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Why UWB?
A Review of Ultrawideband Technology

Report to NETEX Project Office, DARPA

by

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Why UWB?

1. Introduction*

This report, prepared by the Wireless Communication Technologies Group of the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, is intended to provide a perspective on the use of ultra-wideband (UWB) radio technology by evaluating the technical issues that are connected with the use of that technology. The report is funded in part by the Defense Advanced Research Projects Agency (DARPA) under the "Networking in the Extreme" (NETEX) program.

1.1 Background

Having started Phase I of the NETEX program, the DARPA program office is seeking compelling arguments for justifying and selecting Phase II efforts in anticipation of program review. In particular, it is desired to develop a presentation that identifies the unique suitability of UWB technology for the NETEX applications and environment. To introduce the technical issues that are involved, we review the goals of the NETEX program and the stated characteristics of the objective system.

1.1.1 Program Goals

The goal of the NETEX program[1] is the development of "robust and rapid wireless networking in complex, hostile environments using UWB technology." The meanings of the several descriptive words in this statement of the project goal were given as follows:

- *Robust* means a networking scheme and implementation that has immunity to channel fading and equipment outages.
- *Complex* means an operational environment that is relatively harsh to radio communications and/or is subject to the scenario- and location-dependent propagation properties, such as dense urban, indoor, and aboard-ship situations.
- *Hostile* means an environment that necessitates operation with low probability of detection to avoid jamming.
- *Rapid* means networking that can be configured "on the fly" as *ad hoc* networks and without reserving or contending for a spectrum assignment.
- *Using UWB technology* indicates that the attributes of the operational scenario are such that UWB technology is considered to have a particular advantage in meeting the communication system performance requirements.

*Note: References in this report are indicated by superscripted numbers. Their citations are listed at the end of the report.

The advantages claimed for UWB technology for providing reliable and adequate communications in the "extreme" environment include those summarized in Table 1.1

The broad agency announcement (BAA) for the NETEX project[2] states that at the conclusion of the first phase of the project, assessments will be made to answer the following questions:

- Can UWB networks be designed to co-exist with other military radios, radars, sensors and GPS receivers?
- Can we clearly identify operational regimes where UWB performance is superior to narrowband RF systems?
- Which hardware design and implementations as well as protocols offer the maximum robustness for scalable operation in complex environments?

These statements in the BAA emphasize that research under the NETEX program should deal with real-world systems in terms of the networking environment and/or the application of UWB technology.

Table 1.1 Advantages, Disadvantages, and Applications of UWB Waveform Properties

UWB Property	Advantages	Disadvantages	Applications
Very wide fractional and absolute RF bandwidth	• High rate communications[3] • Potential for processing gain[2] • Low frequencies penetrate walls, ground[2,4]	• Potential interference to existing systems[3,5] • Potential interference from existing systems[3,4,6]	• High-rate WPAN[7] • Low-power, stealthy comms[2,4,8] • Indoor localization[2,3] • Multiple access[4]
Very short pulses	• Direct resolvability of discrete multipath components[2,4] • Diversity gain[9]	• Large number of multipaths[8] • Long synchronization times[4,10]	Low-power combined communications and localization[11]
Persistence of multipath reflections[12]	• Low fade margins[11,13] • Low power[11]	Scatter in angle of arrival[14]	NLOS communications indoors and on ships[15]
Carrierless transmission	• Hardware simplicity[2,4] • Small hardware[10]	Inapplicability of super-resolution beam-forming[13]	Smart sensor networks[10]

1.1.2 Objective System Characteristics

We quote the text of the NETEX solicitation:[2]

> With the steady advances in processing technologies, military system designers have come to realize the advantages of distributed systems. In particular, inexpensive processing power makes it possible to spread intelligence throughout a system rather than relying on a more centralized architecture. Distributed platforms generally offer increased fault tolerance, cover a greater geographic area, and support enhanced resolution coverage. Platforms such as Future Combat Systems, for example, have taken the concept of a tank and replaced it with a more capable, more survivable and more maneuverable distributed system for land battle. This trend is expected to continue in many future systems.

The promised potency of decentralized system intelligence, however, cannot be realized without a robust interconnection network tying the nodes together. To enable applications such as the deployment of distributed unattended sensors, military users are faced with the challenges of:

1. Rapidly creating robust networks in complex and hostile environments. Such networks must operate in complex and harsh physical locations including dense urban terrain, which represents the single most hazardous setting for engagement that US military forces are likely to encounter. The system must also operate in a hostile electromagnetic environment where jamming and interception attempts are assumed.

2. Coordinating the assignment of available spectrum. The problem of spectral allocation is compounded by the trend of decreasing domestic military bandwidths and by the inconsistencies of the international spectrum allocation environments.

The goal of NETEX program is to create new wireless networking technologies that address these challenges. The central focus of the program will be to advance capabilities based on ultra-wideband (UWB) radios and to exploit its unique physical layer properties to form robust, scalable networks.

1.2 Survey of UWB Waveforms

In this section we provide a sampling of the various waveforms that have been proposed for UWB communication systems, as well as mathematical models for them.

1.2.1 Waveforms

Perhaps the simplest UWB communication waveform is the monopulse, an example[16] of which is plotted in Figure 1.1. Although it is described as an idealized waveform, it does serve to illustrate the important distinction that must be made between transmitted and received

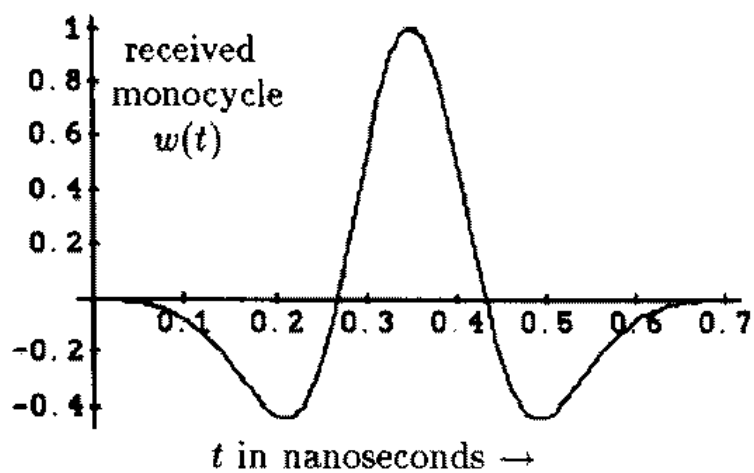
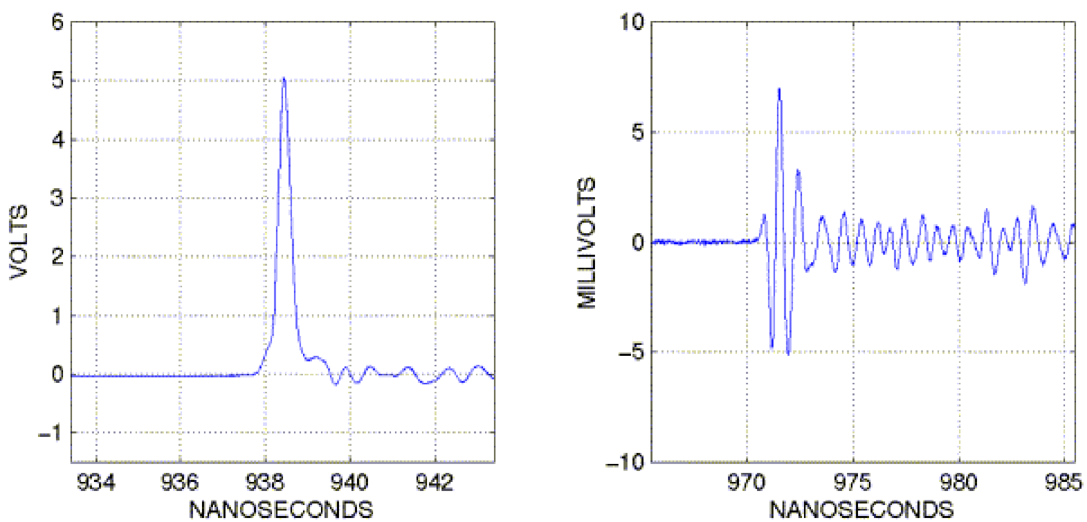


Figure 1.1 Monopulse UWB waveform (from ref. 16).

carrierless UWB waveforms, a distinction that is necessary because the effect of the transmitting and receiving antennas on the shape of the waveform as a function of time is very noticeable, unlike the case of longer duration waveforms using carriers. Without getting into the details of the physical generation of UWB waveforms, it is sufficient to note in this regard that the transmitting antenna has the general effect of differentiating the time waveform presented to it. As a consequence the transmitted pulse does not have a DC (direct current) value—the integral of the waveform over its duration must equal zero. The waveform in Fig. 1.1 satisfies this condition and therefore is a plausible model for a UWB waveform; it is ideal in the sense that, in addition to having no DC value, it has even symmetry about the peak value. In general, such symmetry is not achieved in practice, which we will illustrate in what follows with examples of actual waveforms taken from the literature.

A clear example[17] of how the antennas affect the UWB waveform is given in Figure 1.2, in which an impulse-like pulse is differentiated twice before being received. Also shown in the figure is the reception of multipath components, a characteristic feature of received UWB signals. Another example[18] of an UWB signal measurement is shown in Figure 1.3, which also indicates the bandwidth occupied by the waveform when the basic pulse is used to generate a communications signal with a baud rate of 850 Kbps.



(a) Pulser Output (b) Received Signal

Figure 1.2 Example of the effect of antennas on the UWB pulse shape (from ref. 17)

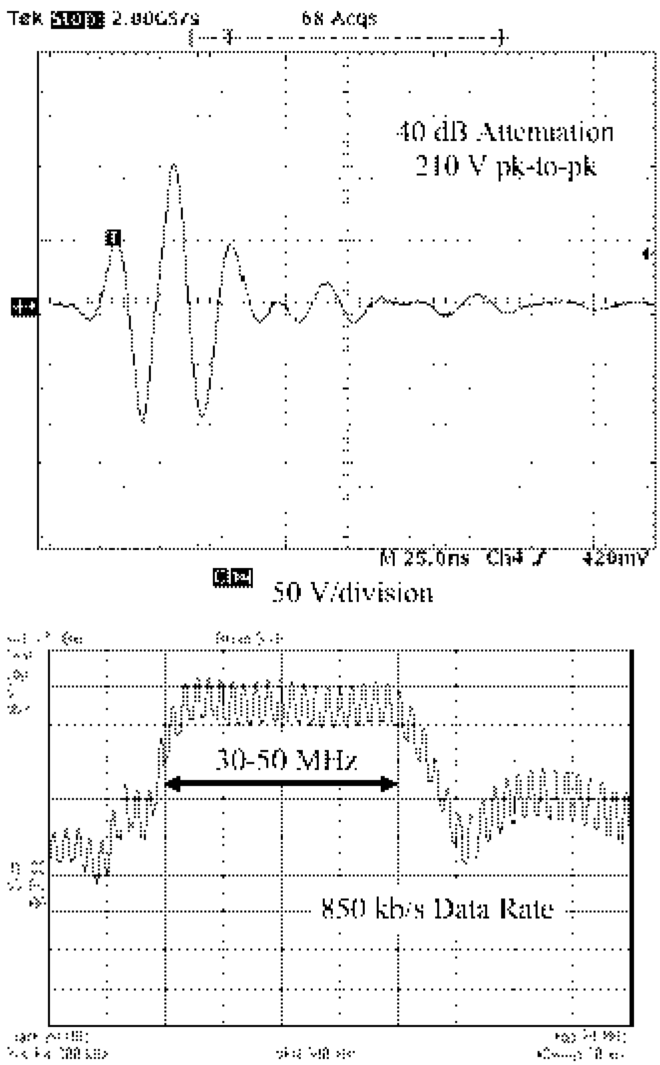


Figure 1.3 Time capture and modulated spectrum of a working UWB communication system (from ref. 18).

1.2.2 Mathematical Models of Waveforms

The monopulse waveform shown previously in Figure 1.1 is an example of the mathematical modeling of UWB pulse shapes. Another very common model is the pulse doublet[19] shown in Figure 1.4.

