Chapter 1
UWB Preliminaries

The chapter starts with the definitions for ultra wideband (UWB). A short history of the technology is presented and pioneers of the field are introduced. We then turn to UWB regulatory history and discuss Federal Communications Commission (FCC) first report and order. The dynamic spectrum access (DSA) is introduced and UWB is viewed as a way to implement DSA. Main attributes of UWB systems including transmit power, transmission capacity, link budget, resilience to multipath fading, and extremely large spreading factor are elaborated in the following sections. The chapter concludes with a discussion of the sweet spots for the UWB technology.

1.1 UWB Definition

Between 1950 and 1990 a number of unconventional communication systems were introduced. They were referred to as carrier-less radios, impulse radio (IR), non-sinusoidal transceivers, or baseband modulation. In addition to having no carrier frequency, these unconventional systems had extremely large bandwidths. The efforts to find commonalities between these systems have led to two definitions.

The first definition was provided by the Defense Advanced Research Project Agency (DARPA[1]). In 1989, a study panel from DARPA defined a new term, known as UWB [1]. As per DAPPA definition, signals with a fractional bandwidth B_f equal to or larger than 0.25 are classified as UWB signals. Fractional bandwidth is the ratio of 3 dB signal bandwidth to center frequency [2], or

$$B_f = \text{Bandwidth}\,(3\,\text{dB})/\text{Center frequency}.$$

In February 2002, FCC in its First Report and order updated UWB signal definition [3]. A signal is considered UWB if either the -10 dB bandwidth of the signal is larger than 500 MHz or its fractional bandwidth is at least 0.2. The fractional bandwidth was defined as

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[1] DARPA was established in 1958. Since then it has funded the development of many vital technologies such as GPS and the Internet.

S. Emami, *UWB Communication Systems: Conventional and 60 GHz*,
DOI: 10.1007/978-1-4614-6753-3_1,

$$B_f = \text{Bandwidth}\,(10\,\text{dB})/\text{center frequency} = 2(f_H - f_L)/(f_H + f_L)$$

where f_L and f_H are the lower and upper 10 dB frequencies of the power spectrum relative to the PSD peak.

These definitions brought the unconventional communication systems under one UWB umbrella. The FCC definition, in fact, encompasses a number of other signals. As such, since its introduction a number of other UWB signals and modulation types have been reported in the literature. References [1, 4] provide excellent reviews of the UWB technology, as well as its history.

Now let us examine the power spectrum of two signals *A* and *B* shown in Fig. 1.1. The lower and upper 3 dB frequencies of signal *A* shown in Fig. 1.1a are $f_L = 0.471$ GHz and $f_H = 1.600$ GHz, respectively. Signal bandwidth and the center frequency are

$$\text{Bandwidth} = 1.6 - 0.471 = 1.129\,\text{GHz}$$

and

$$\text{Center frequency} = \frac{(f_L + f_H)}{2} = 1.0355\,\text{GHz}.$$

Fractional bandwidth becomes $B_f = 1.129\text{e}9/1.0355\text{e}9 = 1.0903$. Signal *A* is considered a UWB signal per DARPA definition.

The fractional bandwidth of signal *A* as per FCC definition is

$$B_f = 2(2.16\text{e}9 - 0.19\text{e}9)/(2.16\text{e}9 + 0.19\text{e}9) = 1.6766\,\text{GHz}$$

since $f_L = 0.19$ GHz and $f_H = 2.16$ GHz, respectively. Both definitions classify signal *A* as a UWB signal.

Now let us compute the fractional bandwidth for signal *B*. The lower and upper 3 dB frequencies of signal *B* is shown in Fig. 1.1b are $f_L = 6.67$ GHz and $f_H = 7.60$ GHz, respectively. Signal bandwidth, center frequency, and fractional bandwidth are

$$\text{Bandwidth} = 7.6 - 6.67 = 0.93\,\text{GHz},$$
$$\text{Center frequency} = \frac{(f_L + f_H)}{2} = 7.135\,\text{GHz}$$

and

$$B_f = 0.93\text{e}9/7.135\text{e}9 = 0.1303\,\text{GHz}.$$

As per DARPA definition, signal *B* is not a UWB signal as its fractional bandwidth is below 0.25.

The fractional bandwidth of signal *B* as per FCC definition is

$$B_f = 2(8.16\text{e}9 - 6.19\text{e}9)/(8.16\text{e}9 + 6.19\text{e}9) = 0.2746\,\text{GHz}$$

