0	11.4	12.3	11.3
200	14.8	7.4	7.1	7.5	6.6
480	9.1	3.8	3.5	N/A	N/A

offers the potential for lower search times due to the larger average energy in the strongest path compared to a pulse-based UWB system occupying the same overall bandwidth.

As mentioned earlier, modern high data rate UWB systems extensively employ digital baseband processing with Nyquist sampling front ends. In these systems, the requirement for fast, accurate timing acquisition/synchronization demands matched filter-based processing. As an example, we describe the Wimedia MB-OFDM UWB system and its preamble structure, which forms the initial part of every transmitted packet and is designed to enable efficient matched filter processing in the receiver. The preamble is designed to keep the overall length $<10 \mu\text{s}$ while yielding a robust acquisition/synchronization architecture with moderate complexity in the receiver. The standard preamble sequence consists of 30 symbols (of $312.5 \mu\text{s}$ duration) and is divided into two segments:

1. The packet/frame synchronization sequence: This segment consists of 24 symbols and is used in the receiver to detect the start of a packet, and to perform timing and coarse frequency error estimation. This segment is formed by concatenating 24 repetitions of a base time domain preamble symbol (and associated $70.1 \mu\text{s}$ zero pad), and overlaying this with a 24 length cover sequence that depends on the particular time-frequency code (TFC) being used. The base time domain symbol is based on a 128 sample length hierarchical binary sequence which is constructed as the Kronecker product of sequences of length 16 and 8. At the receiver, the digital matched filter for this base sequence can be efficiently implemented as an 8 sample long matched filter followed by a 16 sample long

**Fig. 2.16** CDF of fractional energy in strongest multipath component for an example impulse-based UWB system, and a multiband UWB system

matched filter. The cover sequence serves to delimit the end of the first segment, among other functions.

2. The channel estimation sequence: This segment consists of six repetitions of a base channel estimation symbol which is formed by computing the IFFT of a suitably defined random QPSK sequence (and appending the $70.1 \mu\text{s}$ zero pad). This ensures that two channel estimation symbols are provided for each of the three bands spanned by the TFC, and the receiver can employ suitable channel estimation algorithms to exploit these symbols.

Given the above definition, the length of the standard preamble is equal to $9.375 \mu\text{s}$ ($30 \times 0.3125 \mu\text{s}$). In addition, a streaming mode preamble is also defined for improved efficiency when multiple packets are being transferred in burst mode. In this case, the packets after the initial one in the burst can have a shorter packet/frame synchronization sequence of only 12 symbols because the timing offset of this packet is fixed with respect to the first one. Thus, the total preamble length is reduced to $5.625 \mu\text{s}$ ($18 \times 0.3125 \mu\text{s}$) and reduces the overhead while preserving good performance.

2.3.8 Narrowband Interference

Because of their very wide bandwidth, UWB receivers are likely to encounter interference from narrowband systems, especially those in the 3–5 GHz band. Some may be quite powerful, operating in an uncontrolled manner in close proximity to a UWB receiver. Other systems may be outside the passband of the UWB receiver, but if they are close enough, can still degrade UWB performance to some extent.

Both DS-UWB and MB-OFDM have some inherent resistance to narrowband interferers. The code spreading in DS-UWB helps suppress interferers relative to the desired signal, and a narrowband interferer is unlikely to affect more than a few of MB-OFDM's 100–300 data carriers. Of course if the interferer is strong enough, the analog front end for either system could saturate, but these are special situations that must be dealt with by other means (such as time sharing the use of UWB and the interferer). In the remainder of this section, one important example is examined via simulation: WiMax-like interference into a WiMedia PHY 1.1 receiver.

As shown in Fig. 2.17, the simulation models a UWB Transmitter (Tx) located D_u meters from a UWB Receiver (Rx). The Rx is a “victim” because of interference from a nearby WiMax Tx located D_w meters away. Some particulars of the UWB Rx and WiMax Tx are indicated in Fig. 2.17. WiMax systems are expected to appear in the 3.4–3.8 GHz band in Europe and other parts of the world.

Two UWB signal modes are modeled in this simulation. In TFI mode, all three bands are transmitted sequentially, and in FFI mode, only band 3 is transmitted, centered at 4,488 MHz. The goal of the simulation is to compare UWB link performance for these TFI and FFI modes in the presence of a WiMax interferer.