For analysis purposes, various idealized models and generalizations of the elemental UWB pulse waveforms have been developed. One such analytical model[20] is a "polycycle" waveform consisting of *N* cycles of a sinusoid:

$$s(t) = \begin{cases} \sin(\omega_r t), & 0 < t < NT \\ 0, & \text{otherwise} \end{cases} \tag{1.1a}$$

$$= \sin(\omega_r t)\left[u(t) - u(t - NT)\right] \tag{1.1b}$$

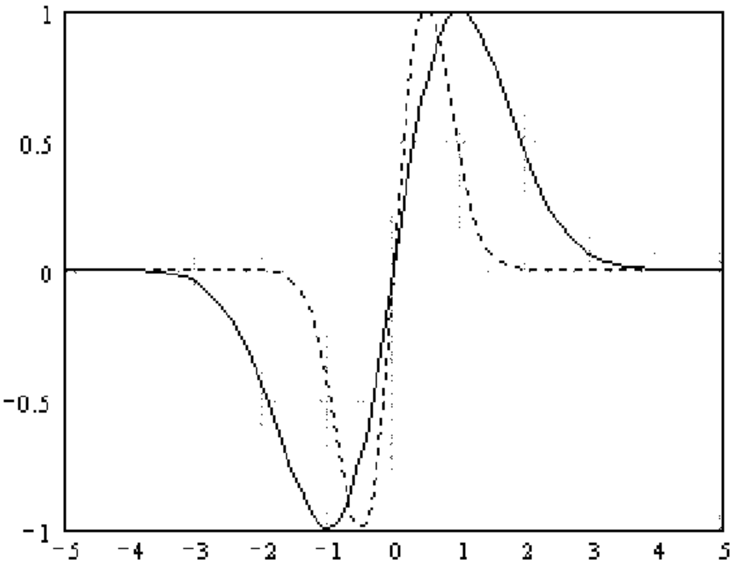


Figure 1.4 Doublet model of an UWB pulse shape (from ref. 19).

where $\omega_r = 2\pi / T$ and $u(t)$ is the unit step function. For integer values of N, the Fourier transform of this waveform is

$$S(\omega) = \left(1 - e^{-jN\omega T}\right) \frac{1/\omega_r}{1 - \left(\omega / \omega_r\right)^2} = e^{-jN\omega T/2} \sin\left(\frac{N\omega T}{2}\right) \frac{2j/\omega_r}{1 - \left(\omega/\omega_r\right)^2} \tag{1.2}$$

This gated waveform and its power spectral density are shown in Figure 1.5. Note that the spectrum is centered at the frequency of the sinusoidal burst and that the mainlobe bandwidth of the signal is inversely proportional to the number of cycles in the burst, N. The signal transitions from UWB to a conventional signal in terms of bandwidth when N is greater than four.[20] These characteristics give some freedom to position the waveform in the spectrum and could be the basis for the generation of multiple UWB frequency-division multiplex (FDM) channels[21] as in conventional communication systems.

Instead of a simple gated-on, gated-off sinusoidal model, one involving a linear-increase and a linear-decrease can be used as a model, where

$$s(t) = \sin\left(\omega_r t\right)\left[\frac{4t}{NT} u(t) - \frac{8\left(t - NT/2\right)}{NT} u\left(t - NT/2\right) + \frac{4\left(t - NT\right)}{NT} u\left(t - NT\right)\right] \tag{1.3}$$

as shown for $N = 5$ and $N = 4.5$ in Figure 1.6. Note that the waveform has a central peak when $N = M + 0.5$, where M is an integer. For N taking integer values, the Fourier transform of this waveform is given by

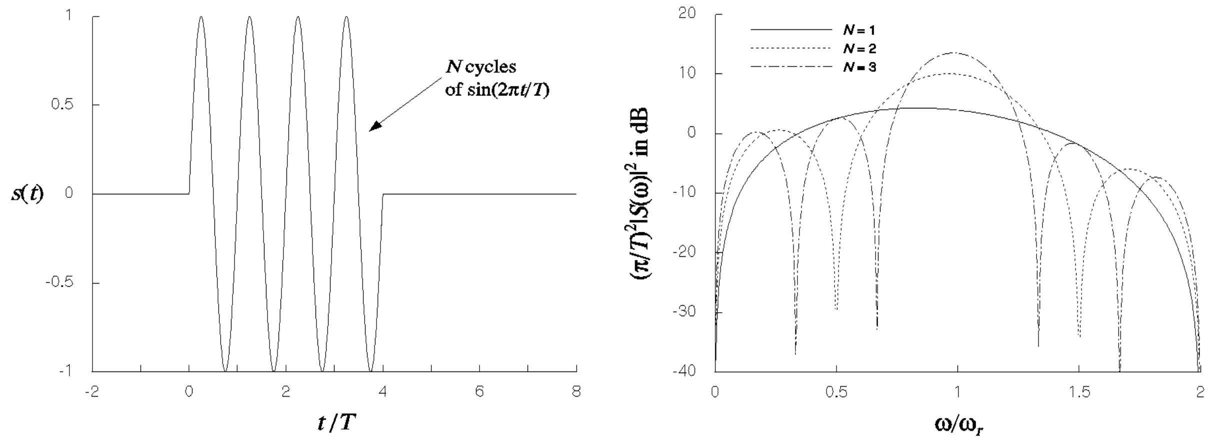
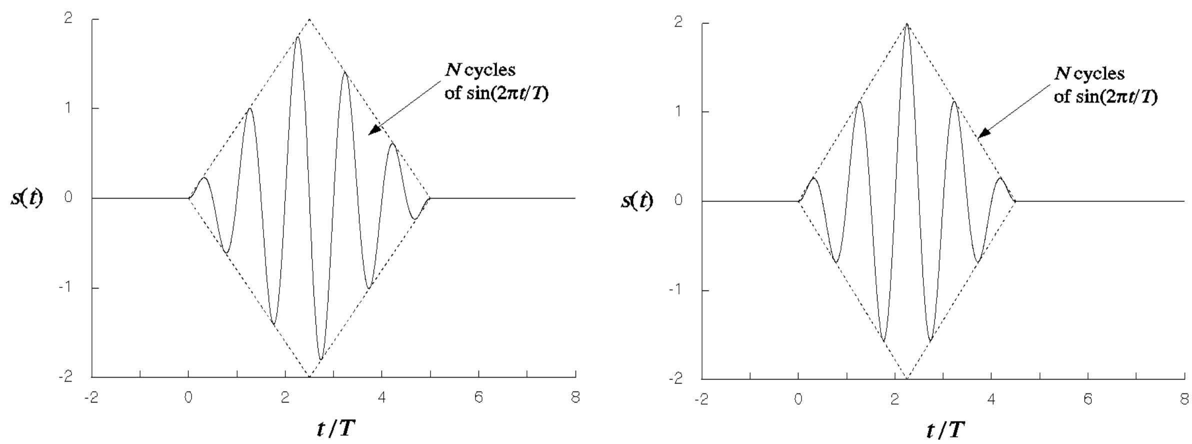


Figure 1.5 Polycycle waveform and power spectral density.



$N = 5$ $N = 4.5$

Figure 1.6 Example *N*-cycle sinusoidal bursts with triangular pulse shaping.

$$
\begin{aligned}
S(\omega) &= \left[1-(-1)^N e^{-jN\omega T/2}\right]^2 \frac{8j\omega / NT\omega_r^3}{\left[1-(\omega/\omega_r)^2\right]^2}, \quad N \text{ an integer} \\
&= e^{-jN\omega T/2} \frac{32 j\omega / NT\omega_r^3}{\left[1-(\omega/\omega_r)^2\right]^2} \times \begin{cases} -\sin^2(N\omega T/4), & N \text{ an even integer} \\ \cos^2(N\omega T/4), & N \text{ an odd integer} \end{cases}
\end{aligned}
\tag{1.4a}
$$

For a non-integer number of cycles ($N = M + 0.5$), the Fourier transform of the waveform is given by

$$
S(\omega) = \frac{8e^{-jN\omega T/2}}{NT} \cdot \frac{(-1)^M \left[1+(\omega/\omega_r)^2\right] - 2(\omega/\omega_r)\sin(N\omega T/2)}{\omega_r^2 \left[1-(\omega/\omega_r)^2\right]^2}
\tag{1.4b}
$$

Plots of the power spectra based on (1.4a) and (1.4b) are shown in Figure 1.7.

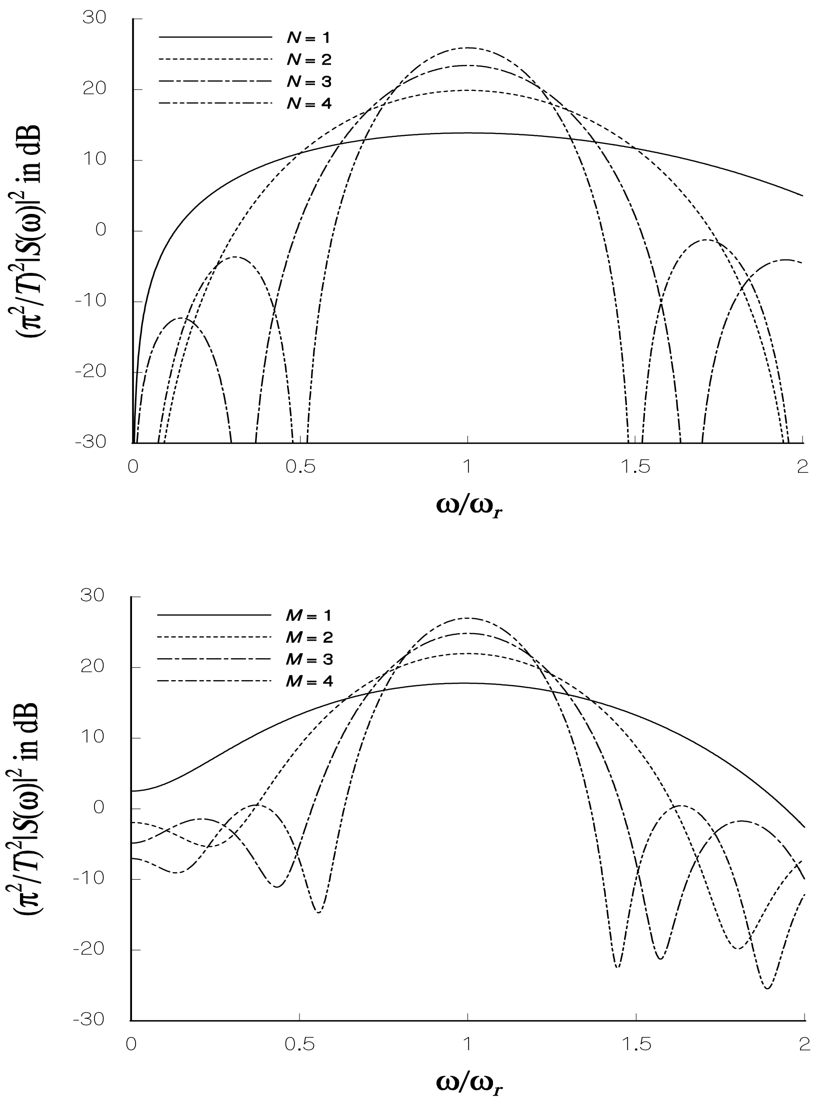


Figure 1.7 Power spectra for sinusoidal bursts with triangular pulse shaping.

Another mathematical model for UWB pulses is based on the resemblance of the so-called Gaussian pulse shape to a monopulse and the fact that its *n*th derivative has *n* zero crossings.[22] The derivatives can be expressed in terms of the original monopulse using Hermite polynomials, as shown in the following equations:

Hermite polynomials:[23]

$$He_n(x) = e^{x^2/2}(-1)^n \frac{d^n}{dx^n}\left(e^{-x^2/2}\right) \tag{1.5a}$$

where

$$He_0(x) = 1,\ He_1(x) = x,\ He_{n+1}(x) = x\,He_n(x) - n\,He_{n-1}(x) \tag{1.5b}$$

A pulse shape based on these concepts is[22]

$$g_n(t) = e^{-t^2/4} He_n(t) = e^{t^2/4}(-1)^n \frac{d^n}{dt^n}\left(e^{-t^2/2}\right) \tag{1.6a}$$

or its parameterized version[19]

$$p_n(t) \equiv p_n(t;T) = g_n(t/T) \tag{1.6b}$$

where T is a convenient measure of pulse width. The recurrence relation in (1.5b) can be applied directly to $g_n(t)$, and it can be shown that the Fourier transform of $g_n(t)$ is given by

$$G_n(\omega) = F\{g_n(t)\} = 2\sqrt{\pi}\, e^{-\omega^2} (-j)^n He_n(2\omega) \tag{1.7a}$$

with the recurrence relation

$$G_{n+1}(\omega) = -2j\omega G_n(\omega) + nG_{n-1}(\omega), \quad G_0(\omega) = 2\sqrt{\pi}\, e^{-\omega^2},\ G_1(\omega) = -2j\omega \times 2\sqrt{\pi}\, e^{-\omega^2} \tag{1.7b}$$

Examples of $g_n(t)$ and of power spectra based on $G_n(\omega)$ are shown in Figures 1.8 and 1.9, respectively. Note in Figure 1.8 that increasing n not only increases the number of zero-crossings (half-cycles by analogy with the polycycle waveforms discussed previously) but also the duration of the overall waveform. The apparent periods of the oscillations in Figure 1.8 are approximately T_n = (6.0, 5.6, 4.6, 3.8, 3.2, 2.8) for n = (0, 1, 2, 3, 4, 5), respectively.