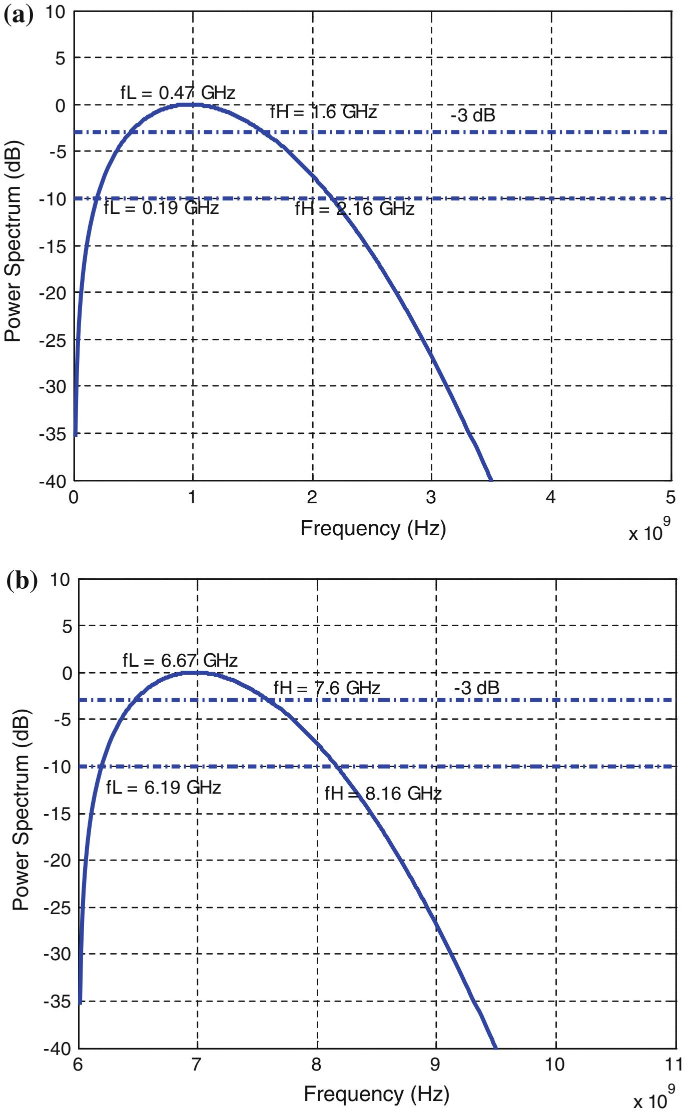


Fig. 1.1 **a** Power spectrum of signal *A* and **b** Power spectrum of signal *B*

since $f_L = 6.19$ GHz and $f_H = 8.16$ GHz, respectively. The FCC definition, contrary to DARPA definition, regards signal B as a UWB signal.

There are a couple of differences between the two definitions. First, the FCC definition of bandwidth, unlike DARPA definition, is based on -10 dB frequency points.

Second, FCC has a lower threshold for UWB fractional bandwidth (0.2 as opposed to 0.25 for DARPA). Consequently, the FCC definition is more inclusive.

1.2 UWB Technology History

The work on IR and carrier-free transmission started in the 1940s and 1950s. Radar was the primary application area [2]. Applications to data communication did not start until the late 1960s [1]. Harmuth, a faculty at Catholic University of America, worked on electromagnetic properties of nonsinusoidal signals and authored several books [5–7]. Ross conducted his dissertation research on what is considered UWB today in the early 1960s [8–9]. Throughout the 1970s and 1980s, Ross, Robins, Bennett, as well as other engineers from Sperry Research worked on applications of baseband radio technology.

By the late 1980s, patents and publications on unconventional communications had become widespread. Unconventional communication schemes were grouped together and labeled as UWB by DARPA. UWB proponents envisioned commercial applications of this technology and shared their vision with FCC. Among the applications was the potential to deliver very large amounts of information over short distances without requiring a dedicated band. The interactions with FCC continued in the 1990s and finally led to legalization of UWB for commercial applications in 2002 [4].

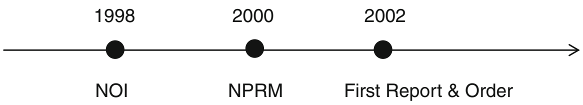
1.3 UWB Pioneers

Over the past 60 years a number of engineers and researchers have worked on what we know as UWB technology today. Their work resulted in many articles and patents. The first books on UWB were written by Harmuth, a faculty at Catholic University of America. The first dissertation on UWB and an instrumental patent on UWB belong to Ross [10]. Among the UWB researchers Harmuth, Ross, Robbins, Van Etten, and Morey are the true pioneers [1].

1.4 UWB Regulatory History

The vision behind legalization of UWB was to allocate a frequency range to unlicensed UWB devices on nonexclusive basis in which their radiation level would be on par with unintentional radiators (limited to −41.3 dBm/MHz). In 1998, the FCC motivated by the enthusiasm and work of UWB proponents issued a notice of inquiry (NOI) [11]. It was basically an inquiry from interested parties to voice their opinion, whether or not they were in favor of legalizing UWB.

Fig. 1.2 The sequence of events that led to legalization of UWB in the US



About 1,000 submissions, some in favor and others against UWB, were made to FCC. They consisted of reports, studies, recommendations, and some prototypes. Together with NTIA,[2] FCC examined the evidence and weighted the benefits of legalizing UWB against the interference potential of UWB to the existing radio services. A primary concern was the interference potential to GPS, as the GPS signal is weak. In 2000, FCC signaled the beginning of UWB era with the release of Notice of Proposed Rule Making (NPRM). Eventually, on February 14, 2002, UWB was made legal in the US. The restrictions associated with the use of UWB are spelled out in the First Report and Order. The sequence of events is shown in Fig. 1.2

1.5 FCC First Report and Order [3]

As per First Report and Order UWB devices would have to operate in-between 3.1 and 10.6 GHz with a PSD limited to −41.3 dBm/MHz.[3] For communication application, an indoor and an outdoor emission mask are provided (Fig. 1.3a–b). Only handheld UWB devices can operate outdoors. In both cases, much smaller radiation is required in GPS band. Sufficient protection for cellular, PCS, and satellite TV services has also been provided. The outdoor mask is somewhat more stringent[4] in regard to protecting these services.

In addition to data communications, the first report and order also authorized the use of UWB for other applications such as imaging devices and vehicular radars. Some of these applications are for civilian and commercial while others are for military purposes. Similar to the data communications case, a radiation mask is specified for each application (Fig. 1.3c–d).