Figure 2.18 displays the spectrum of the received signal at the UWB Rx in FFI mode when $D_u = 10 \text{ m}$ and $D_w = 2 \text{ m}$. As shown, the spectrum is dominated by

WiMax → UWB Interference Simulation Setup

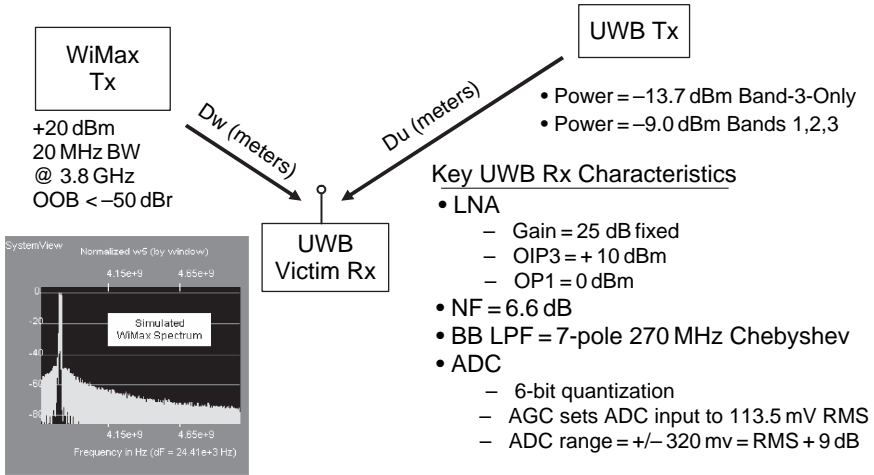


Fig. 2.17 Narrowband interference simulation layout

UWB Signal Spectra for Du = 10 meters, Dw = 2 meters

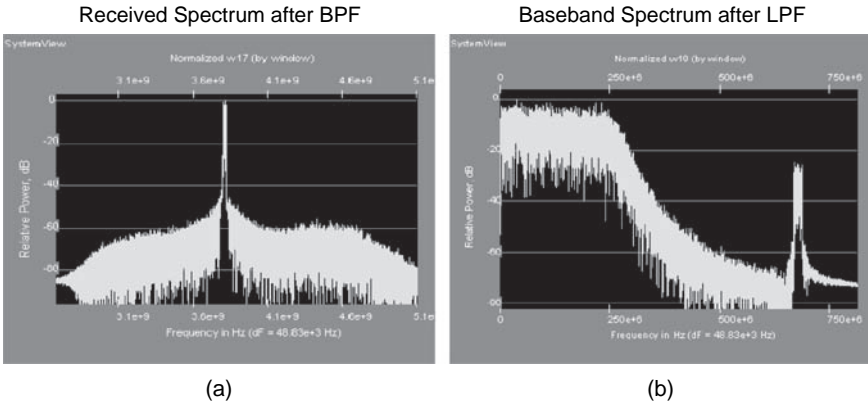


Fig. 2.18 UWB and interferer spectra

the powerful WiMax interferer at 3.8GHz. Figure 2.18 also shows the baseband spectrum in the UWB Rx after down-conversion and low-pass filtering. As shown, the strong WiMax interferer is still present, but it has been suppressed by the low-pass filtering.

Figure 2.19 shows simulated Bit Error Rate (BER) versus WiMax-Tx to UWB-Rx separation (D_w) for FFI and TFI modes and for three values of UWB-Tx to

Simulation Output Example
106.7 Mbps UWB BER vs WiMax-UWB Separation

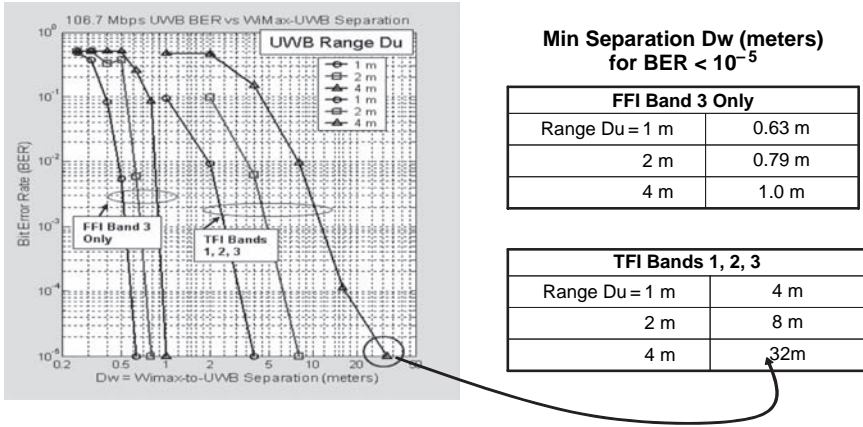


Fig. 2.19 Deriving separation distances for successful operation at 106.7 Mbps

UWB-Rx separation. In each of the six curves, a BER of 10^{-5} is assumed to represent acceptable UWB performance. For example, in TFI mode with $D_u = 4$ m, a minimum WiMax separation of approximately $D_w = 32$ m is required. In FFI mode, a minimum separation of only 1 m is required. By repeating the simulation for various values of D_w and D_u , the data in the tables of Fig. 2.20 were generated.