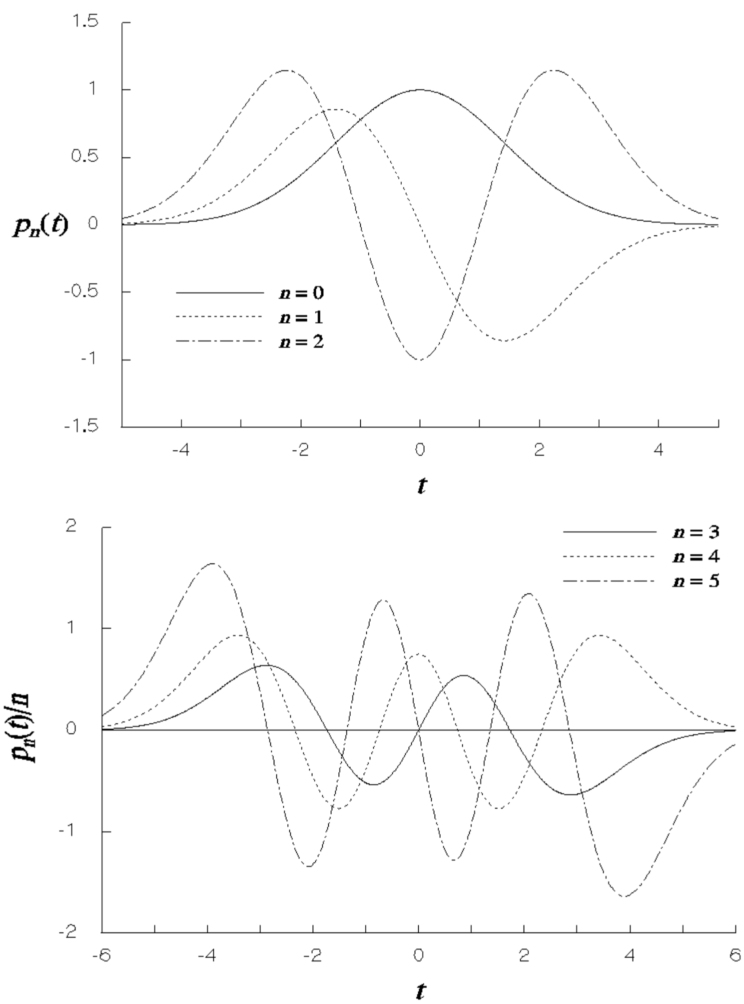
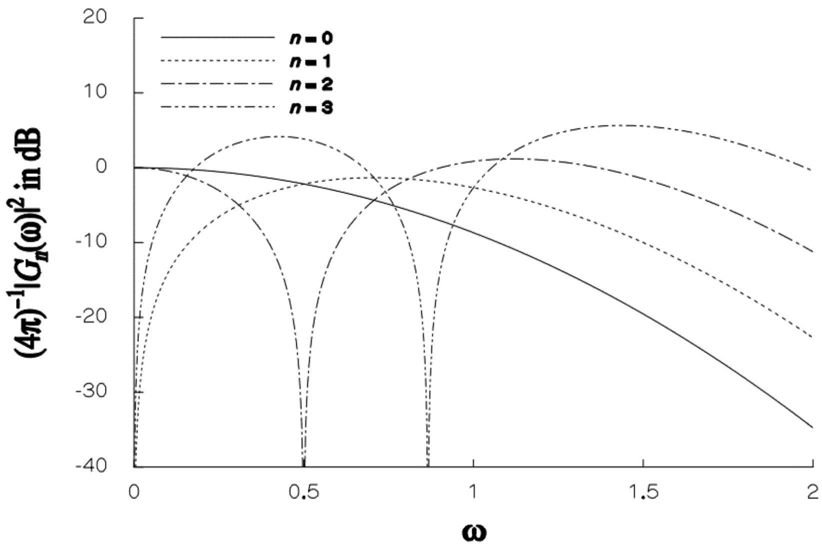
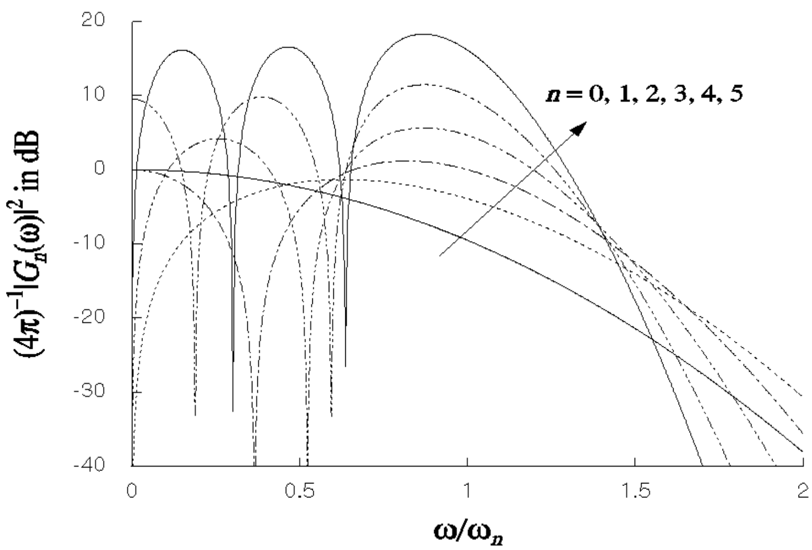


Figure 1.8 Example UWB waveforms based on Hermite polynomials.



(a) Without normalization of the angular frequency



(b) With normalization of the angular frequency by the apparent angular frequency of the oscillations.

Figure 1.9 Power spectra for UWB pulses based on Hermite polynomials.

The angular frequency in Figure 1.9 is shown without normalization in part (a) of the figure, and in part (b) it is normalized (scaled) by the apparent angular frequency $\omega_n = 2\pi / T_n$ in Figure 1.8 for each value of *n*. Similar to the spectra for polycycle waveforms in Figure 1.7, the normalization in part (b) of Figure 1.9 shows Hermite polynomial-based waveforms' spectra becoming narrower about the center frequency of $\omega = \omega_n$; however, it is clear from this figure that these waveforms are far from ideal because in addition to the central peaks in the spectra there are large sidelobes.

In one UWB implementation[10], a "Gaussian doublet" is used for the signaling waveform that is different from the doublet shown in Figure 1.4. This waveform, illustrated in Figure 1.10,

Figure 1.10 Gaussian doublet with delay between positive and negative pulses (ref. 11).

consists of a Gaussian monopulse followed by another Gaussian monopulse of opposite sign at time τ later. The Fourier transform of this waveform is given by

$$G(\omega) = 2\sqrt{\pi}\, e^{-\omega^2}\left(1 - e^{-j\omega\tau}\right) = 2\sqrt{\pi}\, e^{-\omega^2} \cdot 2 j e^{-j\omega\tau/2} \sin\left(\omega\tau/2\right) \qquad (1.8)$$

After normalizing the doublet by ½, its spectrum compares to that of the Gaussian monopulse as shown in Figure 1.11: the doublet's spectrum has nulls at zero frequency and at the values of ω satisfying $\omega\tau = 2n\pi$. It is possible that the nulls can be manipulated to occur at the frequencies of existing narrowband signals to avoid interfering with them.

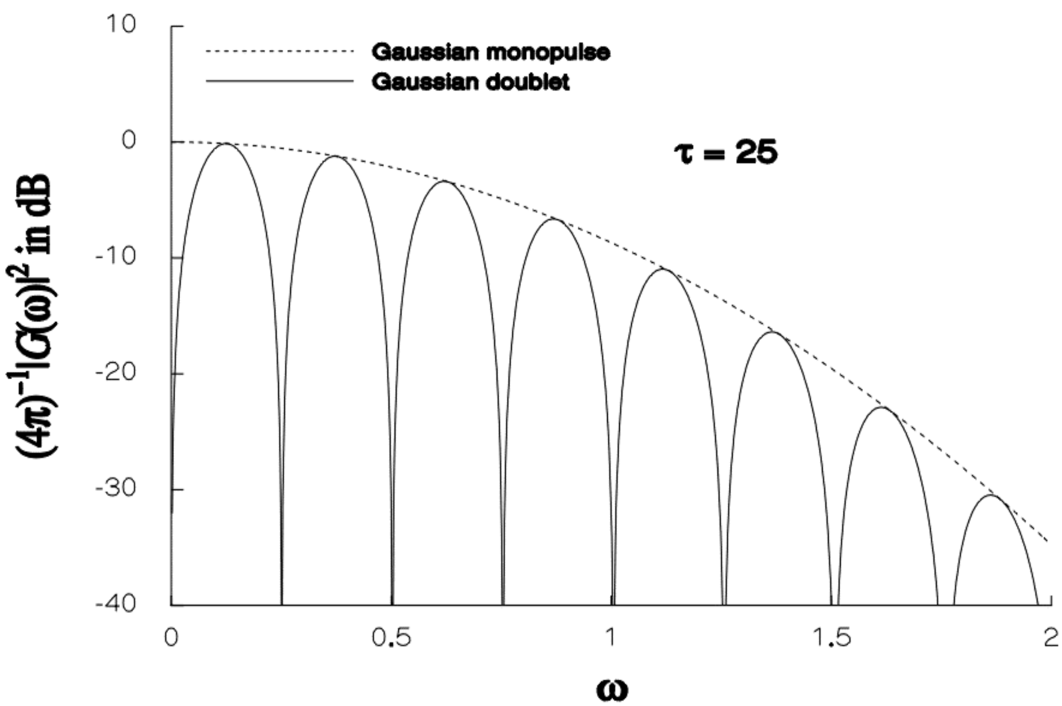


Figure 1.11 Comparison of spectrums of Gaussian monopulse and doublet.

2. Bandwidth Property of UWB Signals

2.1 Background on RF Bandwidth

Bandwidth is perhaps the most prominent characteristic of UWB communication systems, since the concept is "wideband." Although the definition[24] of "ultra-wideband" is a signal with greater than 25% relative (coherent[25]) bandwidth (sometimes termed "fractional bandwidth"[2]), it is also true that UWB signals tend to have large absolute bandwidths.

The relative bandwidth definition of UWB is stated as follows:

$$B_{rel} = \frac{f_h - f_l}{f_{avg}} = 2 \cdot \frac{f_h - f_l}{f_h + f_l} \approx \frac{W}{f_c} \quad (2.1)$$

where f_h and f_l are frequencies at the upper and lower band edges, respectively, W is the absolute bandwidth, and f_c is the center frequency. The difficulty of achieving linearity in conventional heterodyning in transmitter and receivers for greater than about 10% relative bandwidth[2] has led to the development of new signaling techniques involving nonsinusoidal waveforms.

The relative bandwidth property has a profound effect on the kind of waveform that qualifies as UWB. For example, the polycycle waveform illustrated in Figure 1.4 becomes non-UWB according to the 25% relative bandwidth criterion when the number of cycles is $N = 4$, as shown in Table 2.1:

Table 2.1 Relative bandwidths for polycycle waveforms

N	f_h	f_l	B_{rel}
1	$1.31 f_r$	$0.42 f_r$	103%
2	$1.18 f_r$	$0.74 f_r$	46%
3	$1.13 f_r$	$0.84 f_r$	29%
4	$1.11 f_r$	$0.88 f_r$	23%

2.2 Advantages of Large Relative Bandwidth

2.2.1 High-rate Communications

In most digital communication systems, the bandwidth is equal to or nearly equal to the channel symbol rate. Therefore, for conventional "narrowband" systems the trend for higher data rates has resulted in the allocation of higher center frequencies (carriers) in order to implement the system with existing technology. Generally, propagation losses and impairments increase with frequency. UWB technology offers high data rates using relatively low center frequencies.

2.2.2 Potential for Processing Gain

Processing gain in a communication system is defined as the ratio of the noise bandwidth at the front end of the receiver to the bandwidth of the data; usually, this ratio is adequately calculated as the ratio of the channel symbol (modulation) rate, R_s, to the bit rate, R_b:

$$PG = \frac{Noise\,Bandwidth\,In}{Noise\,Bandwidth\,Out} = \frac{R_s}{R_b} \tag{2.2}$$

This definition has embedded in it the concept of gains achieved during signal processing operations such as correlation and averaging (integration) and does not take into account forward error-control coding nor the statistical distribution of the interference. However, it has been shown that with or without coding the definition of processing gain in terms of the final bit rate is valid,[26] and an effect of the processing is that the interference contributions to the receiver output are effectively Gaussian (noiselike).[27]

The bandwidth available using UWB devices (switching rates in the Gigahertz range) is so large that, for many applications, the desired high data rate *and* a margin of processing gain can be achieved simultaneously.

Another aspect of the large bandwidth of UWB signals is that interference to narrowband receivers operating in the same band as a UWB signal will be limited to a small fraction of the UWB signal's power—the narrowband receiver will realize, in effect, a significant processing gain against the UWB interference. This statement applies whether the UWB spectrum is noiselike or has lines.

2.2.3 Penetration of Walls, Ground

As has been noted, conventional narrowband communications signals must use higher carrier frequencies in order to implement a wider bandwidth. As the frequencies of these signals increase, the propagation losses that they experience becomes greater, as illustrated in Figure 2.1. On the other hand, UWB signals can achieve high data rates with lower center frequencies. From (2.1),

$$f_c = \frac{W}{B_{rel}} \quad \Rightarrow \quad f_{c1} < f_{c2} \ \text{ for } \ B_{rel1} > B_{rel2} \tag{2.3}$$

It follows that UWB signals have the potential for greater penetration of obstacles such as walls than do conventional signals while achieving the same data rate.

