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Basic properties of UWB signals and systems

1.1 INTRODUCTION

In this chapter the basic properties of UWB signals and systems are outlined, with details of each of the characteristics being explained in later chapters.

First, we examine the basic shape of an UWB pulse in the time domain and see what the spectrum content is of these pulses. Generally speaking, the extremely short pulses with fast rise and fall times have a very broad spectrum and a very small energy content. We examine the regulatory aspects of power output and frequency by spectral masks.

Next, we see that because UWB pulses are extremely short they can be filtered or ignored. They can readily be distinguished from unwanted multipath reflections because of the fine time resolution. This leads to the characteristic of multipath immunity.

Furthermore, the low-frequency components of the UWB pulses enable the signals to propagate effectively through materials such as bricks and cement.

The large bandwidth of UWB systems means extremely high data rates can be achieved, and we show that UWB systems have a potentially high spectral capacity.

UWB transmitters and receivers do not require expensive and large components such as modulators, demodulators, and intermediate frequency (IF) stages. This fact can reduce cost, size, weight, and power consumption of UWB systems compared with conventional narrowband communication systems.

1.2 POWER SPECTRAL DENSITY

The power spectral density (PSD) of UWB systems is generally considered to be extremely low, especially for communication applications. The PSD is defined as

$$\text{PSD} = \frac{P}{B} \quad (1.1)$$

where P is the power transmitted in watts, B is the bandwidth of the signal in hertz, and the unit of PSD is watts/hertz.

Historically, wireless communications have only used a narrow bandwidth and can hence have a relatively high power spectral density. We can put this another way: since we know that frequency and time are inversely proportional, sinusoidal systems have narrow B and long time duration t . For a UWB system, the pulses have a short t and very wide bandwidth B . It is helpful to review some traditional wireless broadcast and communication applications, and to calculate their PSDs as shown in Table 1.1.

Table 1.1 PSD of some common wireless broadcast and communication systems.

System	Transmission power	Bandwidth	PSD [W/MHz]	Classification
Radio	50 kW	75 kHz	666 600	Narrowband
Television	100 kW	6 MHz	16 700	Narrowband
2G Cellular	500 mW	8.33 kHz	60	Narrowband
802.11a	1 W	20 MHz	0.05	Wideband
UWB	0.5 mW	7.5 GHz	6.670×10^{-8}	Ultra wideband

The energy used to transmit a wireless signal is not infinite and, in general, should be as low as possible, especially for today's consumer electronic devices. If we have a fixed amount of energy we can either transmit a great deal of energy density over a small bandwidth or a very small amount of energy density over a large bandwidth. This comparison is shown for the PSD of two systems in Figure 1.1. The total amount of power can be calculated as the area under a frequency–PSD graph.

For UWB systems, the energy is spread out over a very large bandwidth (hence the name ultra wideband) and, in general, is of a very low PSD. The major exception to this general rule of thumb is UWB radar systems, which transmit at high power over a large bandwidth. However, here we will restrict ourselves to the communications area.

One of the benefits of low PSD is a *low probability of detection*, which is of particular interest for military applications, such as covert communications and radar. This is also a concern for wireless consumer applications, where the security of data for corporations and individuals using current wireless systems is considered to be insufficient [8].

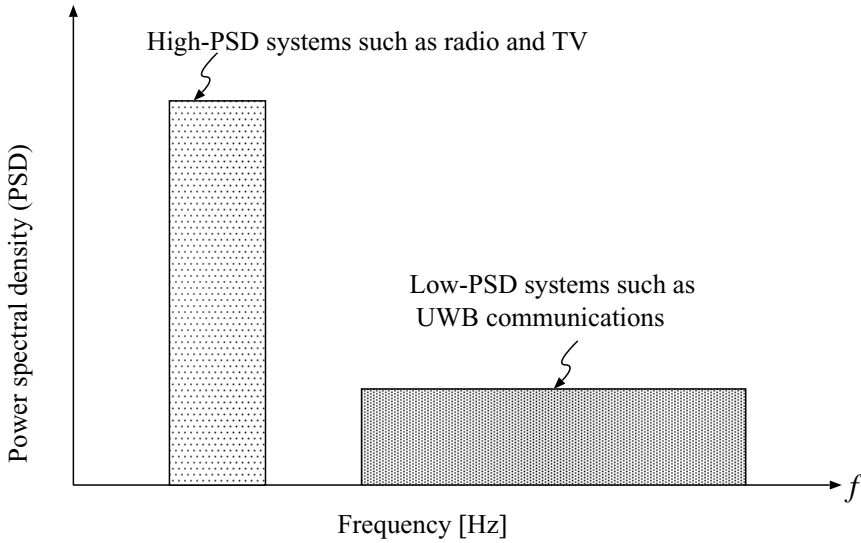


Fig. 1.1 Low-energy density and high-energy density systems.