As shown in the Fig. 2.20, operating a UWB link in FFI mode provides considerable protection against nearby WiMax transmitters even though the WiMax transmitter may be within the passband of the UWB Rx front end. Regulations require

Min WiMax-to-UWB Separation
 D_w (meters) for BER < 10⁻⁵

	Band 3 Only	Speed 53.3 Mbps	106.7 Mbps	200 Mbps	400 Mbps
	FFI Band 3 Only	Range D_u 1/4 m			
	1/2 m			1.0	2.0
	1 m	0.39	0.63	1.0	2.0
	2 m	0.50	0.79	1.3	
	4 m	0.80	1.0	5.0	
	10 m	2.5			

	Band 1, 2, 3	Speed 53.3 Mbps	106.7 Mbps	200 Mbps	400 Mbps
	TFI Bands 1,2,3	Range D_u 1/4 m			
	1/2 m			16	100
	1 m	4	4	32	200
	2 m	8	8	128	
	4 m	16	32	500	
	10 m	64			

Fig. 2.20 Required separation distances for successful operation

that FFI-mode UWB transmit at $10 \log(3) = 4.7$ dB lower power than TFI-mode UWB, but FFI mode still outperforms TFI mode when a WiMax Tx is nearby.

Imperfections in implementation may further limit performance. For example, if the local oscillator associated with the WiMax down-conversion mixer has side tones present, some of these tones may down-convert WiMax interferer energy into the UWB baseband. Depending on its strength, this energy could increase BER to unacceptable levels.

Even with the imperfections above, optional techniques (not required by the standard) may be used to improve performance still further in the presence of WiMax interference. In particular, a switchable bandpass filter sub-system that protects a UWB transceiver from WiMax signals could be used when their presence is detected. This filtering can dramatically reduce the impact of WiMax interferers. Sub-systems like these might be used in conjunction with “detect and avoid” mechanisms under discussion to protect WiMax receivers from possible interference by UWB and to meet emerging international regulations, as will be discussed in the next section.

2.4 Regulatory Environment

2.4.1 *Inside and Outside the United States*

The regulatory process for making UWB systems commercially legal has taken a long road both inside and outside the United States. The FCC first initiated a Notice of Inquiry (NOI) in September of 1998, which solicited feedback from the industry regarding the possibility of allowing UWB emissions on an unlicensed basis following the same power restrictions for unintentional emitters described in the FCC Part 15 rules. Since this would result in UWB signals overlaying other wireless systems, it raised many concerns about the potential for interference to existing systems. In May 2000, the FCC issued a Notice of Proposed Rule Making (NPRM), which solicited feedback from the industry on specific rule changes that could allow UWB emitters under the Part 15 rules. The interference concerns, especially related to safety critical systems like GPS, resulted in very large industry participation in the comment process to the FCC. More than 900 comments were filed during this period, including several very detailed interference studies (see FCC docket 98–153). Finally, on February 14, 2002, the FCC issued its final ruling allowing UWB systems to operate on an unlicensed basis under the Part 15 rules allowing UWB operation from 3.1 to 10.6 GHz at a power spectral density (PSD) of -41.3 dBm/MHz. According to statements by the FCC, these rules reflected a very conservative approach in order to protect existing wireless systems while allowing the technology to be further developed and proven. As a result, the opportunity was created to exploit this newly allocated spectrum, but many people in the industry and government are still watching carefully to ensure that the technology does not disrupt current services.

Although the United States successfully completed an initial round of regulations for UWB emissions which has been followed by a few key updates, including the issuing of a waiver allowing multiband OFDM technology to operate at normal operating power levels, the technology is still not legal anywhere else in the world. Regulatory bodies outside the United States are also in detailed discussions and performing comprehensive interference studies of their own to determine possible rules to allow the use of UWB technology in their geographic region. The International Telecommunications Union (ITU) TG1/8 concluded its work in 2005 on a detailed impact study and possible regulatory framework. However, the results of the studies were very mixed and highly dependent on the assumptions used which resulted in a framework coming out of the ITU which provided a range of results based on the ITU studies and flexibility for regulatory bodies to adopt different emissions limits based on their regulatory philosophies and specific spectrum usage. In Europe, a key difference exists from what was considered during the FCC proceedings which is the allocation of fixed services/WiMax systems above 3.1 GHz. This spectrum was not allocated for such systems in the United States (although the United States recently opened up the spectrum from 3.65 to 3.7 GHz on a quasi-licensed basis for similar types of service), and since the usage models for these fixed services/WiMax systems put them in close proximity to UWB enabled devices, there was a clear interference concern if UWB was able to operate at the FCC levels of -41.3 dBm/MHz. As a result, in order to harmonize as closely with the United States limits while not posing harmful interference into these systems when using the lower frequency bands (3–5 GHz), a “detect and avoid” (DAA) approach was proposed to allow UWB devices to share the available spectrum when there is no nearby narrowband system using the spectrum. This approach has also been promoted in Japan, Korea, and elsewhere as a possible solution to allow existing and future services to share the available spectrum below 5 GHz with UWB devices. There is clearly a desire to have spectrum both below 5 GHz and above 6 GHz to allow for more available channels as applications using UWB technology become more pervasive. In addition, in the near term, current technology capability will allow below 5 GHz silicon solutions sooner than solutions operating above 6 GHz, which would allow for devices to be introduced into these other geographies sooner.