It can be seen in Figure 2.1 that the rate at which the attenuation of the radio signals occurs through various materials is very much a function of the kind of material. The penetrations of radio signals through concrete block and "painted 2×6 board," for example, are very sensitive to frequency, while those for other materials is much less so at center frequencies under consideration for handheld and ad-hoc communication systems. Therefore, the advantage enjoyed by UWB signals in this respect is quite scenario dependent unless very large data rates and bandwidths are under consideration.

Another consideration is the location of the UWB spectrum. If the communication system is restricted to a certain band, say, 3.1–10.6 GHz as under Federal Communications

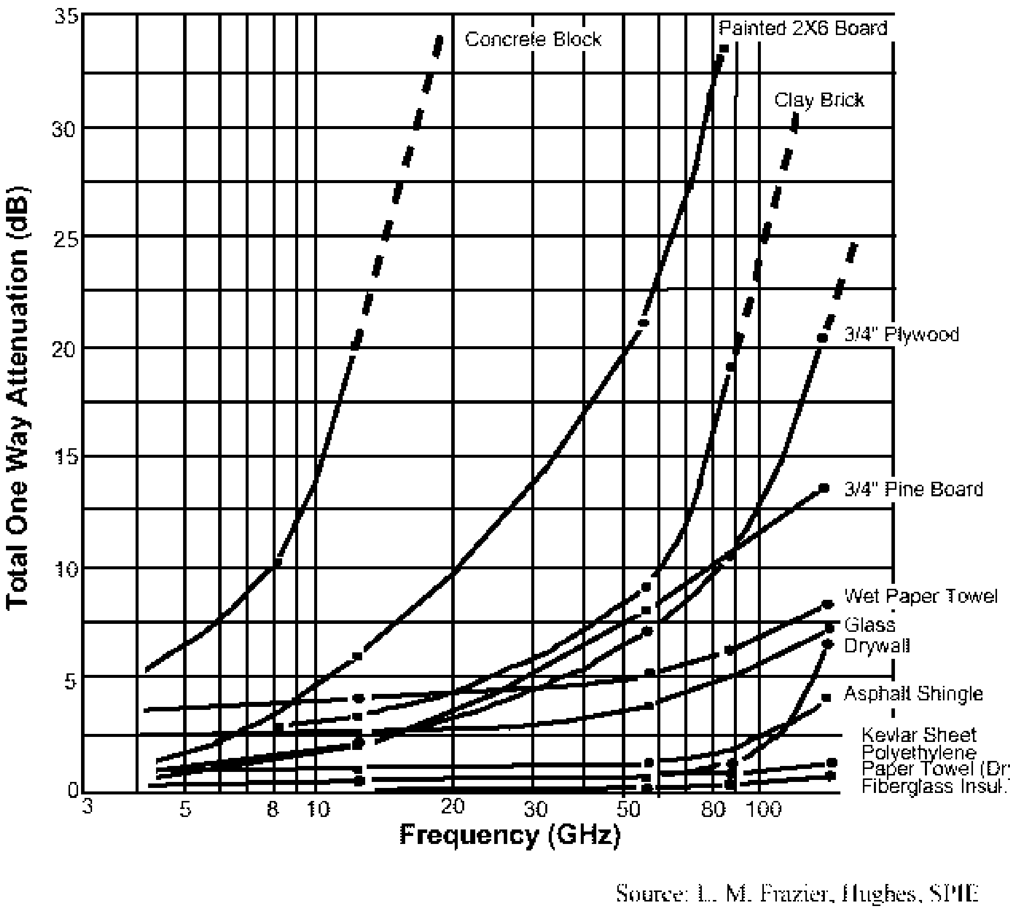


Figure 2.1 Attenuation of radio signals through various materials as a function of frequency (from reference 2)

Commission rules (discussed below in Section 2.3.1), then using (2.1) we find that the minimum center frequency for a waveform with 25% relative bandwidth is 3.55 GHz and the absolute bandwidth is 900 MHz. If the actual data symbol rate is say, 100 MHz, then a conventional communications waveform can be designed with a center frequency of 3.15 GHz. In this case, the conventional signal will penetrate materials slightly better than the UWB signal. This example highlights the fact that the material penetration advantage of UWB signals applies when they are permitted to occupy the lower portions of the RF spectrum.

2.2.4 Note on Propagation Loss for Large Bandwidth Signals

The known effects of RF propagation have been developed over many years under the assumption of conventional, narrowband signals. The question arises whether the conventional characterization of such effects adequately model the propagation of UWB signals.

The following analysis[28] shows that the center frequency of the UWB signal can be used to estimate propagation loss for the signal without incurring a significant error in the calculation of received power: Let the signal spectrum be denoted $G_s(f)$; then the received power in free space is proportional to the integral of $G_s(f)/f^2$ over the bandwidth of the signal, that is, from

$f_c - W/2$ to $f_c + W/2$, where f_c is the center frequency of the signal and W is its bandwidth. Approximating $G_s(f) \approx const./W$, the received power equals

$$P_r \approx const. \times \frac{1}{W} \int_{f_c - W/2}^{f_c + W/2} \frac{df}{f^2} = const. \times \frac{1}{f_c^2 - (W/2)^2} = \frac{const.}{f_c^2} \cdot \frac{1}{1 - (B_{rel}/2)^2} \tag{2.4a}$$

in which the first factor is the power calculated using conventional propagation theory. As shown in Figure 2.3, for signals with relative bandwidths between 25% and 50%, the dB error in estimating received power is approximately 0.068 dB to 0.28 dB. Thus, even though a simplified model was used for the signal spectrum, it is clear from this analysis that reasonable estimates of propagation loss for UWB signals can be obtained using conventional methods and the nominal center frequency of the signal.

Note that (2.4a) can be written

$$P_r \approx const. \times \frac{1}{f_c^2 - (W/2)^2} = \frac{const.}{f_1 f_2} = \frac{const.}{f_g^2} \tag{2.4b}$$

where $f_1 = f_c - W/2$, $f_2 = f_c + W/2$, and $f_g = \sqrt{f_1 f_2}$ is the geometric mean of the lower and upper band-edge frequencies. Thus the received power is estimated correctly using the geometric mean as the nominal frequency.

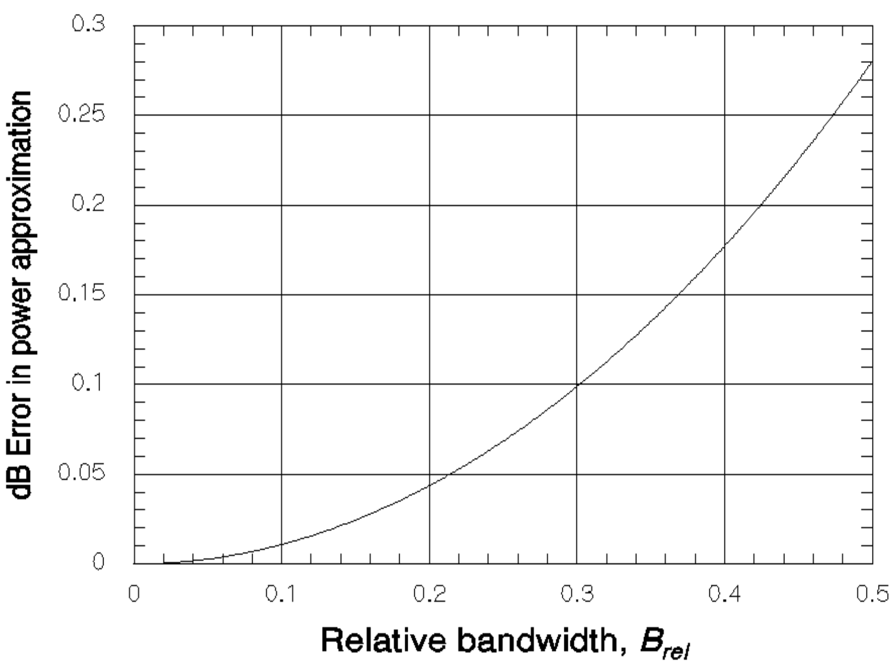


Figure 2.3 dB Error in using narrowband model of propagation loss.

2.3 Disadvantages of Large Relative Bandwidth

By its nature, an UWB signal occupies portions of the radio spectrum previously allocated for various military, civil, and commercial signals. Consideration needs to be given to *both* the potential interference to those signals and their potential interference to the UWB signal.

2.3.1 Potential Interference to Existing Systems

Given a basic UWB pulse waveform such as one of those discussed in Section 1.3, the data-modulated signal can take several forms. For example, antipodal signaling involves modulating the sign (polarity) of the pulse, yielding a data-modulated waveform that can be represented by the following equation:

$$s(t)=\sum_{k=-\infty}^{\infty} d_k p(t-kT_s)=p(t)*\sum_{k=-\infty}^{\infty} d_k \delta(t-kT_s), \quad d_k=\pm 1 \tag{2.5}$$

where $p(t)$ is the basic signaling waveform (pulse). The autocorrelation function of this waveform is[29]

$$R_s(\tau)=\sum_{r=-\infty}^{\infty} R_d(r)R_p(\tau-rT_s)=R_p(\tau)*\sum_{r=-\infty}^{\infty} R_d(r)\delta(\tau-rT_s) \tag{2.6}$$

where $R_d(r)$ is the discrete autocorrelation sequence of the data and $R_p(\tau)$ is the (continuous) autocorrelation function of the pulse. If the data is completely random, then $R_d(r)$ is zero except for $r = 0$, so that the autocorrelation function and spectrum of the signal are identical with the autocorrelation function and spectrum of the pulse, respectively. At the other extreme, if the data is periodic, so that $R_d(r)$ is periodic with period P symbols, then its power spectral density function involves the discrete Fourier transform of $R_d(r)$ and is given by[29]

$$|S(\omega)|^2=|P(\omega)|^2\frac{1}{(PT_s)^2}\sum_{k=-\infty}^{\infty}\mathrm{DFT}_{Rd}\{k\}\cdot\delta\left(\omega-\frac{2\pi k}{PT_s}\right) \tag{2.7}$$

which is a spectrum of impulse functions (spectral lines) whose amplitudes are determined by the pulse spectrum and the DFT of the data autocorrelation sequence. For a real communications signal using periodic framing data, only a small portion of the data, if any, is repetitive framing, so that the signal has a continuous spectrum, possibly with some frequency peaks that resemble spectral lines.[128] Techniques such as dithering (varying the time between pulses pseudo-randomly) and/or using pulse-position modulation can minimize the presence of lines in its spectrum and make the signal appear to be more “noiselike.” Methods exist for pseudorandomly encoding the framing data to remove such spectral lines.[129]

Because of the potential for interference to existing signals, especially spectral line interference, there has been much resistance to changing radio emission regulations to allow the development and use of proposed UWB waveforms. As with any radio coexistence situation, the assessment task is as much concerned with likely scenarios in which transmitters and receivers are in proximity as it is with the technical possibility of interference in the form of either raising the noise floor in the receiver or more serious effects such as cancellation. Consequently, the introduction of communication systems featuring UWB devices and parameters has been controversial, with significant attention being given the possible effects that UWB signals might have on the operation of receivers tracking position using the Global Positioning Satellite (GPS) network, which utilizes spread-spectrum signals at the following frequencies: "Link 1" (L1) at the carrier frequency of 1575.42 MHz and "Link 2" (L2) at the carrier frequency of 1227.60 MHz. In addition, a new GPS broadcast service using a new signal structure, called "Link 5" (L5), is planned to occupy the band of frequencies at 1164-1188 MHz.[30,31]

After hearing from all parties, the Federal Communications Commission (FCC) issued an amendment to its Title 47, Code of Federal Regulations, Part 15 Rules for transmission by unlicensed RF devices[32] to add a section regarding UWB transmissions.[33] The emission restrictions established by these rules are primarily[34] those recommended by National Telecommunications and Information Administration (NTIA) analyses[30] for protection of GPS and other Government systems operating in the 690–1610 MHz band. As shown in Figure 2.3, this band is basically excluded for UWB devices, while emissions in the allowable bands have the limit of –41.3 dBm/MHz, equivalent to that for non-UWB systems. The emissions mask also reflects the desire to protect various other Government systems in the 1610–3100 MHz band and satellite systems above 10600 MHz. Additional stipulations in this ruling include

- Restriction of handheld (portable) UWB devices to the 3100–10600 band, as determined by their 10-dB bandwidths.
- In addition to the limits on average power levels shown in Figure 2.3, there are limits on the peak levels of emissions above 1 GHz and on quasi-peak levels below 1GHz.