1.3 PULSE SHAPE

A typical received UWB pulse shape, sometimes known as a *Gaussian doublet*, is shown in Figure 1.2. More details regarding Gaussian and other waveforms are discussed in Chapters 2 and 6. This pulse is often used in UWB systems because its shape is easily generated. It is simply a square pulse which has been shaped by the limited rise and fall times of the pulse and the filtering effects of the transmit and receive antennas. A square pulse can be easily generated by switching a transistor on and off quickly.

We show a simple pulse generator model in Figures 1.3 and 1.4, which demonstrate the creation of Gaussian doublets at a transmitter, antenna effects and reception. We start with a rectangular pulse in Figure 1.4(a). UWB pulses are typically of nanosecond or picosecond order. The fast switching on and off leads to a pulse shape which is not rectangular, but has the edges smoothed off. The pulse shape approximates the Gaussian function curve. A Gaussian function $G(x)$ is one which fits the well-known equation

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-x^2/2\sigma^2} \quad (1.2)$$

where Equation (1.2) is assumed to be zero-mean. This is the origin of the name Gaussian pulse, monocycle or doublet. A simple circuit for creation of the Gaussian doublet is shown in Figure 1.3. Transmitting the pulses directly to the antennas results in the pulses being filtered due to the properties of the antennas. This filtering operation can be modeled as a derivative operation [9]. The same effect occurs at

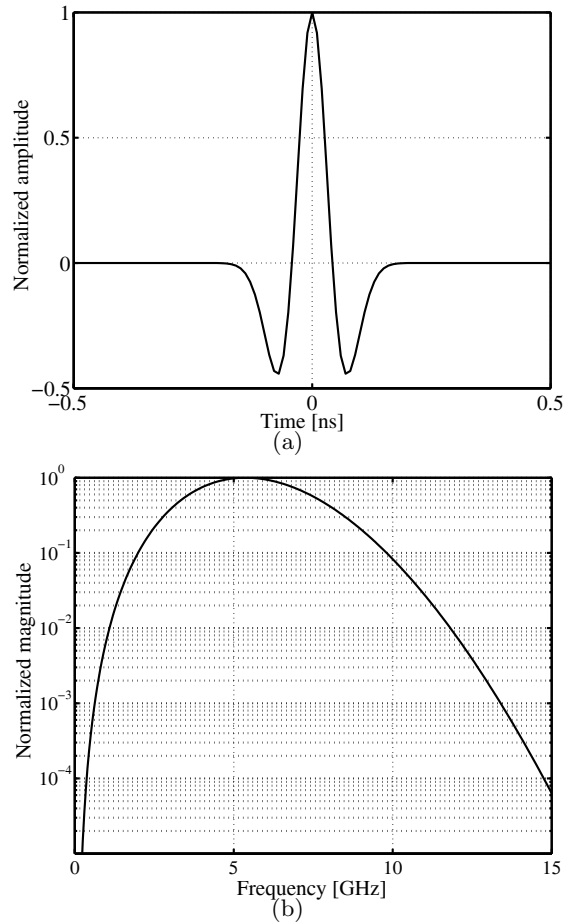


Fig. 1.2 (a) Idealized received UWB pulse shape p_{rx} and (b) idealized spectrum of a single received UWB pulse.

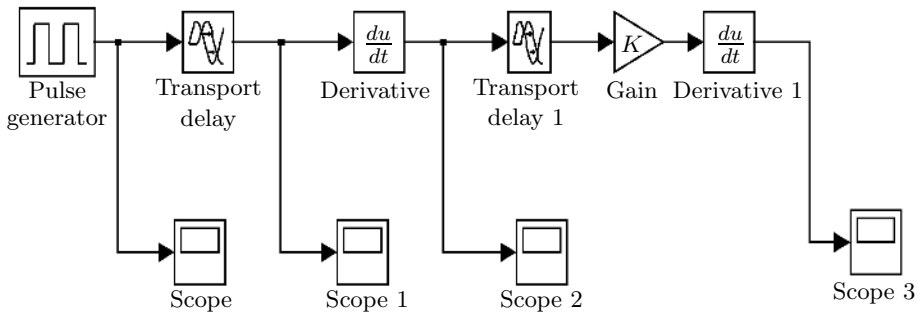


Fig. 1.3 A simple Matlab circuit model to create the Gaussian doublet.