The spectral mask in Fig. 2.21 shows the current draft emissions mask being considered for Europe and Japan, which includes part of the band which may be available immediately after the decision without requiring DAA (including 6–8.5 GHz, and hopefully 4.2–4.8 GHz), while part of the band will have to wait until DAA is approved (mainly impacting the bands below 4.8 GHz). The current proposed Japanese mask is also shown, which differs from the European mask in a couple of important ways: (1) DAA may be required all devices starting in January, 2009 compared with “phase-in” dates of 2010 being considered in Korea and 2010–2012 being considered in Europe, and (2) the upper limit starts a 7.25 GHz rather than 6 GHz which will make having a single harmonized radio able to operate worldwide difficult. The regulations for DAA are still being defined and must be proved to work effectively before regulators will adopt the mitigation technique. Possible architectures and issues for DAA are discussed in a following section. Other geographies

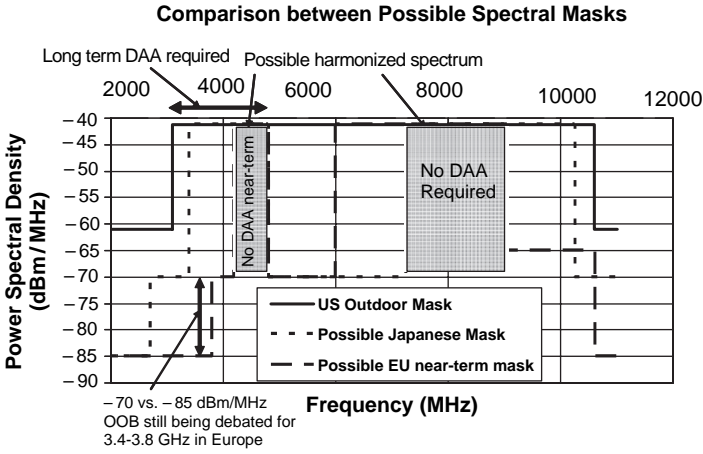


Fig. 2.21 Proposed UWB emission masks being considered in Europe and Japan

are also in the process of developing rules, including Canada, Korea, China, and others. From a UWB industry perspective, having some harmonized spectrum to allow single implementations to be used around the world with a part of the spectrum which could be used as a control channel to help identify the location would be a useful goal. It remains to be seen if this will happen.

2.4.2 Interference Modeling

Clearly, proper interference analysis and modeling is critical for determining viable UWB regulations both to ensure existing services are protected from harmful interference and to ensure fair access to that spectrum from UWB devices under realistic operating conditions. The first question which usually arises is how to model the UWB interference given the range of UWB waveform options. The simplest model is to just assume the UWB interference looks like additive white Gaussian noise (AWGN). However, this model is only valid for UWB systems with a pulse repetition rate greater than or equal to the bandwidth of the victim narrowband system [16]. In order to illustrate this, Fig. 2.22 shows the uncoded probability of error for a victim narrowband system as a function of SIR for different ratios of the pulse repetition frequency to the victim bandwidth (denoted as N_p in the figures) and bipolar modulation for the UWB pulses. In this case, the AWGN approximation to the interference is fairly accurate until the pulse repetition frequency becomes much lower than the victim bandwidth.

As another example to illustrate the impact of a different modulation scheme, Fig. 2.23 shows the inference comparison with AWGN for a binary PPM system. In this case, since the modulation is a non-zero mean modulation scheme, it will have

Fig. 2.22 Performance of “narrowband” system with a UWB interferer using bipolar modulation

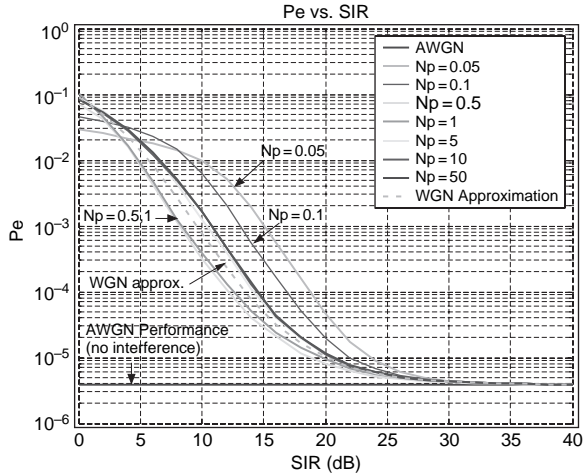
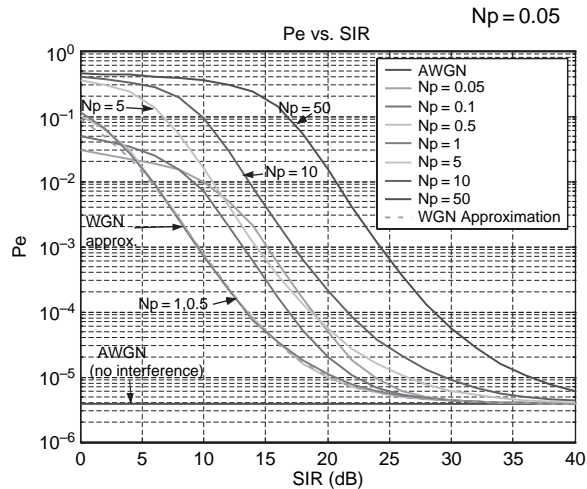