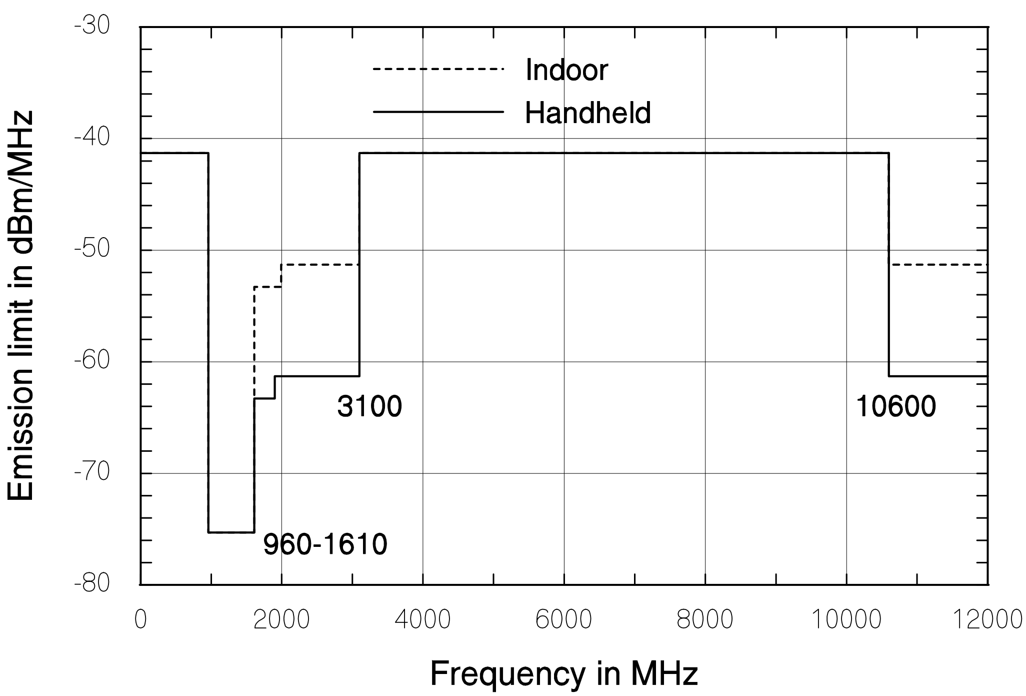


Figure 2.3 FCC emissions mask for average intentional radiation by UWB devices.

The restriction on peak levels is based on the fact that modulated UWB signals can have spectral lines and the finding that the "impact of UWB signals on a receiver appears to depend on the randomness of the UWB signal and the relationship between the pulse repetition frequency (PRF) of the UWB signal and the bandwidth of the receiver."[33]

Note that the FCC emissions mask shown in Figure 2.3 also gives extra protection from a UWB device at frequencies containing the existing 2.4 GHz ISM (Industrial, Scientific, and Medical) band that is used by current wireless local area networks (WLANs) such as IEEE 802.11 and wireless personal area networks (WPANs) such as Bluetooth.

UWB systems emitting spectral lines can in some cases be modified to relocate the spectral lines so as not to interfere with known narrowband systems. The FCC in its ruling demurred from telling manufacturers where and how to place any spectral lines and instead issued limits on the power of any such lines.

In the upper part of Figure 2.4, we show that a good fit to the FCC mask is not made by an UWB waveform based on the rectangular polycycle of (1.2) and Figure 1.5; note how the high sidelobes also make it difficult to avoid the notched-out GPS band. However, as shown in the lower part of Figure 2.4, the triangular polycycle of Figure 1.6 can be made to fit with additional effort to reduce the lower sidelobe.

Recently a study was published by the FCC[35] that indicates the existing ambient RF interference levels in the GPS and navigational aid bands of operation is in most cases above the receiver thermal noise level and well above the emission limits on UWB devices. The sample environments were largely selected to represent situations in which GPS would be used to locate cellular emergency calls. These results tend to support the previous FCC decision to amend Part 15 of its rules in order to permit UWB devices to operate in the unlicensed bands. However, there still is some concern that a concentration of several UWB devices can exceed the individual emission limits and cause harmful interference to GPS or to aircraft navigational radio equipment.

2.3.2 Potential Interference from Existing Systems

Since the power of a proposed UWB system's signal may be spread over a very wide bandwidth containing existing frequencies allocated to multiple existing narrowband systems, it is certain in such a case that the UWB system is subject to interference *from* those narrowband systems.

The amount of interference at an UWB receiver due to a narrowband emitter is highly dependent on the antennas used in the respective systems as well as their orientation.[3]

Use of direct-sequence (DS) or time-hopping (TH) spread-spectrum (SS) modulation not only smoothes out any lines in the UWB spectrum but also makes it possible to notch out a powerful narrowband interferer without significantly impacting the UWB receiver's ability to process the desired signal.[4,11] In addition, minimum mean-square error (MMSE) multiuser detection schemes with the ability to process multipath data are capable of rejecting strong narrowband interference.[5]

A narrowband intentional interference (jamming) waveform is potentially more disruptive to a SS system than an external noiselike waveform with equal power because the interference power can be concentrated where it will have the most effect. On the other hand,

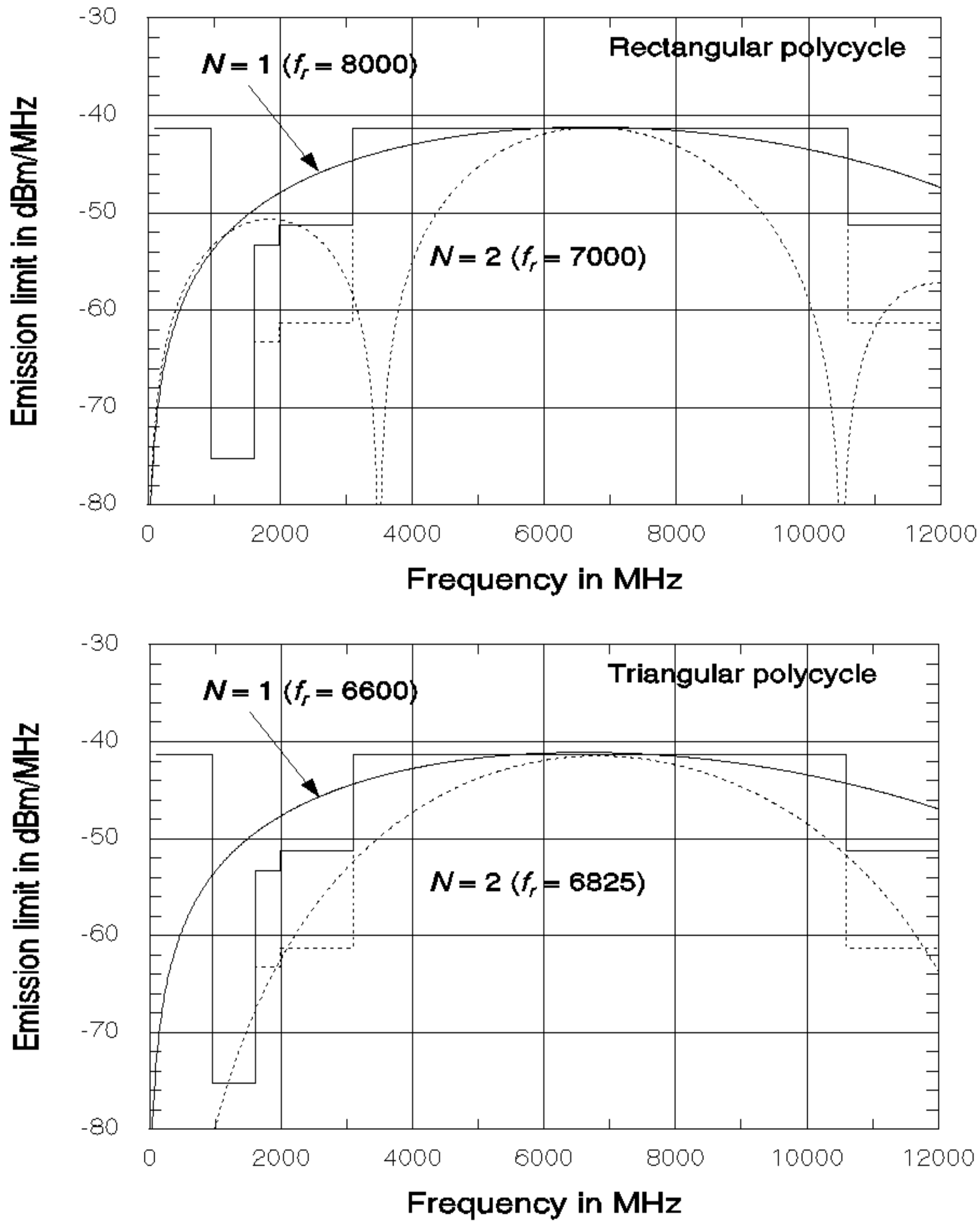


Figure 2.4 Fit of rectangular and triangular polycycle spectra to the FCC emissions mask.

unintentional narrowband interference power may be concentrated where it will have the least effect. For UWB waveforms with significant spectral lines, it follows from matched filtering principles that avoidance of placing those lines in the bandwidths of coexisting narrowband systems will simultaneously render the UWB system less susceptible to interference from those narrowband systems.

2.4 Applications of Large Relative Bandwidth

There are many applications for large bandwidth in today's wireless commercial market as well as in traditional military and government communication systems. Here we discuss only a few such applications that have been specifically related to UWB systems.

2.4.1 High-rate WPANs

Wireless local area networks (WLANs)[36], with a transmission radius on the order of hundreds of meters, and wireless personal area networks (WPANs)[37], with a transmission range on the order of tens of meters or less, are rapidly becoming established as popular applications of wireless technology, and the demand for more bandwidth is continually increasing. In addition to the IEEE 802.11 WLAN products ("Wi-Fi") and Bluetooth-based IEEE 802.15 WPAN products, there is a great variety of wireless networking products for home and commercial applications.[38] This demand for bandwidth has led, in quick succession, to formation, first, of the 802.15.3 Task Group for development of a standard for high-rate WPANs[39] and then of a new study group (IEEE 802.15.SG3a—now a task group, IEEE 802.15.3a) to consider an alternative high-rate physical layer (PHY) that possibly will be implemented using UWB technology.[40] In concept, the new high-rate PHY will interface with the same medium access control layer (MAC) as is being developed for the IEEE 802.15.3 high-rate WPAN standard.

The prototypical applications submitted in support of forming the Alt-PHY study group for high-rate WPANs included the following:

- Wireless video projectors and home entertainment systems with wireless connections between components.[41]
- High-speed cable replacement, including downloading pictures from digital cameras to PCs and wireless connections between DVD players and projectors.[42]
- Coexistence and networking of audio, still video, and motion pictures for fixed and portable low-power devices.[43]
- Wireless replacement for Universal Service Bus (USB) connections among computers and peripherals in the office environment.[44]
- Home network of audio and video with Internet gateway.[6]
- Multimedia wireless distribution system for dense user environments, such as multi-tenant units/multi-dwelling units (MTU/MDU).[45]
- Office, home, auto, and wearable wireless peripheral devices.[46]

The data rate requirements for the candidate applications that were submitted to SG3a are summarized in Table 2.2.[47]

Based on these targeted applications, the SG3a group of IEEE 802.15, as part of its documentation for becoming a regular Task Group with the ability to receive proposals for the alternative PHY, has developed Technical Requirements[48] and Selection Criteria[49] documents that do not specify the type of waveform to be used but require of any PHY proposal that the

Table 2.2 Data requirements for candidate high-rate WPAN applications.

Requirement	***Source***
100 / 200 / 400 and 480 Mb/s up to 4.5 m range	*02/031r0*
20 Mb/s to 10 m range	*00/075r0*
60 Mb/s, 90, >100 Mb/s (kiosk)	*02/043r0*
2-25 Mb/s; 31-63 Mb/s 10 m and 30 m	*02/047r0*
6-32 Mb/s; 15-50 MB/s; 20-70 Mb/s; 30-100 Mb/s 10 m or 30-50 m range	*02/119r0*
Voice at 10kb/s to high quality at 128k and 348 kb/s 2 Mb/s at 30 m distance; 30 Mb/s at 10 m Capacity to 300 Mb/s: scalable >10 m range to 3 m range	*02/137r1*
1.5 Mb/s, 12 Mb/s, 480 Mb/s to < 5 m range; 10 -1000 Mb/s desired	*02/139r0*
50 Mb/s – 500 Mb/s 1 m on body to 5 m ranges: scalable – very low bit rate to high bit rate	*02/143r0*

"payload bit rate at the PHY-SAP [Service Access Point: interface between PHY and MAC layers] should be at least 110 Mbps at a 10 meter range."

2.4.2 Low-power, Stealthy Communications

The potential bandwidth afforded by UWB waveforms is far in excess of that required for high-rate data communications, so there is room for the data signal to be spread by a fast-running pseudorandom (PN) code. The processing gain available by correlating the PN code with a local reference at the receiver can be used to lower the transmission power while achieving the same (post-correlation) received signal-to-noise ratio (SNR). Except for very unfavorable intercept geometries, the resulting UWB signal is below the noise floor of many receivers due to the wide distribution of signal energy in bandwidth.[4] The response of most intercept receivers to UWB pulses is therefore very weak[7] (See Section 3.1.2 below for an assessment of the response of a narrowband receiver to an UWB pulse.)

The promise of reducing the interceptibility of WLAN transmissions on board ships and in Government offices led the Office of Naval Research to request FY 2001 proposals for a fourth, UWB physical layer for IEEE 802.11 WLANs.[2,50] The feasibility of such a physical layer was shown previously for a non-standard MAC layer.[9]

2.4.3 Indoor Localization

Localization of radio signals indoors is difficult because of the presence of shadowing and of multipath reflections from walls and objects. The wide bandwidth of UWB signals implies a fine time resolution that gives them a potential for high-resolution positioning applications, provided that the multipaths are dealt with (see Section 3.2 below).