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[2] In US, FCC regulates the use of air waves for nongovernment users. On the other hand, National Telecommunication Information Agency (NTIA) is in charge of spectral issues for federal government entities.

[3] As per FCC Part 47 Sect. 15, the radiated emissions from an intentional radiator operating above 960 MHz must be limited to electric field strength of 500 μV/m at 3 m away from the radiator in every 1 MHz. The radiated power is given by

$$P = E_o^2 4\pi R^2 / \eta$$

where E_o, R and η denote the electric field, the radius of the sphere at which field strength is measured and characteristic impedance of vacuum ($\sim 377\ \Omega$), respectively. Upon substitution into the radiated power equation, we end up with an emitted power of roughly 75 nW or 10log(75e−9/0.001) = −41.3 dBm/MHz.

[4] An additional 10 dB compared to the indoor mask.

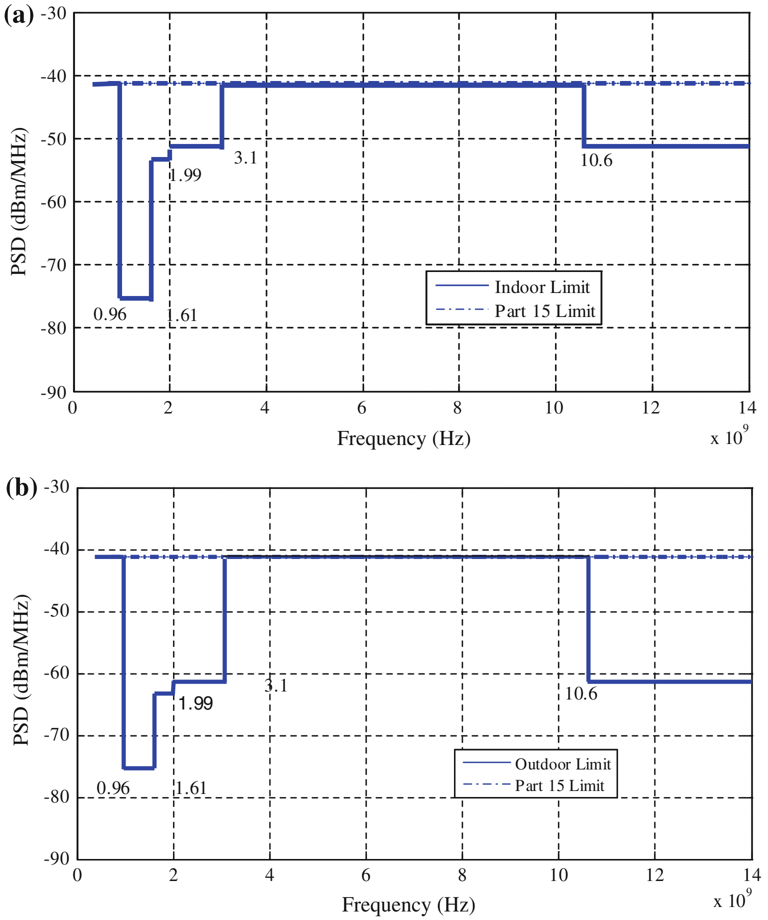

Fig. 1.3 FCC UWB masks: **a** indoor; **b** outdoor; **c** imaging; and **d** vehicular

Automotive or vehicular radars monitor the space in the vicinity of an automobile. They can be used to either provide feedback to the driver or activate brakes, if collision is unavoidable. In addition to collision avoidance, it can be used for cruise control, airbag activation, and roadside assistance. Note that unlike other UWB systems, automotive radar systems operate in 22–29 GHz range.

UWB imaging systems can be divided into ground penetration radars (GPR), wall imaging, through-wall imaging, and medical imaging. The emission limits for these imaging systems are listed in Table 1.1. The goal of GPR is to search for and locate the objects underneath the ground. The objects inside or behind a wall are revealed in wall imaging. The GPR and wall imaging usage is limited to public safety, research community, and commercial mining. Through-wall imaging, as the name implies, allows one to examine the adjacent rooms to look for people or objects of interest. Its usage is licensed and is limited to law enforcement,