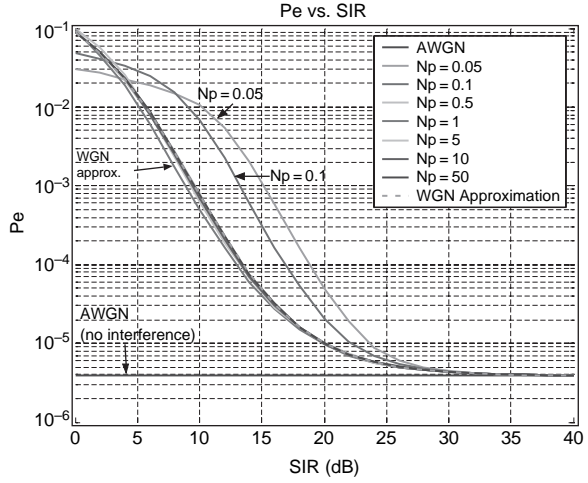
Fig. 2.23 Performance of “narrowband” system with a UWB interferer using 2-PPM and $f_0 T_p$ an integer



spikes in the spectral domain, and so the interference depends on N_p as well as the relationship between the center frequency of the narrowband waveform (f_0) and the pulse repetition period (T_p). When the product $f_0 \times T_p$ is an integer, then there will exist a spectral line in the spectrum of the narrowband waveform which may cause the interference to look different than AWGN. This is illustrated in Fig. 2.23 which shows that the interference could actually increase significantly relative to AWGN when the pulse repetition rate is high.

However, this effect can be minimized by proper randomization of the position of the pulse, as illustrated in Fig. 2.24. In this case, the random location of the pulse eliminates the spectral line, and the AWGN approximation again becomes a valid model.

Fig. 2.24 Performance of “narrowband” system with a UWB interferer using R-PPM (uniform $[0, T_p]$) and $f_0 T_p$ an integer



One of the other significant concerns from victim services is the impact of multiple UWB devices in the same area (referred to as the aggregate interference scenario). In order to properly analyze this case, it is critical to make realistic assumptions in the analysis. To illustrate this, the following discussion summarizes a detailed analysis of the impact of the aggregate interference scenario for a fixed service (FS) application (representing either a point-to-point or point-to-multipoint system). A number of assumptions need to be made in order to accurately model the inference. For illustrative purposes, the urban environment is described here, and the results will be presented for both suburban and urban environments (see [17] for additional details). The aggregate interference in urban and suburban scenarios is evaluated via Monte Carlo simulations of large areas of UWB deployment with the following topologies: circular area with 10,000 UWB devices/km² and 6 km radius; building density is 1, 200 km⁻²; building height probabilities according to Milan, Italy statistics; device height probabilities are obtained explicitly from the building height probabilities; victim antenna is located at the center of the area; and for provision of Fresnel zone clearance, paths below main beam of the victim antenna has only UWB devices more than 25 m lower than the main beam axis, which corresponds to 7 floors maximum building height for a 45 m antenna and 12 floors for the 60 m antenna and path width is 25 m on both sides of the main beam.

The path loss model (from the UWB emitter to the FS antenna) is also critical to model realistically. The following model was adopted here. For each device, it is randomly chosen if it is line-of-sight (LoS) or non-LoS (NLoS) to the victim, according to probabilities based on floor layout and building heights. Then, the outdoor path loss is calculated as follows:

- Indoor to outdoor path
 - Random attenuation with a given probability distribution (see below)
- Outdoor path for LoS – free space

- Outdoor path for NLoS:
 - Low height floors (<10 m): IEEE 802.16 Category B – NLOS [18, 19]
 - Medium and high height floors (>10 m): IEEE 802.16 Category C: NLOS [18, 19]

In addition, the following probability distributions of indoor-to-outdoor attenuations are considered:

- 15% devices with 12 dB attenuation
- 15% – 40 dB attenuation
- 70% – linear from 12 to 40 dB.