In additions to these general considerations of the special properties of UWB signals in relation to localization, the fact that GPS signals are often too weak indoors to provide positioning solutions motivates examination of UWB for systems that are likely to be used indoors and in other places where GPS signals are weak. This argument for UWB is somewhat lessened by recent advances in processor technology for GPS that has been driven by the requirement for cellular phones to have geolocation capabilities[51], including massively parallel correlation processing that makes it possible to fix position with GPS signals as weak as –150 dBm[52].

2.4.4 Multiple Access Communications

Due to its significant bandwidth, an UWB-based radio multiple-access communication system can accommodate many users.[4] Although it is possible to contemplate using frequency-division multiplexing (FDM) using UWB pulses with different numbers of zero crossings, usually it is preferred[21] to conceive of multiple access with UWB signals as being accomplished with code-division multiplexing (CDM) in conjunction with either pulse-position modulation[2,16,53] (PPM) (time-hopping) or antipodal pulse modulation[25,32] because code correlation is a useful method for isolating multipaths.

A typical PPM signal format for the *n*th user in a multiple access system is given by[16]

$$s^{(n)}(t) = \sum_k p\left(t - kT_f - c_k^{(n)} T_c - d_{[k/N_s]}^{(n)} \tau_d\right) \tag{2.8}$$

in which

$p(t) =$ the UWB pulse waveform

$T_f =$ the nominal frame or pulse repetition interval

$c_k^{(n)} \in \{0, 1, \ldots, N_h - 1\} =$ a user-specific nonbinary PN code chip for scrambling the data

$N_h =$ the number of integer values that a PN code chip may take

$T_c =$ the amount of time shift for a 1-valued PN code chip

$d_{[k/N_s]}^{(n)} \in \{0,1\} =$ the user's data symbol sequence, constant for N_s PN chips

$\tau_d =$ the amount of time shift for a 1-valued data symbol

In this formulation, it is assumed that the nominal pulse repetition interval is a large multiple of the duration of the UWB pulse waveform, so that the signal has very low duty cycle. It is also assumed that $N_h T_c \le T_f$, so that the pseudorandom time hopping for a particular data symbol takes place within a single frame interval; time hopping over the maximum allowable interval is recommended to avoid "catastrophic"—that, is periodically repeated—collisions of pulses from different users. A possible value for τ_d within these constraints is $\tau_d = T_c / 2$, giving a total of

$2N_h$ possible positions for the pulse within a frame, as illustrated in Figure 2.5 for the case of $N_h = 4$. Using PPM waveforms of this type for multiple access, it is estimated[54] that thousands of users can be accommodated with low bit error rates and a combined transmission capacity of over 500 Mbps.

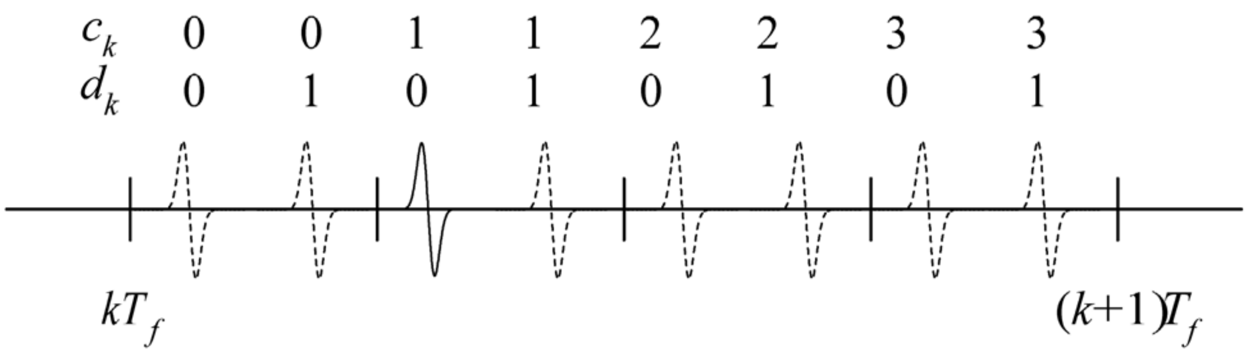


Figure 2.5 Example of PPM modulation.

In general, the spectrum of a PPM signal tends to have a continuous component based on the shape of the pulse (as seen previously for antipodal modulation) plus a line spectrum with the frequency spacing of the lines determined by the baud rate ($1/T_f$ in the notation above). The proportion of total power in the continuous and line spectrums depends on the randomness of the pulse-position modulation;[55,56,57] with dithering to make the regularly-spaced pulse positions appear more random, the proportion of power in the line spectrum can be minimized but not entirely eliminated, as illustrated in Figure 2.6[58]. However, if the polarity of the pulses is pseudorandomly switched and/or used to convey data, the lines can be eliminated.[128]

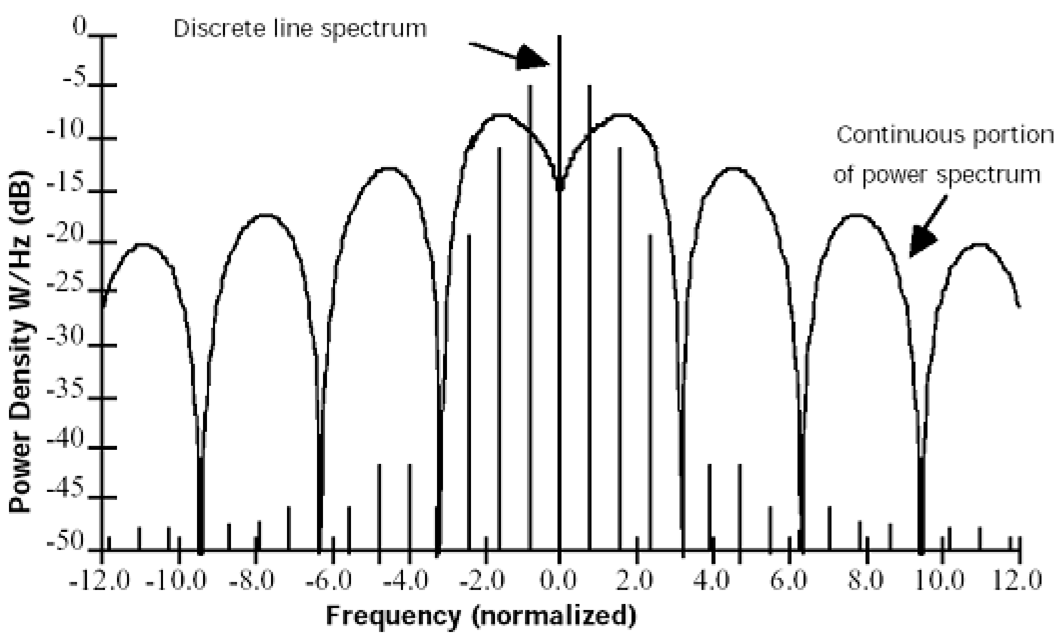


Figure 2.6 Example PPM spectrum (from ref. 58).

3. Time-Domain Properties of UWB Signals

Although the large-bandwidth properties of UWB signals are well known, the technology is generally known as a time-domain technology because the focus throughout its development so far has been on the generation of very short pulses.

3.1 Background on UWB Time-Domain Properties

As background on the time domain properties of UWB signals, we briefly survey the development of UWB communications as a field, then illustrate the impact of short pulses on classical communication theory by showing how they affect a narrowband receiver

3.1.1 Brief Survey of UWB Development

There are many useful resources and surveys on the development of UWB signal generation techniques.[59,60,61] What is relevant here are those developments related to the use of UWB technology for communications.

After the development in the 1960s of subnanosecond baseband pulse generation techniques for measuring the impulse response of electronic components and systems, the potential for the application of such "carrierless" pulses to radar and communications was realized.[60] A related development in the same timeframe was the formulation of generalized concepts for baseband signal transmission.[62] Research and experimentation in the 1970s led to the definition of components and techniques for engineering applications in the field of "time-domain electromagnetics,"[63] including "pulse train generators, pulse train modulators, switching pulse train generators, detection receivers and wideband antennas," some of which trace their concept to techniques used in sampling oscilloscopes.[61] In the 1980s, the refinement of communication system designs using UWB technology enabled implementation of low probability of intercept and detection (LPI/D) radios for military use,[60] and the term "ultra wideband" was coined by a Government-sponsored panel to describe the technology.[64] In the 1990s, techniques for implementing UWB signaling using low-power devices were invented.[60]

As an example of pulse processing that was developed for receivers based on impulses, a conceptual sketch of a pulse compressor (pulse train matched filter) is given in Figure 3.1. Using a simple rectangular pulse for illustration purposes, the figure shows a polarity- and interval-coded pulse train arriving at the receiver, which uses a matched filter to process each pulse optimally and a delay-and-sum correlator that is matched to the coding of the pulse train. In such a system, information can be encoded in the pulse delay intervals and polarities, requiring a bank of correlators, or simply by inverting or not inverting the periodic repetition of the same pulse sequence. Note that the correlator, which we have shown in rather general form here, can be programmed with smaller delay intervals to match a pulse train with a higher PRF (pulse repetition frequency) or with larger delay intervals to match a pulse train with a lower PRF. In this manner the receiver can implement signal selectivity for carrierless waveforms just as conventional radio receivers are tuned to carrier frequencies.

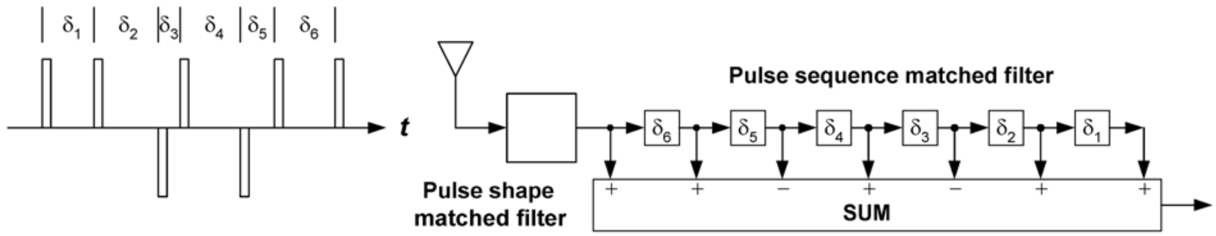


Figure 3.1 Example correlation receiver for carrierless waveforms.

3.1.2 Analysis Involving Short Pulses

In the 1960s and in connection with the transmission of signals in the form of pulses instead of carrier-modulated waveforms, theoretical alternatives to the usual Fourier analysis of signals were put forth. For example, it was shown[62,65] that waveforms can be analyzed according to a "generalized Fourier transform" in terms of the rate of zero crossings instead of in terms of sinusoidal functions, which form a system of orthogonal periodic basis functions; the signals can be expressed as combinations of periodic, orthogonal nonsinusoidal functions, such as time functions based on the Walsh sequences shown in Table 3.1.[29] Note that when the digital logic values "0" and "1" are mapped to the algebraic values "+1" and "−1", respectively, Walsh sequence W*i* becomes the Walsh function $W_i(t)$ having *i* zero crossings per period, as illustrated in Figure 3.2 for Walsh functions of order 8.

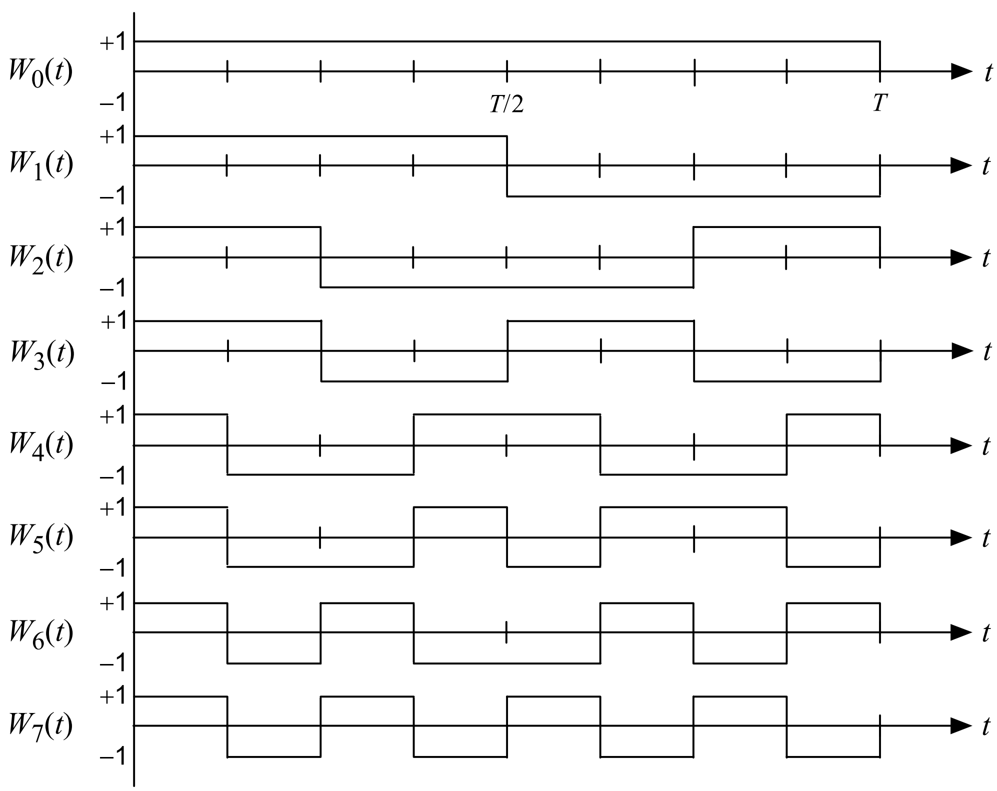


Figure 3.2 Walsh functions of order 8 (from reference 29).