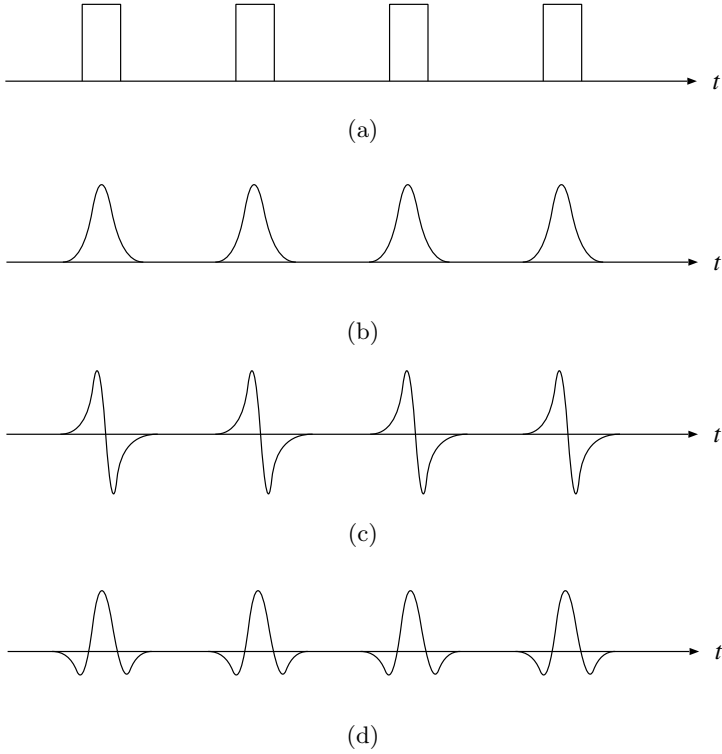


Fig. 1.4 Details of the pulses generated in a typical UWB communication system: (a) square pulse train; (b) Gaussian-like pulses; (c) first-derivative pulses; (d) received Gaussian doublets.

the receive antenna. Here, we model the channel as a delay and assume the pulse is amplified at the receiver.

In this chapter we will limit our discussion to this typical received pulse shape, which is assumed for the large majority of UWB research and is reasonably close to received pulses that have been measured. Details of pulse generation and a detailed discussion of pulse shaping can be found in Chapters 2 and 6.

This idealized received pulse shape p_{rx} can be written as [10]

$$p_{rx} = \left[1 - 4\pi \left(\frac{t}{\tau_m} \right)^2 \right] e^{-2\pi(t/\tau_m)^2} \quad (1.3)$$

which is the equation used to generate the pulse shown in Figure 1.2(a). Here, τ_m is assumed to be 0.15. It should be mentioned that τ_m is the single parameter of Equation (1.3) and determines the time and frequency characteristics of the Gaussian doublet uniquely.

The spectrum of the Gaussian doublet is shown in Figure 1.2(b). The center frequency can be seen to be approximately 5 GHz, with the 3 dB bandwidth extending over several GHz. In comparison with narrowband or even wideband communication systems the large bandwidth is evident and, hence, the name ultra wideband communication can easily be inferred.

1.4 PULSE TRAINS

One pulse by itself does not communicate a lot of information. Information or data needs to be modulated onto a sequence of pulses called a *pulse train*.

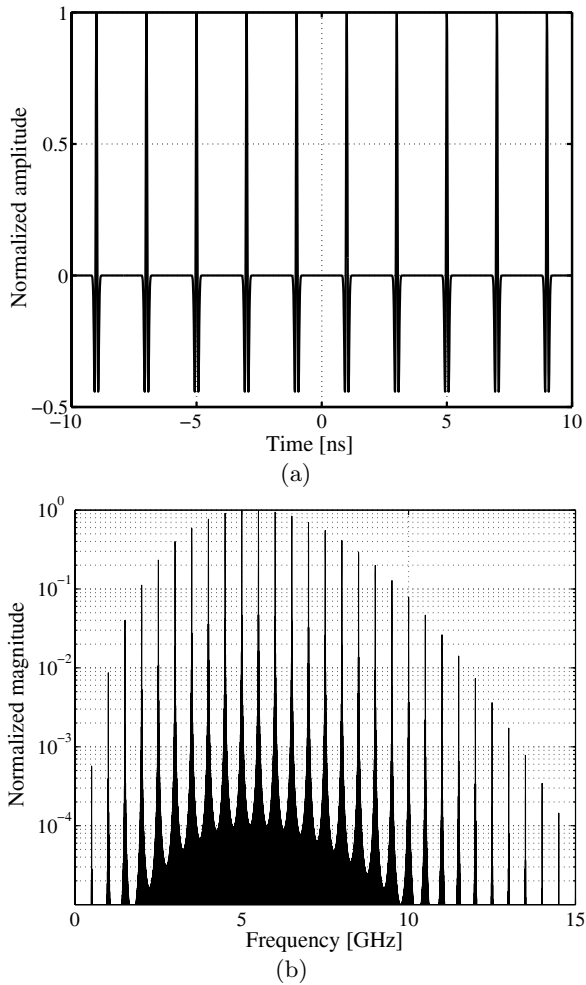


Fig. 1.5 (a) UWB pulse train and (b) spectrum of a UWB pulse train.