Finally, for aggregate interference analysis, it is important to have a realistic activity factor for when the UWB devices are actually transmitting. A detailed evaluation of the expected usage models for UWB devices, it is expected that, when considering a very large population of UWB devices, fewer than 1% would be active at any particular time. Table 2.5 shows the results of the final analysis with different assumptions for the activity factor, consideration of an additional shadowing term in the path loss model, and power control which will likely be used by devices in very close proximity.

The results of this analysis show that the UWB interference impact is highly dependent on the assumptions of the analysis. However, when using realistic assumptions, it is likely to be well below the noise floor of the narrowband receiver. Similar analysis exists for fixed satellite services and other services, which is necessary to justify the appropriate power spectral density levels allowed for UWB devices.

2.4.3 Possible Detect and Avoid Architecture

Here, we briefly describe how the “detect and avoid” (DAA) procedure could be defined in UWB regulations and how it could be specified for implementation in

Table 2.5 I/N ratios with 95% confidence levels for various activity factors

# item	Shadowing (9 dB)	Power control 0–8 dB	Activity factor %	I/N value (dB) urban/suburban
1	No	No	1	–21/–23
2	No	No	5	–16/–18
3	No	No	17	–12/–14
4	No	No	100	–5/–7.5
5	Yes	No	1	–21/–23
6	Yes	No	5	–15/–18
7	Yes	No	17	–11/–14
8	Yes	No	100	–3.5/–7
9	Yes	Yes	1	–24/na
10	Yes	Yes	5	–18.5/na
11	Yes	Yes	17	–14/na
12	Yes	Yes	100	–7/na

appropriate standards. This is still a current area of research and we need to continue developing on these ideas in order to address the full range of interference scenarios.

In developing the DAA approach, the definition of the problem scenarios, and the expected performance in these situations is quite important. To start with, in the regulatory domain, the DAA approach is intended as an interference mitigation solution in the case when a single UWB device is in close proximity to a particular kind of narrowband communications system, namely broadband wireless access (BWA) systems such as indoor WiMAX subscriber stations (SS). It is important to note that, in the end, the DAA approach must be demonstrably generic, in that it should not rely on very detailed features or parameters of the victim system – rather, it should exploit general behavior of the class of BWA systems. That having been said, the initial focus is on WiMAX systems in the 3.5 GHz band, since these are the systems that are currently specified and being considered for commercial deployment. In what follows, we refer to WiMAX but keep in mind the requirements of more general BWA systems.

The WiMAX SS can be in a number of different states: (i) active bidirectional communication with the WiMAX base station (BS), with the link carrying a variety of different traffic – VOIP, video streaming on the downlink, or TCP/IP data traffic; (ii) idle or sleep state, in which the SS is mostly dormant, and wakes up at periodic intervals to listen for messages on the downlink, and responds with messages on the uplink frequencies; (iii) being powered “on”, in which case the SS is said to be in a network entry state and is executing a defined series of steps – this starts with listening to, and acquiring, downlink synchronization signals before initiating uplink transmissions. The detailed behavior of the SS in different kinds of BWA systems may vary, but the general characteristics in terms of these different states are expected to be similar, particularly since the system requirements are mostly similar.

The UWB DAA device can also be in different states – (i) starting up following “power on” and (ii) “active” state, in which the UWB device is in either active communication with other UWB devices, or in idle mode.

Different interference scenarios can be defined for DAA to address based on the interaction between the states of the WiMAX SS and the UWB device(s).

The main tools in the DAA “toolkit” are listed below:

1. *A narrowband signal detection function*: whenever the WiMAX BS or SS are transmitting, the UWB device potentially has the opportunity to detect these transmissions. In order to preserve as much generality as possible, it is assumed the detection only relies on features such as power in a given bandwidth. Associated with this function is a detection threshold. In general, detection with a low-enough threshold in order to reliably detect the BS downlink transmissions even at the edges of the cell may not be feasible in practice. Further, even if it were practical to do so, this would result in higher false alarms caused by any number of spurious signals, and would result in unneeded performance degradation in the UWB system. Since the interference of concern to the WiMAX SS occurs in close proximity to the UWB devices, by reciprocity the UWB device

should receive the WiMAX SS uplink transmissions with relatively high signal levels. This suggests an approach that sets the detection threshold based on the assumption that uplink transmissions are to be detected (of course, over some fraction of the cell this would also mean that downlink transmissions from the BS are also detectable). A number of factors should be considered in determining the appropriate detection threshold. These include (i) lack of certainty regarding whether the WiMAX system is FDD or TDD (ii) whether transmission power control (TPC) is in effect on the uplink/downlink, (iii) the amount of margin to be provided to account for uncorrelated fading between the detection path (WiMAX uplink transmission detected at the UWB device) and the interference path (UWB interference experienced at the WiMAX SS in the downlink frequencies) (iv) typical levels of spurious emissions in the neighborhood of UWB devices performing detection. These factors will all need to be considered, and the detection threshold will need to be determined through analysis and extensive testing.