Table 3.1 Walsh sequences of order 64, indexed by no. of zero crossings (from reference 29)

W0	0000000000000000000000000000000000000000000000000000000000000000
W1	0000000000000000000000000000000011111111111111111111111111111111
W2	0000000000000000111111111111111111111111111111110000000000000000
W3	0000000000000000111111111111111100000000000000001111111111111111
W4	0000000011111111111111110000000000000000111111111111111100000000
W5	0000000011111111111111110000000011111111000000000000000011111111
W6	0000000011111111000000001111111111111111000000001111111100000000
W7	0000000011111111000000001111111100000000111111110000000011111111
W8	0000111111110000000011111111000000001111111100000000111111110000
W9	0000111111110000000011111111000011110000000011111111000000001111
W10	0000111111110000111100000000111111110000000011110000111111110000
W11	0000111111110000111100000000111100001111111100001111000000001111
W12	0000111100001111111100001111000000001111000011111111000011110000
W13	0000111100001111111100001111000011110000111100000000111100001111
W14	0000111100001111000011110000111111110000111100001111000011110000
W15	0000111100001111000011110000111100001111000011110000111100001111
W16	0011110000111100001111000011110000111100001111000011110000111100
W17	0011110000111100001111000011110011000011110000111100001111000011
W18	0011110000111100110000111100001111000011110000110011110000111100
W19	0011110000111100110000111100001100111100001111001100001111000011
W20	0011110011000011110000110011110000111100110000111100001100111100
W21	0011110011000011110000110011110011000011001111000011110011000011
W22	0011110011000011001111001100001111000011001111001100001100111100
W23	0011110011000011001111001100001100111100110000110011110011000011
W24	0011001111001100001100111100110000110011110011000011001111001100
W25	0011001111001100001100111100110011001100001100111100110000110011
W26	0011001111001100110011000011001111001100001100110011001111001100
W27	0011001111001100110011000011001100110011110011001100110000110011
W28	0011001100110011110011001100110000110011001100111100110011001100
W29	0011001100110011110011001100110011001100110011000011001100110011
W30	0011001100110011001100110011001111001100110011001100110011001100
W31	0011001100110011001100110011001100110011001100110011001100110011
W32	0110011001100110011001100110011001100110011001100110011001100110
W33	0110011001100110011001100110011010011001100110011001100110011001
W34	0110011001100110100110011001100110011001100110010110011001100110
W35	0110011001100110100110011001100101100110011001101001100110011001
W36	0110011010011001100110010110011001100110100110011001100101100110
W37	0110011010011001100110010110011010011001011001100110011010011001
W38	0110011010011001011001101001100110011001011001101001100101100110
W39	0110011010011001011001101001100101100110100110010110011010011001
W40	0110100110010110011010011001011001101001100101100110100110010110
W41	0110100110010110011010011001011010010110011010011001011001101001
W43	0110100110010110100101100110100101101001100101101001011001101001
W44	0110100101101001100101101001011001101001011010011001011010010110
W45	0110100101101001100101101001011010010110100101100110100101101001
W46	0110100101101001011010010110100110010110100101101001011010010110
W47	0110100101101001011010010110100101101001011010010110100101101001
W48	0101101001011010010110100101101001011010010110100101101001011010
W49	0101101001011010010110100101101010100101101001011010010110100101
W50	0101101001011010101001011010010110100101101001010101101001011010
W51	0101101001011010101001011010010101011010010110101010010110100101
W52	0101101010100101101001010101101001011010101001011010010101011010
W53	0101101010100101101001010101101010100101010110100101101010100101
W54	0101101010100101010110101010010110100101010110101010010101011010
W55	0101101010100101010110101010010101011010101001010101101010100101
W56	0101010110101010010101011010101001010101101010100101010110101010
W57	0101010110101010010101011010101010101010010101011010101001010101
W58	0101010110101010101010100101010110101010010101010101010110101010
W59	0101010110101010101010100101010101010101101010101010101001010101
W60	0101010101010101101010101010101001010101010101011010101010101010
W61	0101010101010101101010101010101010101010101010100101010101010101
W62	0101010101010101010101010101010110101010101010101010101010101010
W63	0101010101010101010101010101010101010101010101010101010101010101

The concept of using Walsh functions to analyze UWB transmissions did not "catch on." However, the use of Walsh functions for orthogonal multiplexing of subchannels has found use in various communication systems including second- and third-generation CDMA digital cellular systems.[29,66]

Together with the somewhat "exotic" hardware components used to generate and process impulse radar signals, the advancement of non-Fourier analysis of these signals for a while created the impression of a "mystique" for UWB technology in that some wondered if it was adequately analyzed using Maxwell's equations and Fourier theory. However, it is now well established that conventional measurement and analysis principles are useful for UWB signals and systems.

The short duration of UWB basic waveforms (pulses) facilitates the analysis of the effects of the individual pulses on narrowband receivers in the same band. Consider the polycycle UWB waveform discussed in Section 1.3.2 and illustrated in Figure 1.5, with N cycles of a sinewave of frequency $f_r = \omega_r / 2\pi = 1/T$, and its reception by a direct-conversion quadrature (I/Q) receiver matched to a narrowband signal with pulse shape $h_0(t)$ modulating the carrier frequency $f_c = \omega_c / 2\pi$ at rate $1/T_0$. Since $NT \ll T_0$, it is straightforward to calculate I (in-phase) and Q (quadrature) baseband receiver outputs due to the UWB pulse as convolutions of the baseband filter impulse response with (1.1b) multiplied by in-phase (cosine) and quadrature (sine) local oscillators, respectively. Using that approach, we have

$$I(t) = \left[s(t)\cos(\omega_c t + \varphi)\right] * h_0(t) = \int_0^{NT} d\tau \left[s(\tau)\cos(\omega_c \tau + \varphi)\right] h_0(t-\tau) \quad (3.1a)$$

and

$$Q(t) = \left[-s(t)\sin(\omega_c t + \varphi)\right] * h_0(t) = \int_0^{NT} d\tau \left[-s(\tau)\sin(\omega_c \tau + \varphi)\right] h_0(t-\tau) \quad (3.1b)$$

where φ is a random phase. Now, since the interval of integration is very short compared to the duration of the baseband filter response, we can substitute the following approximate expression in these integrals:

$$h_0(t-\tau) \approx h_0(t) + \tau \cdot \frac{h_0(t-NT) - h_0(t)}{NT}, \quad 0 \le \tau \le NT \quad (3.2)$$

The resulting approximate expression for the I baseband filter output, for example, is

$$I(t) \approx h_0(t)\int_0^{NT} d\tau\ s(\tau)\cos(\omega_c \tau + \varphi) + \frac{h_0(t-NT) - h_0(t)}{NT}\int_0^{NT} d\tau\, \tau\, s(\tau)\cos(\omega_c \tau + \varphi) \quad (3.3a)$$

where

$$\int_0^{NT} d\tau\ s(\tau)\cos(\omega_c \tau + \varphi) = \frac{1}{2}\int_0^{NT} d\tau\ \sin\left[(\omega_r + \omega_c)\tau + \varphi\right] + \frac{1}{2}\int_0^{NT} d\tau\ \sin\left[(\omega_r - \omega_c)\tau - \varphi\right]$$

$$= \begin{cases} \dfrac{\omega_r}{\omega_r^2 - \omega_c^2}\left[\cos\varphi - \cos\left(\omega_c NT + \varphi\right)\right], & \omega_r \neq \omega_c \\ -\dfrac{NT\sin\varphi}{2}, & \omega_r = \omega_c \end{cases} \quad \text{for } \omega_r T = 2\pi \tag{3.3b}$$

and

$$\int_0^{NT} d\tau\, \tau\, s(\tau)\cos\left(\omega_c\tau + \varphi\right) = \frac{1}{2}\int_0^{NT} d\tau\,\tau \sin\left[\left(\omega_r + \omega_c\right)\tau + \varphi\right] + \frac{1}{2}\int_0^{NT} d\tau\,\tau\sin\left[\left(\omega_r - \omega_c\right)\tau - \varphi\right]$$

$$= \begin{cases} \dfrac{2\omega_r\omega_c}{\left(\omega_r^2 - \omega_c^2\right)^2}\left[\sin\varphi - \sin\left(\omega_c NT + \varphi\right)\right] - \dfrac{NT\omega_r\cos\left(\omega_c NT + \varphi\right)}{\omega_r^2 - \omega_c^2}, & \omega_r \neq \omega_c \\ -\dfrac{NT\cos\varphi}{4\omega_r} - \dfrac{\left(NT\right)^2\sin\varphi}{4}, & \omega_r = \omega_c \end{cases} \quad \text{for } \omega_r T = 2\pi \tag{3.3c}$$

For example, let $1/T$ = 4 GHz and f_c = 5 GHz; then the I component of the response to an N-cycle pulse is given by

$$I(t) = h_0(t)\cdot\left[-7.074\times10^{-11}\cos\varphi - \frac{5.004\times10^{=11}}{N}\left[\sin\varphi - \sin\left(\varphi + 5N\pi/2\right)\right]\right]$$

$$+h_0\left(t - NT\right)\cdot\left[7.074\times10^{-11}\cos\left(\varphi + 5N\pi/2\right) + \frac{5.004\times10^{-11}}{N}\left[\sin\varphi - \sin\left(\varphi + 5N\pi/2\right)\right]\right]$$

This quadrature baseband waveform is plotted in Figure 3.3 for an ideal (rectangular) baseband filter, for which $h_0(t) = \text{sinc}\left(t/T_d\right)$, with a data rate of $1/T_d$ = 20 Mbps. For small N, the waveform is basically the impulse response of the filter.

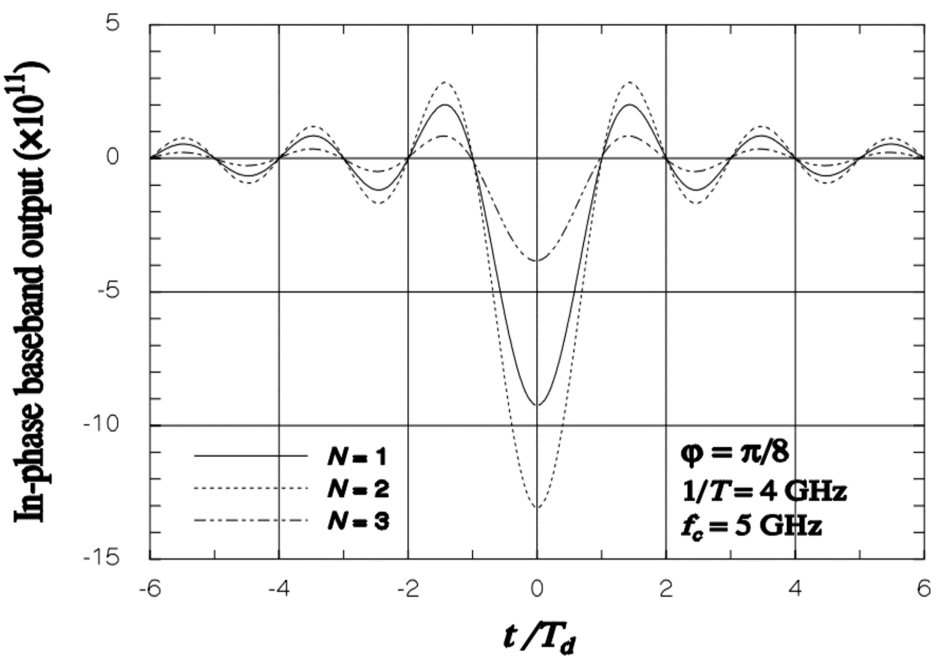


Figure 3.3 Example of baseband respond to N-cycle sinusoid.

3.2 Advantages of Short Pulse Width

The literature cites several advantages to be had from transmissions involving very short pulses, two of which will be discussed here: the direct resolvability of multipath components and the relatively easy realization of diversity gain.