When pulses are sent at regular intervals, which is sometimes called the *pulse repetition rate* or the *duty cycle*, the resulting spectrum will contain peaks of power at certain frequencies. These frequencies are the inverse of the pulse repetition rate. These peak power lines are called *comb lines* because they look like a comb. See Figure 1.5(b) for an example.

These peaks limit the total transmit power undesirably. One method of making the spectrum more noise-like is to ‘dither’ the signal by adding a small random offset to each pulse, either delaying the pulse or transmitting slightly before the regular pulse time. The resultant spectrum from such a random offset is shown in Figure 1.6 and should be compared with Figure 1.5(b).

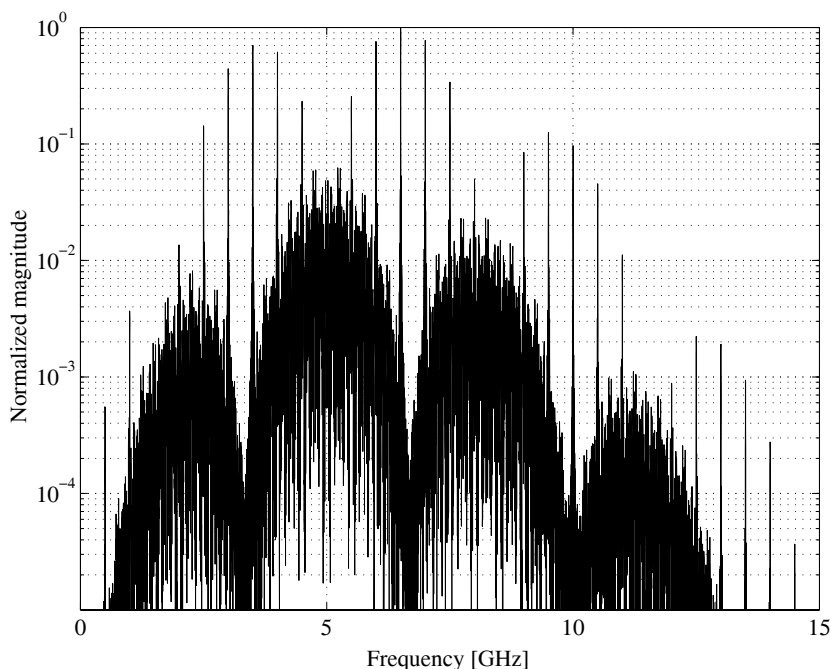


Fig. 1.6 Spectrum of a pulse train which has been ‘dithered’ by shifting pulses forward and backward of the original position.

As we will see in Chapter 5, by making this delay not completely random but cyclic according to a known pseudo-noise (PN) code, information can be modulated onto the pulse waveform. This is known as *pulse position modulation* (PPM) and has been investigated in different communication systems such as optical wireless communications.

1.5 SPECTRAL MASKS

The spectrum of a UWB signal is one of the major issues confronting the industry and governments for the commercial use of UWB. In fact, the very name ultra wideband suggests that the issue of spectrum is at the very heart of the UWB technology.

All radio communication is subject to different laws and regulations about power output in certain frequency bands. This is to prevent interference to other users in nearby or the same frequency bands.

UWB systems cover a large spectrum and interfere with existing users. In order to keep this interference to a minimum, the FCC and other regulatory groups specify *spectral masks* for different applications, which show the allowed power output for specific frequencies.

In Figure 1.7 an example is shown of the FCC spectral mask for indoor UWB systems. A large contiguous bandwidth of 7.5 GHz is available between 3.1 GHz and 10.6 GHz at a maximum power output of -41.3 dBm/MHz.