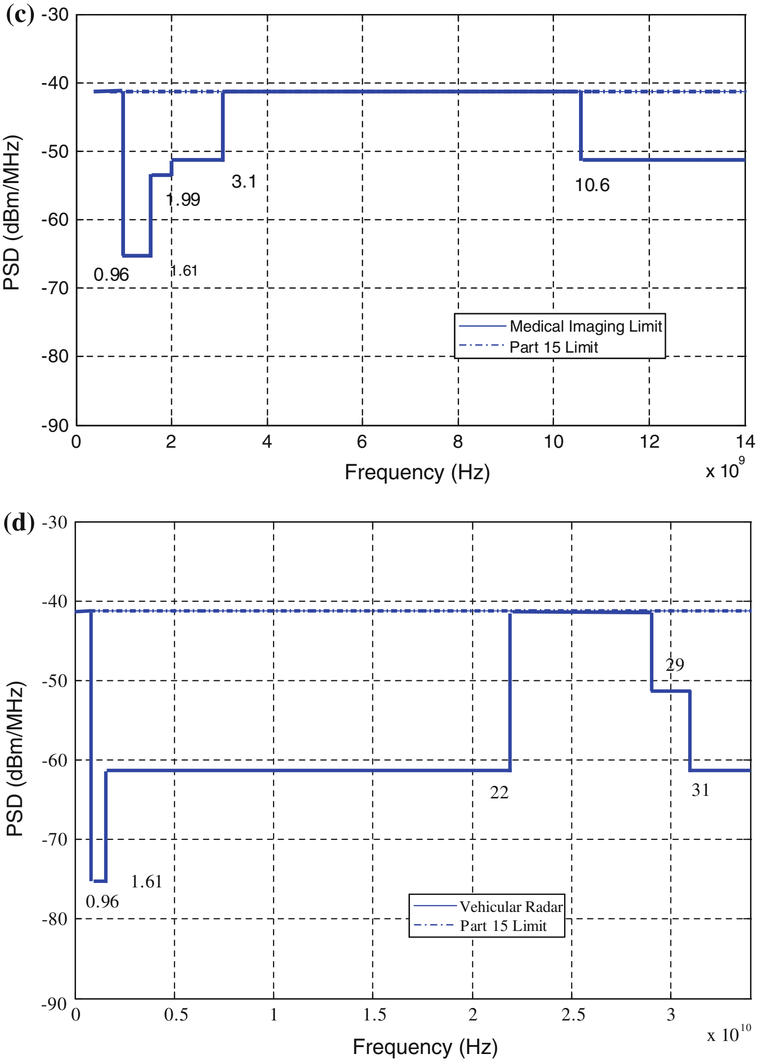

Fig. 1.3 continued

emergency rescue, and fire fighters. A related application is surveillance in which an RF perimeter is monitored. The technology must operate in 1.9–10.6 GHz range and its use is limited to public safety, emergency rescue organizations, manufacturing, and petroleum licensed users. Imaging systems must operate between 3.1 and 10.6 GHz. This technology requires a license and can only be used by healthcare practitioners.

Table 1.1 Emission limits (dBm) for various UWB applications

Frequency range (MHz)	960–1,610	1,610–1,990	1,990–3,100	3,100–10,600	Above 10,600	1,164–1,240[a] 1,559–1,610[a]
GPR	−65.3	−53.3	−51.3	−41.3	−51.3	−75.3
Through-wall imaging (below 960 MHz)	−65.3	−53.3	−51.3	−51.3	−51.3	−75.3
Through-wall imaging (1.99–10.6 GHz range)	−46.3	−41.3	−41.3	−41.3	−51.3	−56.3
Surveillance systems	−53.3	−51.3	−41.3	−41.3	−51.3	−63.3

[a] These emissions are to be measured with a resolution bandwidth of no less than 1 kHz while all others are to be measured with a resolution bandwidth of 1 MHz

1.6 Dynamic Spectrum Access

In conventional spectrum allocation regime, the spectrum is allocated exclusively to a certain service. Others have to stay away from the allocated spectrum. Studies have shown that the conventional allocation scheme leads to congestion and inefficient use of spectrum. It is desirable to bring in secondary users to utilize the unused spectrum. DSA offers schemes that improve the efficiency of spectrum usage through accommodation of secondary users.

DSA can be divided into three access models. Among them the hierarchical access model is most compatible with the wireless systems of today's and FCC's vision. The concept behind hierarchical access model is to share the licensed bands with the secondary users, while limiting the interference to primary users. The hierarchical access consists of two spectrum sharing approaches namely spectrum overlay and spectrum underlay. In spectrum overlay[5] there are two types of users known as primary and secondary users. Primary users have priority over the secondary users in terms of spectrum access. Secondary users can only use the spectrum when primary users are absent. As soon as a primary is detected, secondary has to leave the band within a short time. In underlay scheme, the secondary user transmits at all times but it has a very low emission profile. Because of the low emission profile, the impact of the secondary on primary's performance is negligible. In conclusion, in spectrum overlay only the unused spectral regions are targeted while spectrum underlay takes advantage of underused regions.

1.7 UWB Regulations in Other Countries

UWB spectrum covers a large swath of frequencies that have been home to a number of different wireless systems and services. They include services such as WiMAX, 3G/4G, satellite communications, various types of radars, and radiolocation. The incumbent users of spectrum feel somewhat uneasy about sharing their resources with UWB for a couple of reasons. First, they are accustomed to traditional paradigms of exclusive spectrum assignment. Second, spectrum sharing based on primary/secondary assignment (or spectrum overlay/underlay) is somewhat of uncharted territory.

In the United States, the First Report and order FCC allocated the spectrum from 3.1 to 10.6 GHz for UWB communications. FCC feels that provisions in the First Report and Order provide adequate protection for the existing services. Above and beyond that, the regulations will be revisited if any unforeseen issues arise.

Regulators around the world have had more conservative views with respect to UWB and spectrum overlay/underlay. European and far-eastern regulators have proposed a couple of protection mechanisms for incumbent users of spectrum.

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[5] Also known as opportunistic spectrum access.

Detect and avoid (DAA) is the primary protection mechanism. It essentially means that upon detection of a primary user, the secondary user would need to either leave the band or lower its emission level to a predetermined amount. The other mechanism is low duty cycle (LDC). To qualify as an LDC device (a) the transmission time within each second would have to be upper bounded by 5 %, (b) the transmission time within each hour has to be less than 0.5 %, and (c) duration of each transmission would have to be limited to 5 ms. In what follows, we review the UWB regulatory status in Europe, Japan, Korea, China, and Singapore at the time of this writing [12, 13]. Changes and updates to the regional rules are quite likely.