2. A means of ensuring that adequate *silent periods* are created in a synchronized manner in transmissions within a given UWB device cluster. As a consequence of the DAA system's reliance on uplink detection as described above, some interference scenarios require provision of a mechanism through which an as yet undetected WiMAX SS can be enabled to come into a state in which it can be detected by the UWB DAA system. The most promising current approach for this is to ensure that the UWB transmissions have adequate periods of no transmission – both in terms of duration and frequency of occurrence – on the potentially affected WiMAX frequencies. This can help a WiMAX SS that is in network entry state in the vicinity of a UWB device cluster. For instance, the WiMAX SS will be provided a reasonable probability of establishing the downlink synchronization, and when it subsequently commences uplink transmissions, the UWB DAA devices will be able to detect it and thus triggering interference avoidance mechanisms. The optimum range of values for the parameters such as the duty cycle, duration, and average frequency of occurrence of these silent periods needs to be determined through extensive testing with a range of systems.
3. The third component of DAA toolkit is the *avoidance* mechanisms. UWB systems may be able to avoid interference to the detected WiMAX SS in a number of ways. The key is that once the detection mechanism is triggered, it also provides an estimate of the frequency of the WiMAX system (UL/DL). The UWB device can then employ a narrowband notch filter, or a scheme such as avoidance of transmission on a broad band of frequencies (e.g., the MB-OFDM system can suppress transmission on an entire 528 MHz wide subband which spans the estimated location of the WiMAX DL transmission), or it can employ time-domain avoidance techniques based on either a priori or estimated information about the WiMAX transmissions. It is important to take into consideration various factors in framing the avoidance mechanism, such as the uncertainty about the location of the WiMAX downlink transmissions, if the detected signal is the uplink signal in a FDD WiMAX system, for example.

Table 2.6 Parameters for detect operation ([XX] refers to values that are yet to be defined)

Parameter	Value	Remarks
Narrowband signal detection threshold	$P_{th}=[xx] \text{ dBm/MHz}$	The UWB device shall detect the presence of a “victim” when arriving at the UWB Rx with this minimum PSD level
Initial channel availability check time	$T_{init}=[xx] \mu\text{s}$	Upon initial power-on, or when the UWB device has been inactive for more than [XX] seconds, the UWB devices shall observe the channel for this time before using the channel
In-service channel availability check time	$T_{in}=[xx]$	The UWB device must detect the presence of a “victim” within this time when a victim moves into detection range. This may vary with “victim” traffic and operational profiles
Continuous in-service minimum silent interval	$T_{silent}[xx] \mu\text{s}$ per $T_{sper}[yy]$ seconds in minimum blocks of $T_{sblk}[zz] \mu\text{s}$	The local UWB system shall be able to allocate this minimum continuous silent interval periodically to allow new “victim” devices to begin operation. The UWB device shall also be able to detect a “victim” transmission during this period
Detection reliability	$R = [99]\%$	This shall be measured via test procedures to be defined in ETSI and shall be met for the different coexistence scenarios described here

Table 2.7 Parameters for avoid operation

Parameter	Value	Remarks
Maximum emission level in avoid operation	$xx \text{ dBm/MHz}$	The UWB device, after it has detected a “victim” service, shall reduce the emission level below this value in the “victim” channel
<i>Mitigation time period</i>	$T_{mit}=[xx] \text{ min}$	The UWB device, after it has detected a “victim” system, shall leave the “victim” channel for a minimum of this time
<i>Response time</i>	$T_{resp}=[xx] \mu\text{s}$	The UWB device shall reduce emissions in the detected bands within this time of successfully detecting a “victim” system

Tables 2.6 and 2.7 show examples of DAA parameters which could be specified in the regulatory domain, but the final numbers for these parameters require further research. This would allow for UWB standards and devices to be developed that can be verifiably demonstrated to meet the intent of the regulations and provide interference mitigation.

2.5 Cognitive Radios And Other Future Areas For Research

In 2003, under ET Docket 03-108, the FCC began an investigation of cognitive or “smart” radios that can

[operate on an] opportunistic basis, finding idle spectrum, using it as they need, then vacating the band for others to use, all without human intervention. This model presumes

no need for spectrum policy, allocation tables, or regulatory bodies to manage spectrum resources.¹⁷

UWB designs, especially those based on OFDM, are a significant step toward the cognitive concept. ECMA-368 (WiMedia, ECMA-368) transceivers already feature wide-bandwidth/low-noise front ends, low cost, broadbanded antennas, and especially transmitted spectra that are modifiable “on the fly” under software control. When combined with detect-and-avoid, many of the essential elements of a cognitive design will already be present. OFDM-based UWB radios may well be the progenitors of the cognitive designs called for by the FCC. In addition, because they are based on OFDM, WiMedia designs are technical “cousins” of OFDM-based 802.11, 802.16, and some cellular technologies, raising the possibility of common architectural approaches and shared functions among wireless personal-area, local-area, and wide-area wireless communications systems.