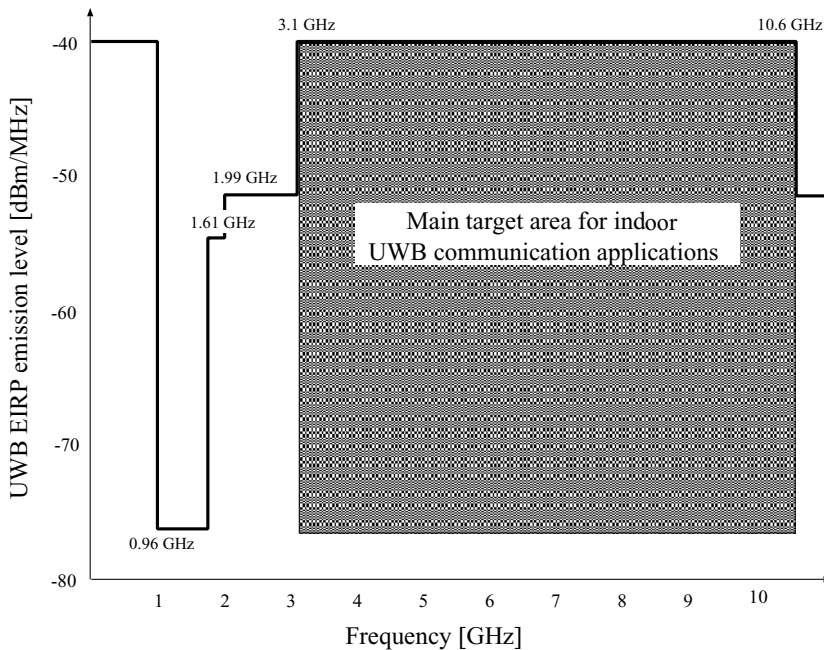


Fig. 1.7 Spectral mask mandated by FCC 15.517(b,c) for indoor UWB systems.

The major reasons for the extremely low allowed power output in the frequency bands 0.96–1.61 GHz is due to pressure from groups representing existing services, such as mobile telephony, GPS, and military usage. The allowed level of -41.3 dBm/MHz itself is considered conservative, and many groups have lobbied for higher allowed power output.

1.6 MULTIPATH

In this section we will look at the effects of multipath, particularly in an indoor wireless channel, on the basic UWB pulse we have described. We will see that, because of the extremely short pulse widths, if these pulses can be resolved in the time domain then the effects of multipath, such as *inter-symbol interference* (ISI), can be mitigated.

Multipath is the name given to the phenomenon at the receiver whereby after transmission an electromagnetic signal travels by various paths to the receiver. See Figure 1.8 for an example of multipath propagation within a room. This effect is caused by reflection, absorption, diffraction, and scattering of the electromagnetic energy by objects in between the transmitter and the receiver. If there were no objects to absorb or reflect the energy, this effect would not take place and the energy would propagate outward from the transmitter, dependent only on the transmit antenna characteristics. However, in the real world, objects between the transmitter and the receiver cause the physical effects of reflection, absorption, diffraction, and scattering, and this gives rise to multiple paths. Due to the different lengths of the paths, pulses will arrive at the receiver at different times, with the delay proportional to the path length.

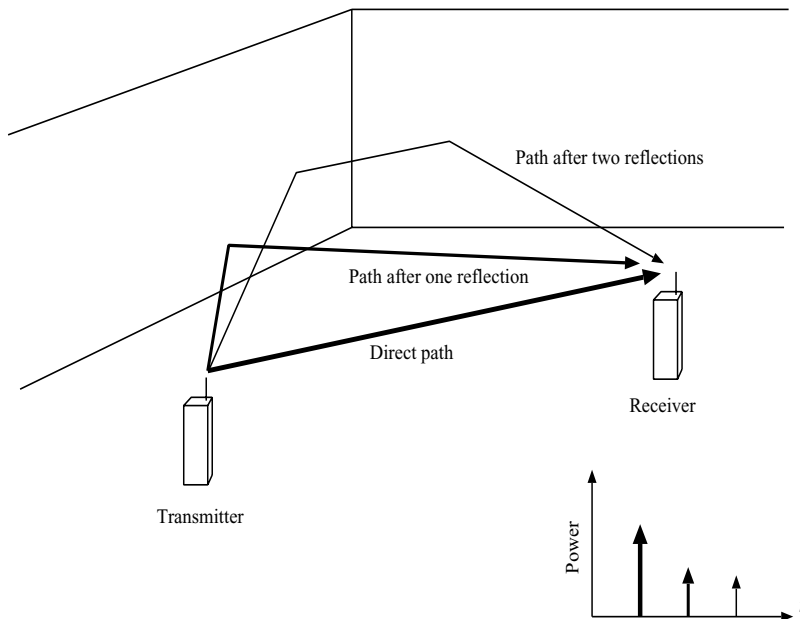


Fig. 1.8 A typical indoor scenario in which the transmitted pulse is reflected off objects within the room, thus creating multiple copies of the pulse at the receiver, with different delays.