Japan—UWB devices in Japan can only operate indoors in the following range:

$$\text{UWB Spectrum}_{\text{Japan}} = [(3.4 - 4.8)U(7.25 - 10.25)]\,\text{GHz}.$$

For operation in the low band, namely 3.4–4.8 GHz, DAA functionality is a requirement. The requirement can be waived, if the emission level is lowered from the usual −41.3 to −70 dBm/MHz. Unlike in the US, Japanese law requires conducted emission tests as opposed to radiated testing. Operation in the high band, namely 7.25–10.25 GHz, requires the emission limit of −41.3 dBm/MHz and no DAA. In Japan, UWB devices are required to have a minimum data rate of 50 Mbps.

Korea—Korean allocated UWB spectrum is defined as

$$\text{UWB Spectrum}_{\text{Korea}} = [(3.1 - 4.8)U(7.2 - 10.2)]\,\text{GHz}.$$

DAA capability or LDC is only a requirement while UWB devices operate in 3.1–4.8 GHz band. Similar to Japanese regulations, with the emission limit of −70 dBm/MHz, the DAA requirement can be waived. UWB devices operating in the high band, namely 7.2–10.2 GHz, require the emission limit of −41.3 dBm/MHz. UWB devices in Korea can only operate indoors.

China—Chinese allocated UWB spectrum consists of union of a low band, 4.2–4.8 GHz, and a high band or 6–9 GHz. In other words,

$$\text{UWB Spectrum}_{\text{China}} = [(4.2 - 4.8)U(6 - 9)]\,\text{GHz}.$$

The lower portion of UWB band is for indoor use only, while the upper portion of band can be utilized for both indoor and outdoor use. Only UWB devices operating in the low band are required to implement DAA. However, the DAA requirement can be waived upon lowering of emission to −70 dBm/MHz. Operation in 6–9 GHz is subject to the emission limit of −41.3 dBm/MHz. The Chinese UWB regulations are not finalized yet and are subject to change.

Europe—The allocated UWB spectrum in Europe is

$$\text{UWB Spectrum}_{\text{Europe}} = [(3.1 - 4.8)U(6 - 9)]\,\text{GHz}.$$

UWB devices operating in 3.1–4.8 GHz range and subject to emission level of −41.3 dBm/MHz should be DAA or LDC capable. The requirement can be dropped, if the limit is lowered to −80 dBm/MHz for 3.4–3.8 GHz range and to −70 dBm/MHz for 3.1–3.4 and 3.8–4.2 GHz ranges. As we stand today, 6–8.5 GHz band is open to UWB devices with no DAA requirement and subject to the limit of −41.3 dBm/MHz. DAA or LDC is required for operation in 8.5–9 GHz range. However, if the emission level is lowered to −65 dBm/MHz DAA requirement can be dropped. A minimum utilized bandwidth of 50 MHz for UWB devices is required in Europe.

Singapore—Following a period of public consultation IDA[6] established the regulations for UWB consumer and business data communication systems. As per these regulations UWB systems operating in 3.4–4.8 GHz range must utilize a mitigation technique such as DAA. However, UWB devices can operate in 6–9 GHz band with no DAA requirement. In either case, the emissions are limited to −41.3 dBm/MHz.

1.8 Spectrum Overlay/Underlay Classification

We have so far described UWB signal, the UWB regulations in a number of countries, as well as DSA. The question before us is whether UWB can be considered as spectrum overlay or spectrum underlay. It turns out that the answer depends not only on UWB signal definition but on the frequency band of operation, PSD level and specific country/region.

The situation is clear cut in US, as UWB devices are authorized to operate simultaneously with the primary user in 3.1–10.6 GHz range, subject to emission limit of −41.3 dBm/MHz. Clearly, in the US spectrum underlay approach is applicable to UWB devices. Unfortunately, situation elsewhere is not nearly as clear. For instance in Japan as long as a UWB device stays in the upper band, it can operate simultaneously in primary user band. As such spectrum underlay is applicable. However, while operating in the lower band, PSD becomes a key parameter. If PSD stays below −70 dBm/MHz, UWB device can operate simultaneously in primary user band. This falls within spectrum underlay regime. But if -70 dBm/MHz $< PSD < -41.3$ dBm/MHz, then we are dealing with the opportunistic access or spectrum overlay. The classification for a number of countries and a region are provided in Table 1.2A and B. In summary, regulators in Europe, Japan, Korea, and China authorize spectrum underlay subject to (1) a very low emission limit (at least −70 dBm/MHz) or (2) operation in a high frequency band (above 6 GHz).

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[6] IDA stands for Infocomm Development Authority.

Table 1.2 Overlay/Underlay classification

A

Country	Lower band	Upper band
Japan	3.4–4.8 GHz: if −70 dBm/MHz < *PSD* < −41.3 dBm/MHz OVERLAY if *PSD* < −70 dBm/MHz UNDERLAY	7.25–10.25 GHz: UNDERLAY
Korea	3.1–4.8 GHz: if −70 dBm/MHz < *PSD* < −41.3 dBm/MHz OVERLAY if PSD < −70 dBm/MHz UNDERLAY	7.2–10.2 GHz: UNDERLAY
China	4.2–4.8 GHz: if −70 dBm/MHz < *PSD* < −41.3 dBm/MHz OVERLAY if *PSD* < −70 dBm/MHz UNDERLAY	6–9 GHz: UNDERLAY
Singapore	3.4–4.8 GHz: OVERLAY	6–9 GHz: UNDERLAY