While there has been considerable progress in UWB, there are still many opportunities for future research that are especially important to UWB. Some of these are outlined below.

1. Antennas – broadband antennas, including those with frequency response to help reduce interference to and from the UWB device.
2. Tunable band-pass filters – wide-dynamic range or passive (non-saturating) designs that can protect UWB receiver front ends and reduce UWB interference to other systems.
3. Low-noise all-CMOS analog front ends – designs that can accommodate higher frequencies (up to 10.6 GHz) with good sensitivity and low noise figure.
4. High-speed, low power ADC/DAC designs – low-power-consumption designs that can over-sample analog signals with 6-bit or higher precision.
5. Dynamic spectrum control – “on the fly” sculpting of transmitted spectra to accommodate local conditions and regulations.

2.6 Summary and Conclusions

The first radios, dating back to the late nineteenth century, were based on “spark” technology and were ultrawideband out of necessity rather than choice. Following the invention of the vacuum tube triode, it became possible to control bandwidth very precisely, and ultrawideband systems disappeared by the 1920s, emerging again for defense purposes in the 1960s. With the declassification of that work in the 1990s, research groups and small entrepreneurial companies began investigating the potential of UWB for commercial purposes. After a lengthy deliberation at the FCC, with more than 900 submitted comments, rules for unlicensed, Part-15-based operation of UWB were issued in February, 2002. After that date, activity in UWB

¹⁷ FCC Report and Order, Released March 11, 2005, ET Docket No. 03-108, FCC 05-57, Paragraph 3.

increased dramatically, and a wide variety of UWB technologies emerged. Many were, and still are, based on “traditional” narrow-pulse techniques. One in particular, known as DS-UWB, combines pulse-based transmission with spread-spectrum techniques. Others, in particular the ECMA-368 approach largely described in this chapter, combine UWB with modern digital techniques like OFDM. Each approach offers a different set of trade-offs among performance, cost, energy efficiency, and spectral flexibility.

As described in Section 2.3, the very wide bandwidth of a UWB channel presents both opportunities and challenges. On the plus side, a UWB system should be much less vulnerable to Rayleigh fading than a traditional narrowband system. Multipath inevitably suppresses some narrow spectrum segments, but the rest will still get through, and some will actually be enhanced by multipath. Typical indoor channels will contain several hundred paths, spread over tens of nanoseconds. Impulse-based designs attempt to resolve individual paths, combining the energy from a few of the paths via RAKE -based techniques. OFDM-based systems typically spread their information over hundreds of sub-carrier tones, capturing most all of the signal energy that the channel has to offer. Both systems use error correction, commonly convolutional codes and Viterbi-based decoders, to recover transmitted data.

As described in Section 2.3, UWB antenna and analog-front-end designs present new challenges relative to traditional narrowband antennas. UWB antennas not only need to be efficient radiators over a wide spectrum but also, in the case of pulse-based UWB, need to cause as little pulse dispersion as possible in order to limit inter-symbol and inter-channel interference. Broad-band analog front ends need low noise figures for any UWB technology, and in the case of OFDM-based UWB, linearity and dynamic range are especially important.

While the low permitted power of all UWB-based systems provides some inherent protection for potential nearby victim systems, some degree of (preferably dynamic) spectral control is a desirable feature of a practical UWB system. As described in Section 2.4, UWB systems also need to detect the presence of potential nearby victims and estimate what frequencies need protection. For both the *detect* and *avoid* functions, the FFT function in OFDM-based UWB systems can be used to spot both the presence and frequency of potential victims. Furthermore, the digitally created waveforms and multiband design in MB-OFDM can avoid interfering with other systems by using selectable sub-bands or by suppressing individual sub-carriers under software control.

Because of their wideband front-end response, all UWB systems are themselves potential victims of any narrowband interferers within the receiver passband. DS-UWB-based systems mitigate this interference by spreading and decorrelating the interferer energy over multiple pulses. OFDM-based systems mitigate the interference by sacrificing a few of the affected sub-carrier tones. Both types of systems are vulnerable to very strong interferers that could saturate the receiver front end.

Generally speaking, pulse-based UWB systems are simpler than OFDM-based systems, depending on the multipath channel, because the former do not need

IFFT/FFT engines operating at very high rates. However, when the need to detect and avoid interference is included in a pulse-based UWB system, complexity comparisons are not as clear.

Finally, as described in Section 2.5, OFDM-based systems appear to be a first step toward future *cognitive* designs, as called for by the FCC. This and other areas, like broadband antennas, filters, analog front ends, and ADC/DAC technologies remain areas for continued research.

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