UWB systems are often characterized as *multipath immune* or *multipath resistant*. Examining the pulses described previously, we can see that if pulses arrive within

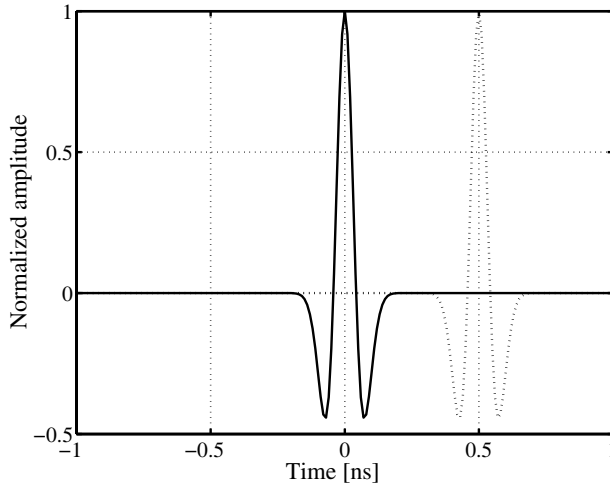


Fig. 1.9 Two pulses arriving with a separation greater than the pulse width will not overlap and will not cause interference.

one pulse width they will interfere, while if they are separated by at least one pulse width they will not interfere. If pulses do not overlap, then they can be filtered out in the time domain or, in other words, ignored. Assuming one symbol per pulse, they will not produce interference with the same symbol. Alternatively, the energy can be summed together by a *rake receiver*. Figures 1.9 and 1.10 demonstrate nonoverlapping and overlapping pulses, respectively.

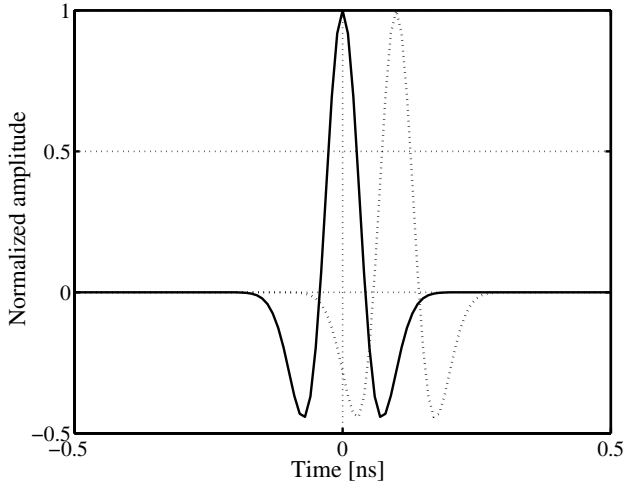
Example 1.1

Assuming a received pulse shape similar to Figure 1.2, how much extra distance must a second pulse travel to not interfere with the original pulse? If the pulse width was halved, what would be the separation between multiple paths needed?

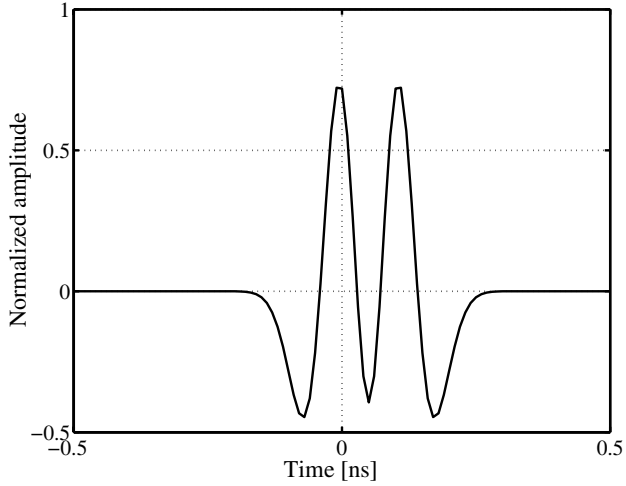
Solution

From Figure 1.2 the pulse width is approximately 0.4 ns. Using the relation that distance is the product of velocity with time travelled, $d = v \cdot t$, and since electromagnetic energy travels at a velocity of approximately 3×10^8 m/s, the extra distance travelled via the second path to avoid interference at the receiver is 12 cm. If the pulse width was halved, the required distance between multipaths to avoid interference would be halved also, to 6 cm.

As we can see from Example 1.1 the separation distance required between multipaths decreases with decreasing pulse width. This is one reason for smaller pulse widths, particularly in indoor environments.



(a)



(b)

Fig. 1.10 (a) Two overlapping UWB pulses, and (b) the received waveform consisting of the overlapped pulses.

Another method to avoid multipath interference is to lower the duty cycle of the system. By transmitting pulses with time delays greater than the maximum expected multipath delay, unwanted reflections can be avoided at the receiver. This is inherently inefficient and places limits on the maximum speed of data transmission for a given modulation system. In the limit, if pulses were transmitted continuously, then the system would resemble a sinusoidal system. These issues are discussed in Chapter 5.

1.7 PENETRATION CHARACTERISTICS

One of the most important benefits of the UWB communication system that has been raised is the ability of pulses to easily penetrate walls, doors, partitions, and other objects in the home and office environment. In this section we will examine the reported results for penetration of UWB pulses and comment on how these will affect communication in the home and office.