B

Region	3.1–3.4 GHz	3.4–3.8 GHz	3.8–4.2 GHz	6–8.5 GHz	8.5–9 GHz
Europe	if −70 dBm/MHz < *PSD* < −41.3 dBm/MHz	if −80 dBm/MHz < *PSD* < −41.3 dBm/MHz	if −70 dBm/MHz < *PSD* < −41.3 dBm/MHz		if −65 dBm/MHz < *PSD* < −41.3 dBm/MHz
	OVERLAY	OVERLAY	OVERLAY		OVERLAY
	if *PSD* < −70 dBm/MHz	if *PSD* < −80 dBm/MHz	if *PSD* < −70 dBm/MHz	UNDERLAY	if *PSD* < −65 dBm/MHz
	UNDERLAY	UNDERLAY	UNDERLAY		UNDERLAY

1.9 UWB Properties

1.9.1 Transmit Power

Let’s consider a UWB transmitter occupying the 3.1–10.6 GHz frequency range. The total power in the band is

$$P = \mathrm{PSD}\left(\frac{\mathrm{dBm}}{\mathrm{MHz}}\right) + 10\log(\text{Bandwidth in MHz})$$

$$P = -41.25 + 10\log(7500) = -2.55\,\mathrm{dBm\,or\,0.55\,mW}.$$

In practice, a UWB device will utilize only a fraction (1/3 to 1/5) of the spectrum. The total transmitted power will then be a fraction of a milli-watt (0.1–0.2 mW).

Table 1.3 PSD of some wireless systems [12]

Wireless system	Transmit power spectral density (dBm/MHz)
WCDMA	18
WLAN	[7 17]
Bluetooth 2.0	[−29.20 −15.23]
UWB	−41.25

Two UWB modulation schemes, known as multiband-OFDM (MB-OFDM)[7] and DS-UWB,[8] will be introduced in Chap. 4. Let us compare their transmit power. Multiband-OFDM utilizes slightly over 1.5 GHz of bandwidth, or 3 × 528 MHz to be exact [14]. The total transmit power is

$$P = -41.25 + 10\log(3 \times 528) = -9.25\,\text{dBm}.$$

DS-UWB, the other UWB technology, offers two options [15]. Low band option is 1.75 GHz wide while the high band option is 3.5 GHz wide. The power associated with the two options can be computed in the following way:

$$\begin{aligned} P &= -41.25 + 10\log(1750) = -8.82\,\text{dBm} \quad \text{(low band option)} \\ P &= -41.25 + 10\log(3500) = -5.81\,\text{dBm} \quad \text{(high band option)}. \end{aligned}$$

Let us compare PSD level associated with UWB with that of other services such as WLAN and WCDMA. As per Table 1.3, there is roughly 60 and 50 dB differential in PSD levels between UWB and WCDMA and WLAN, respectively. Thus, the PSD associated with UWB is considerably less than that of GSM and WCDMA. The low PSD level associated with UWB in comparison with that of narrowband systems demonstrate that UWB can peacefully coexist with other narrowband systems (Fig. 1.4).

1.9.2 Capacity

Shannon-Hartley capacity theorem [16] states the relationship between the capacity, signal-to-noise ratio (SNR), and bandwidth (B).

$$C = B\log_2\left(1 + \frac{S}{N}\right)$$

Capacity can be improved by increasing the bandwidth or the SNR. As seen the relationship between capacity and bandwidth is linear, while the relationship

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[7] MB-OFDM is the basis for WiMedia UWB technology as well as ECMA-368 and ISO/IEC 26907 standards.

[8] DS-UWB Physical Layer Submission to 802.15 Task Group 3a, IEEE 802.15.3a Working Group, P802.15.03/0137r0, 2004.

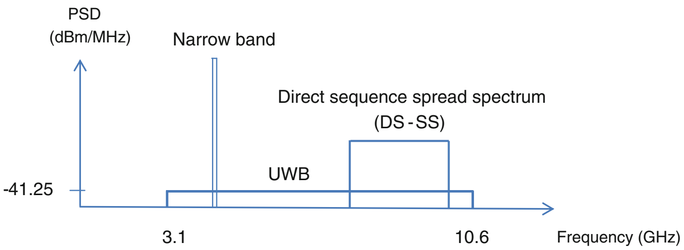

Fig. 1.4 PSD of various systems

between the capacity and SNR is logarithmic. Linear relationships grow much faster compared to the logarithmic relationships. UWB technology increases the capacity linearly through bandwidth increase.

Capacity of UWB system in terms of UWB system parameters can be computed in the following fashion. Let S and N denote the received power at the receiver and noise floor, respectively. Both signal and noise power are expressed in dB. By definition

$$\mathrm{SNR}_{\mathrm{dB}} = S - N.$$

The received signal power at the transmitter site is given as

$$S = P_T + G_T + G_R - L - I$$

where P_T, G_T, G_R, L, and I denote transmitted power, transmitter gain, receiver gain, path loss, and implementation loss, respectively. Path loss is specified by the following well-known expression [16]:

$$L = 20\log(4\pi d f_c/c).$$

where d and fc represent the transmitter/receiver spacing and the center frequency, respectively. Noise power is defined as

$$N = 10\log(\mathrm{KT}) + 10\log(B) + 10\log(F)$$

where 10log(KT) and F are −174 dBm/Hz and noise figure, respectively. Finally we get

$$\mathrm{SNR}_{\mathrm{dB}} = P_T + G_T + G_R - L - I - N.$$

A convenient form of capacity is obtained upon converting $\mathrm{SNR}_{\mathrm{dB}}$ to linear scale and substitution into the Shannon-Hartley equation

$$C = B\log_2\left(1 + 10^{(P_T+G_T+G_R-L-I-N)/10}\right).$$

Consider a UWB system with a bandwidth of 1,500 MHz and omnidirectional antennas at both transmitter and receiver. Various parameters of the system are specified in Table 1.4.