Frequency f and wavelength λ are related by the speed of light c as is shown in the following well-known equation:

$$\lambda [m] = \frac{c [\text{m/s}]}{f [\text{Hz}]} \quad (1.4)$$

In other words, as the frequency increases the wavelength becomes shorter, and for lower frequencies the wavelength is longer.

In conventional sinusoidal communication, lower frequency waves have the characteristic of being able to ‘pass through’ walls, doors, and windows because the length of the wave is much longer than the material that it is passing through. On the other hand, higher frequency waves will have more of their energy reflected from walls and doors since their wavelength is much shorter.

UWB pulses are composed of a large range of frequencies, as is shown in Figure 1.2(b). One of the basic characteristics of early prototype UWB communication systems was their ability to ‘pass through walls’, especially in comparison with IEEE 802.11 wireless local area network (WLAN) systems. The penetration capabilities of UWB come only from the lower frequency components which were, for early systems, mostly centered on 1 GHz. Since the 2002 ruling by the FCC (see Figure 1.7), the center frequency for most UWB systems has substantially increased. This means that the penetration characteristics of the signals have substantially decreased, especially in comparison with the IEEE 802.11b systems which are centered at 2.4 GHz.

1.8 SPATIAL AND SPECTRAL CAPACITIES

Another basic property of UWB systems is their high *spatial capacity*, measured in bits per second per square meter [bps/m²] [11]. Spatial capacity is a relatively recent term, and its use stems from the interest in even higher data rates, even over extremely short distances.

Spatial capacity can be calculated as the maximum data rate of a system divided by the area over which that system can transmit. The transmission area can be calculated from the circular area, assuming a transmitter in the center; however, in practice a rule of thumb is to use the square of the maximum transmission distance:

$$\text{Spatial capacity [bps/m}^2] = \frac{\text{Maximum data rate [bps]}}{\text{Transmission area [m}^2]} \quad (1.5)$$

$$\text{Transmission area [m}^2] = \pi \times (\text{Transmission distance})^2 \quad (1.6)$$

Table 1.2 Comparison of the spatial capacity of various indoor wireless systems.

System name	Maximum data rate [Mbps]	Transmission distance [m]	Spatial capacity [kbps/m ²]	Spectral capacity [bps/Hz]
UWB	100	10	318.3	0.013
IEEE 802.11a	54	50	6.9	2.7
Bluetooth	1	10	3.2	0.012
IEEE 802.11b	11	100	0.350	0.1317

For narrowband systems the most popular measure of capacity has been *spectral capacity*, measured in bits per second per hertz (bps/Hz), because the spectrum has been the most limited resource. Power has generally only been limited by safety and commercial reasons, such as the battery life of mobile devices:

$$\text{Spectral capacity [bps/Hz]} = \frac{\text{Maximum data rate [bps]}}{\text{Bandwidth [Hz]}} \quad (1.7)$$

For UWB systems, which operate in other licensed spectra, the power has to be kept very low. This is compensated for by the use of extremely large bandwidths. Using the traditional measure of spectral capacity [bits/Hz], UWB has very low spectral capacity compared with existing systems. However, when comparing spatial capacity, UWB is extremely efficient. Table 1.2 shows a comparison of spatial and spectral capacity among various indoor wireless systems.

1.9 SPEED OF DATA TRANSMISSION

One of the advantages of UWB transmission for communications is its high data rate. While current chipsets are continually being improved, most UWB communication applications are targeting the range of 100–500 Mbps [12], which is roughly the equivalent of wired Ethernet to USB 2.0. It is significant that this data rate is 100 to 500 times the speed of Bluetooth, around 50 times the speed of the 802.11b, or 10 times the 802.11a WLAN standards.

As can be seen in Table 1.3 the current target data rate for indoor wireless UWB transmission is between 110 Mbps and 480 Mbps. This is fast compared with current wireless and wired standards. In fact, the speed of transmission is currently being standardized into three different speeds: 110 Mbps with a minimum transmission distance of 10 m; 200 Mbps with a minimum transmission distance of 4 m; and 480 Mbps with no fixed minimum distance.

The reasons for these particular distances lie mostly with different applications. For example, 10 m will cover an average room and may be suitable for wireless connectivity for home theater. A distance of less than 4 m will cover the distance

Table 1.3 Comparison of UWB bit rate with other wired and wireless standards.

Speed [Mbps]	Standard
480	UWB, USB 2.0
200	UWB (4 m minimum), 1394a (4.5 m)
110	UWB (10 m minimum)
90	Fast Ethernet
54	802.11a
20	802.11g
11	802.11b
10	Ethernet
1	Bluetooth

between appliances, such as a home server and a television. A distance of less than 1 m will cover the appliances around a personal computer.