Table 1.4 System parameters

Parameter	Values
Transmit power (P_T)	−9.25 dBm
Center frequency (fc)	4 GHz
Noise figure (F_{dB})	7 dB
Implementation loss (I)	3 dB

Let us compare UWB and 802.11g[9] in terms of capacity at various distances. In 802.11g channels are 20 MHz wide, center frequency is at 2.4 GHz, and the maximum transmit power is 30 dBm. Figure 1.5 shows a capacity comparison between the two systems. It is evident that UWB offers an extremely large capacity at short distances.

1.9.3 Link Budget

Let us answer a question: is UWB high speed communications possible. We shall consider a few scenarios first, namely 100 Mbps @ 10 m, 200 Mbps @ 4 m, and finally 500 Mbps @ 2 m. Then, we shall make some assumptions. Subject to the 1.5 GHz of bandwidth, the transmitted power will be −10 dBm. The transmit/receive antenna gains are assumed to be 0 dBi as they are omnidirectional. The SNR values [with strong forward error correction codes (FEC)] are 4, 5, and 6 dB depending on the FEC rate. Finally, implementation loss due to non-ideal filtering, mixing, etc., is assumed to be limited to 3 dB.

We will take away the losses and signal strength requirement at the receiver from the transmit power. Whatever margin is left will be used to combat multipath fading and shadowing. Consequently,

$$M = P_T + G_T + G_R - L - N - \mathrm{SNR} - I,$$

where M, N, and L denote margin, noise power, and path loss, respectively. The expressions for noise power and path loss are

$$N = -174 + 10\log(R) + 10\log(F)$$

with $R = 100$, 200, and 500 Mbps and $F = 7$ dB,

$$L = 20\log(4\pi \mathrm{d} f_c/c)$$

with $f_c = 3{,}850$ MHz.

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[9] IEEE 802.11g is a wireless protocol for wireless local area networks implemented using direct sequence spread spectrum (DSSS) and orthogonal frequency division multiplexing (OFDM) signaling methods in 2.4 GHz ISM band. In the United States IEEE 802.11g operates under FCC Part 15 regulations.

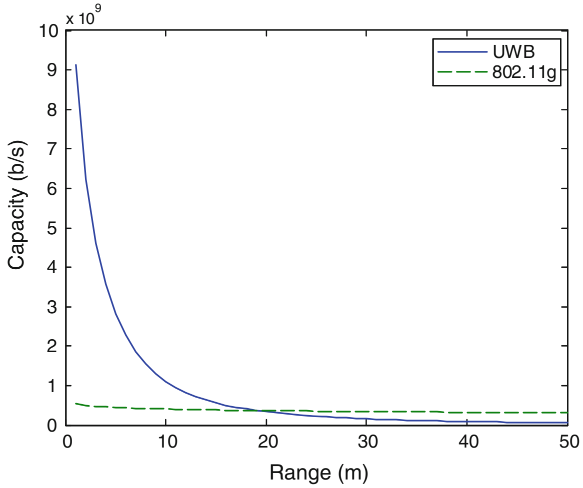

Fig. 1.5 Capacity versus range

Table 1.5 Margin for the three scenarios

Data rate	100 Mbps	200 Mbps	500 Mbps
M (dB)	5.8	9.8	10.8

The computed margins for different data rates are listed in Table 1.5. There is, clearly, adequate margin to combat multipath and shadowing in each of the three scenarios.

1.9.4 Resilience to Multipath Fading

The spectral notch created by destructive multipath fading could take away the spectrum of a narrowband system. This phenomenon results in serious performance degradation. However, the same spectral notch removes only a small percentage of UWB signal as the signal bandwidth is much larger compared to a narrow band system. Consequently, UWB is resilient to multipath fading and requires a smaller fading margin compared to narrowband systems. The scenario is illustrated in Fig. 1.6.

1.9.5 Excellent Temporal Resolution

Short pulses and high resolution of UWB signal make them ideal for ranging. Ranging is treated in Chap. 5. Cramer-Rao lower bound (CRLB) for ranging error

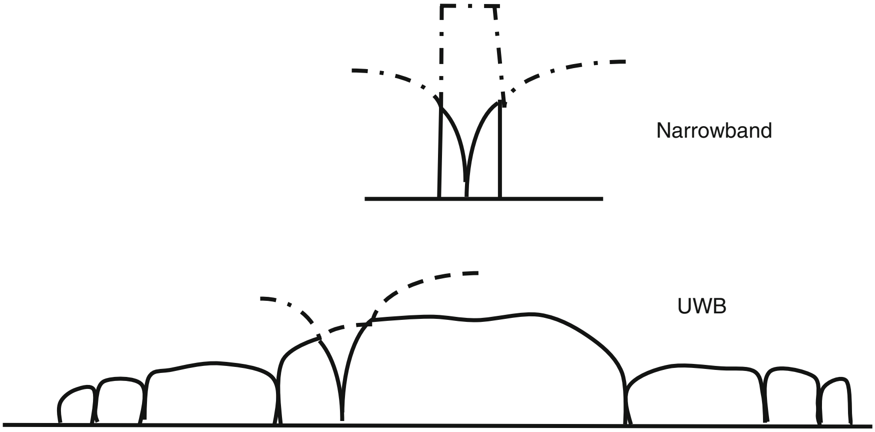

Fig. 1.6 Spectra of narrowband and UWB signals in presence of multipath fading

will be introduced enabling us to compare ranging systems. As we will see at SNR of 10 dB, a 500 MHz UWB signal achieves a lower bound of approximately 2 cm while a 802.11a/g signal with a bandwidth of 20 MHz has a lower bound of roughly 50 cm. The temporal resolutions gained by UWB signals are far superior to those of narrowband systems.

1.9.6 Extremely Large Spreading Factor

The link budget analysis revealed that high data rates are achievable at short ranges. UWB systems could have very large spreading ratio due to having extremely large bandwidths. By spreading the signal one can gain range at the expense of reducing the data rate. Both extremes offer commercial applications. While high data rate systems can deliver high definition content around home, low-throughput systems, such as IEEE 802.15.4a,[10] offer range for applications such as sensing and automation.

1.9.7 Non-exclusive Spectral Allocation

Typically, when new wireless services/technologies are established they are given spectrum of their own. The cost of spectrum acquisition is passed on to the consumer in one form or another. One of the main attractions of UWB systems is

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[10] This standard is covered in Chap. 3.

that they do not require exclusive spectrum allocation. UWB is essentially a spectrum underlay/overlay technology. As such they share the spectrum with the primary users.

1.10 UWB Over Cable

Often one associates UWB with wireless transmission, but UWB signals can be transmitted over coaxial cable as well. Splitters, couplers, and coaxial cable attenuate UWB signal. However, it has been shown that a properly designed coaxial home network can support high data rates (up to 600 Mbps) between 3 to 5 GHz up to a range of 300 ft [17, 18].

Both existing and newly constructed homes vary in size significantly. As such it is difficult to cover the entire home with wireless UWB transmission only. The exiting coaxial backbone can be used to deliver content to individual rooms. Then, UWB wireless transmission provides coverage within each room. Pulselink[11] and Sigma Designs[12] both offer UWB over cable solutions. The technology behind Pulelink's is proprietary CWave Technology while Sigma Designs advocates its WiMedia-based solution.

1.11 UWB Sweet Spots

Each wireless technology shines in some application space (Fig. 1.7). For instance, ZigBee's forte is in low data rate throughput applications of up to 250 kbps and ranges upto 10 m. WiFi shines in Internet delivery applications with rates in tens of megabits per second and ranges upto 100 m. From what we have seen here so far, it appears that UWB will be a great candidate in short ranges for very high-throughputs upto perhaps 1 Gbps. UWB is also a good candidate for low data rate applications (up to 3 Mbps) with longer ranges (30–50 m).

What We Learned

- The two definitions of UWB signal and their differences.
- The regulatory history of UWB and FCC First Report and Order.
- Various applications of UWB technology; corresponding spectral limits; and the usage restrictions.
- Differences between UWB regulations in the US and other countries.
- Relationship between DSA and UWB as well as overlay/underlay classification of UWB.

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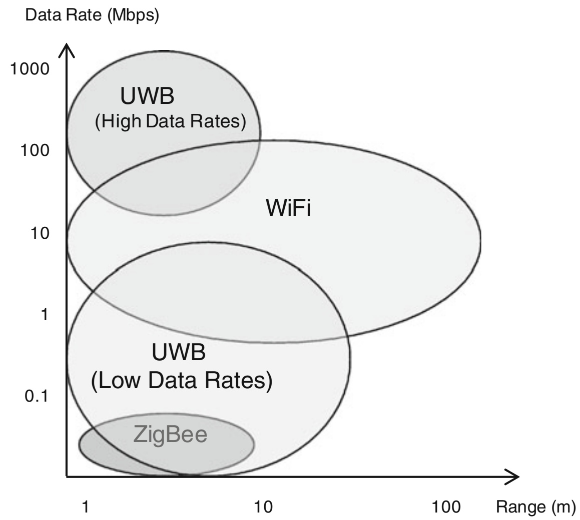
[11] http://pulselink.com/

[12] http://www.sigmadesigns.com/. It appears that UWB-based solutions are not offered any longer.

Fig. 1.7 Wireless systems position



- Link budget and capacity calculations for UWB systems.
- Fine resolution capability and multipath resilience properties of UWB systems.
- The sweet spots for UWB technology.

Problems

1. The mathematical definition for the Gaussian pulse and Gaussian monocycle pulse is given as

$$g_0(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}}$$

and

$$g_1(t) = -\frac{t}{\sqrt{2\pi}\sigma^3} e^{-\frac{t^2}{2\sigma^2}}.$$

Find the 10 dB bandwidth and fractional bandwidth of the two pulses when $\sigma = 0.0353$ ns.

2. Does either of the two pulses in problem 1 fit the FCC indoor mask?
3. Find the capacity of a UWB system that utilizes the band ranging from 3.1 to 5.1 GHz. Compare the system capacity with that of another UWB system that operates between 5.1 and 7.1 GHz. Can you draw any conclusions?
4. A UWB system utilizes the spectrum ranging from 4 to 5 GHz. Can this system support a range of 4 m with a data rate of 300 Mbps? Justify any assumptions that you make.

5. Compare the transmission range of low-band and high-band options of DS-UWB systems.
6. A UWB communication system occupies the frequency range from 3.1 to 4.6 GHz. Another UWB system with 4 GHz of bandwidth is devised to have a transmission range identical to that of the other system. Determine the lower/upper 10 dB frequencies of this system.

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