1.10 COST

Among the most important advantages of UWB technology are those of low system complexity and low cost. UWB systems can be made nearly ‘all-digital’, with minimal radiofrequency (RF) or microwave electronics. The low component count leads to reduced cost, and smaller chip sizes invariably lead to low-cost systems. The simplest UWB transmitter could be assumed to be a pulse generator, a timing circuit, and an antenna.

However, as higher data rates are required, more complex timing circuitry is needed. To provide a multiple access system, additional complexity is required. Rake receivers add further circuitry, and the cost increases. Furthermore, chipset costs depend heavily on the number of units manufactured.

To reduce costs, during later product cycles more functionality is implemented on fewer chips, reducing die area and, thus, manufactured cost.

Therefore, at this early stage it is extremely difficult to quantify the cost of UWB communication systems. To take one early example, it has been reported [13] that the XtremeSpectrum chipset is priced at US\$19.95 for 100 000 units.

1.11 SIZE

The small size of UWB transmitters is a requirement for inclusion in today’s consumer electronics. In the 802.15 working groups, consumer electronics companies have targeted the size of the wireless circuit to be small enough to fit into a Memory Stick or secure digital (SD) Card [12]. A chipset by XtremeSpectrum has a small size which enables compact flash implementation [13].

The main arguments for the small size of UWB transmitters and receivers are due to the reduction of passive components. However, antenna size and shape is another factor that needs to be considered. UWB antennas are considered in Chapter 7.

1.12 POWER CONSUMPTION

With proper engineering design the resultant power consumption of UWB can be quite low. As with any technology, power consumption is expected to decrease as more efficient circuits are designed and more signal processing is done on smaller chips at lower operating voltages.

The current target for power consumption of UWB chipsets is less than 100 mW. Table 1.4 shows some figures for power consumption of current chipsets [12].

Table 1.4 Power consumption of UWB and other mobile communication chipsets (LSI, large scale integration; RISC, reduced instruction set computer; MPU, microprocessor unit; TFT, thin film transistor).

Application chipset	Power consumption [mW]
802.11a	1500–2000
400 Mbps 1394 LSI	700
Mobile telephone RISC 32-bit MPU	200
Digital camera 12-bit A/D converter	150
UWB (target)	100
Mobile telephone TFT color display panel	75
MPEG-4 decoder LSI	50
Mobile telephone voice codec LSI	19

1.13 SUMMARY

In this chapter the basic properties of UWB signals were outlined, starting with the basic shape and spectrum of an UWB pulse. We saw that the power output and spectrum of UWB pulses are limited by regulation.

We showed that because UWB pulses are extremely short, with the consideration of fading, they can be filtered or ignored. They can readily be distinguished from unwanted multipath reflections because of the fine time resolution. This leads to the characteristic of multipath immunity.

The low-frequency components of the UWB pulses enable the signals to propagate effectively through materials, such as bricks and cement.

The large bandwidth of UWB systems means extremely high data rates can be achieved, and we showed that UWB systems have a potentially high spectral capacity.

Finally, we stated that UWB transmitters and receivers do not require expensive and large components, such as modulators, demodulators, and IF stages. This fact

can reduce cost, size, weight, and power consumption of UWB systems compared with conventional narrowband communication systems.

Problems

Problem 1. Investigate the transmission power and bandwidth of three systems *not* shown in Table 1.1. (*Hint:* radio and television systems may differ significantly from those shown in the table due to differing local conditions.) Calculate their power spectral densities.

Problem 2. Implement the Matlab circuit of Figure 1.3, and confirm the output of the four scopes. Apply some modifications to the circuit if necessary.

Problem 3. Based on the Matlab circuit of Figure 1.3, implement a three-path multipath channel model. Add Gaussian noise. Show the output of the four scopes for two different values of delay of the second and third paths. Comment on the effect of multipath on the receiver and receiver design.

Problem 4. Write a Matlab program to output Figures 1.5(a) and 1.5(b).

Problem 5. Investigate the current FCC (or the regulator in your own country) regulations for UWB applications. What differences or similarities can you find with Figure 1.7?

Problem 6. Investigate and calculate the spatial and spectral capacities of three other wireless systems (outdoor wireless systems are acceptable) *not* shown in Table 1.2.

Problem 7. Investigate the reported speed of at least five current commercial UWB communication or laboratory prototypes. Plot a graph, with time as the horizontal axis and speed as the vertical axis.

Problem 8. Find the cost of five different wireless chipsets. Compare and contrast the complexity of the chipset, the maturity of the system, and the cost of the chipset. What, in your opinion, is the dominating factor for the cost of wireless chipsets?

Problem 9. For one standard or system (for example, UWB or IEEE standard 802.11a) find the cost of five commercial products. What fraction of the total product cost is contained in the wireless chipset?