3.2.1 Resolvability of Multipath Components

A general model for the received signal in an environment characterized by multipath is the superposition of delayed replicas of the signal, denoted $s(t)$:

$$r(t) = \sum_n \alpha_n s(t-\tau_n) = s(t) * \sum_n \alpha_n \delta(t-\tau_n) \tag{3.4}$$

Further descriptions of the multipath channel are given below in Section 3.3.1. Here we note that, unlike continuous-wave (CW) or sinusoidal waveforms, UWB pulse waveforms, when reflecting (scattering) from objects and surfaces near the path between transmitter and receiver, tend not to overlap in time because of the extreme shortness of the UWB pulses. Thus there is very little Rayleigh fading for these waveforms[2] and in principle it is possible to resolve (isolate) multipath receptions by time gating, as illustrated conceptually in Figure 3.4. The time gating is a form of matched filtering in the time domain and can be used to develop a "duty cycle processing gain" relative to a receiver that is continuously open to front-end noise.[2]

It is obvious that time gating of such narrow pulses to implement "direct" resolution of multipaths requires the receiver to achieve synchronization with the incoming pulse stream in some manner. Another means of isolating the multipaths for a time-hopped waveform[4] is to use a correlator as illustrated in Figure 3.1; the output of the correlator for a single data symbol that is encoded as the polarity of a sequence of N pulses is the sum of N samples of the incoming signal, noise, and multipath interference, which can be written for the kth data symbol as

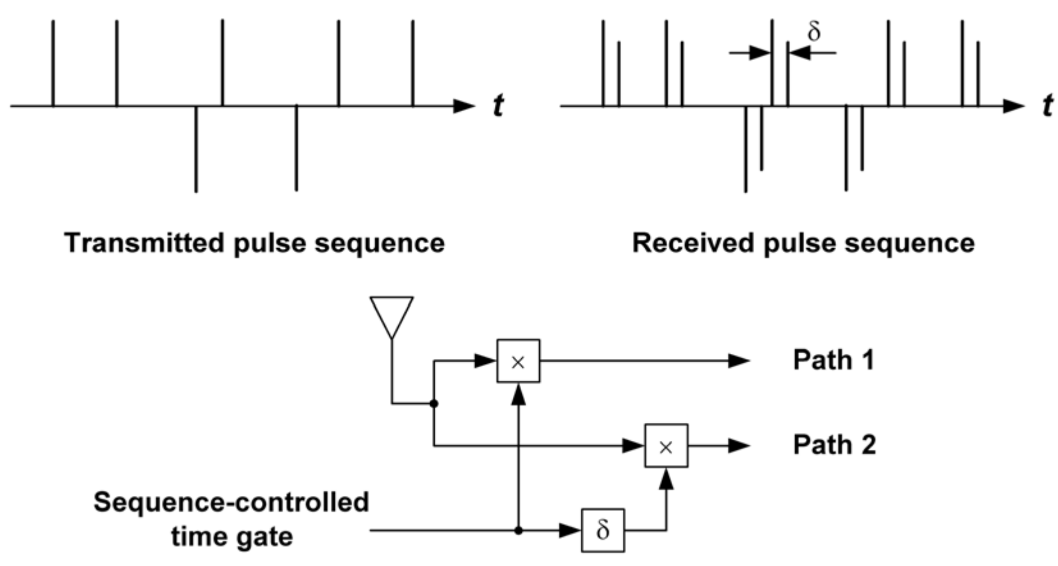


Figure 3.4 Conceptual diagram showing direct resolution of multipaths.

$$x_{out}\left(t_k\right) = \sum_{i=0}^{N-1}\left(A_k + \nu_i\right) = NA_k + n_k \tag{3.5}$$

where $A_k = \pm A$ is the polarity-coded data amplitude per pulse, the $\{\nu_i\}$ are the noise plus interference samples accompanying the signal samples, and n_k is the sum of the $\{\nu_i\}$. If the noise samples are independent and each have variance σ^2, then the variance of n_k (i.e., the noise power) is $N\sigma^2$, while the signal power is N^2A^2. Thus, ideally the SNR at the output of the correlator is *N* times that of one of the pulses—a coherent processing gain is realized.

In the presence of multipath reflections, the output of the correlator in Figure 3.1 would appear as illustrated in Figure 3.5 for the (nonoptimal) example pulse code. The multipaths identify themselves as delayed and attenuated versions of the main correlation. In a multipath combining receiver, the correlator can be used to identify such multipaths and to estimate the timing and weighting needed for the combining. Note how the delay spread (the time after a pulse when significant multipath energy is received) can be a consideration in the selection of the pulse and data symbol spacings: it is desirable to avoid overlapping of the intervals in which multipaths corresponding to different data symbols occur.

3.2.2 Diversity Gain

Because multipath reflections of UWB signals are resolvable, there is a potential for combining them to achieve a diversity gain. The total power in received multipaths in some instances is enough to change the effective propagation power law. For example,[67] swept-frequency power measurements in the band 5 GHz ± 625 MHz were made in 23 homes with a network analyzer to develop over 300,000 indoor line-of-sight (LOS) and non-LOS (NLOS) complex channel frequency responses; fitting power-law curves to the data as shown in Figure 3.6, it was found that the LOS data points clustered about a power-law curve showing that the median propagation loss is proportional to $1/d^{1.7}$, compared to $1/d^2$ for free space.

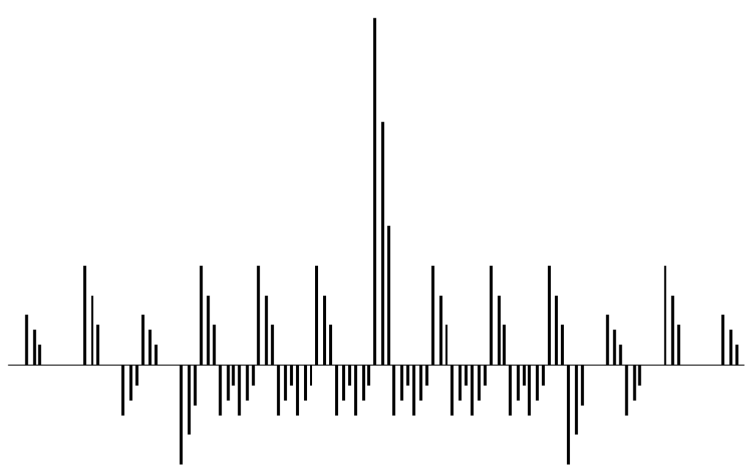


Figure 3.5 Correlator output with multipath.

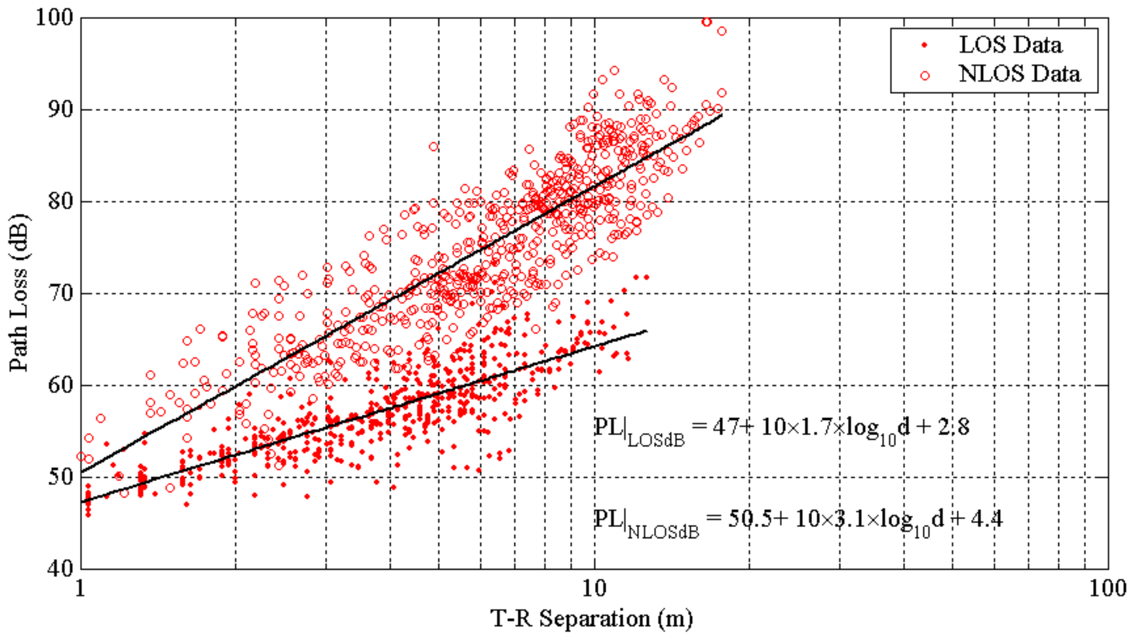


Figure 3.6 Experimental data for indoor propagation loss at 5 GHz (from ref. 67).

Recovery of the power available at a receiver in the form of multipath reflections is done using a "rake" receiver* to implement maximal ratio combining.[68,69] In principle, maximal ratio combining weights the received paths in proportion to their amplitudes and, for narrowband signals, aligns them in carrier phase. An *L*-"finger" rake receiver uses estimates of the channel response to determine the weights given to *L* parallel processor outputs in the combination. In practice, it is difficult to isolate the multipath components of a received CW signal because they overlap in time. If the signal is spread using DS-SS techniques, the multipaths can be approximately isolated following despreading using the correlation properties of the PN codes; such a scheme is used in the IS-95 CDMA cellular system, which uses a "search receiver" to estimate the delays of three or four multipaths and assigns finger receivers to track them.[29] In the case of UWB pulsed signals, as noted previously, the multipaths may actually arrive isolated as non-overlapping (but interleaved) signals, making it easier to perform diversity combining.

Suboptimal diversity combining schemes are often used. Under "equal-gain combining" (EGC), the combining is done at baseband and different weights are not used. In the sense that an effort is made to combine received signal components with significant amplitude, the EGC scheme is essentially a 0 or 1 weighting scheme, with the weight based on detecting a multipath with a particular delay. A noncoherent form of rake receiver can be based on post-detection combining at baseband (in the case of carrierless UWB signals, the arriving signals are already at baseband). The weighting and combining of three correlator outputs is illustrated in Figure 3.7 for the example of Figure 3.5; in Figure 3.7, the shaded lines represent multipath correlations that would be absent if the correlators are preceded by time gating (sampling) that selects the desired multipath and excludes the other multipaths.

Another suboptimal form of diversity combining is the so-called "pre-Rake combining" method.[70,71] In the original version of this scheme, the transmitter sends multiple copies of the signal that are delayed by the same amounts of time that a rake receiver would delay the normal

* The term "rake" refers to the garden rake-like parallel structure of the receiver in the original design.[66]

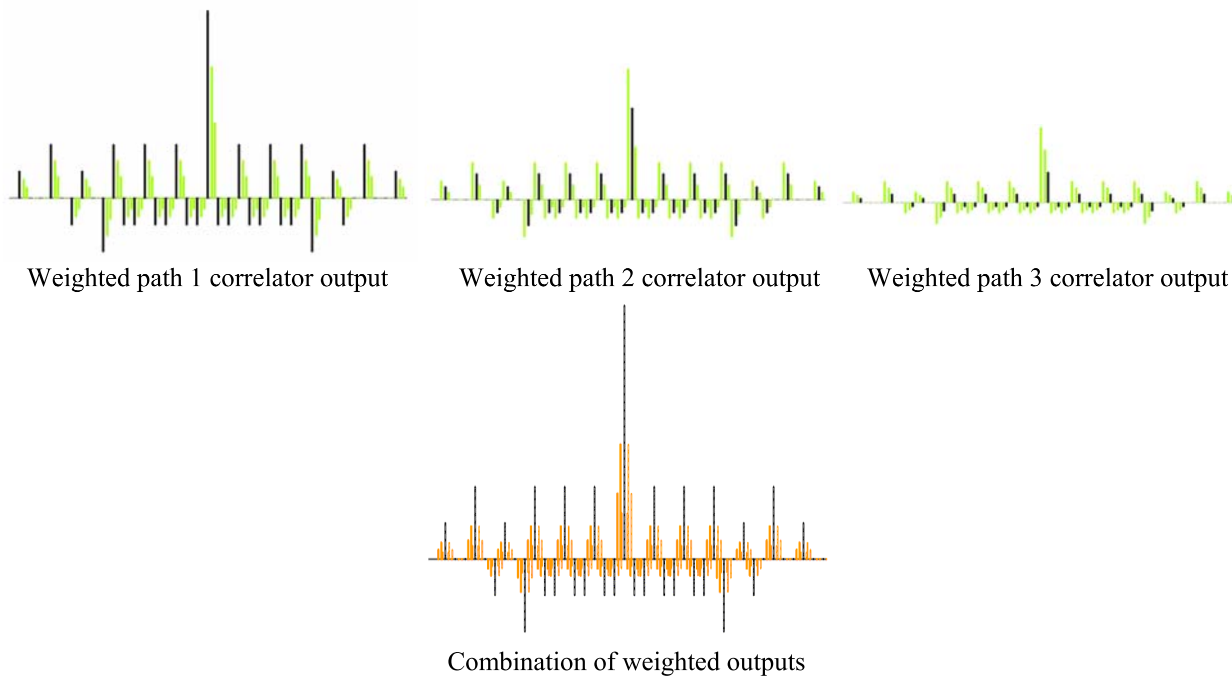


Figure 3.7 Example rake combining of correlator outputs.

signal in order to align the multipath components in time. By this method, the receiver can get away with using only one correlator while still performing "rake" combining. A modified version of this scheme, used in some IEEE 802.11b receivers, performs the rake combining at the front end of the receiver and therefore needs only one correlator.[72,73] Essentially this technique is a form of channel equalization, which is known to be a suboptimal[74] method for processing multipaths but works well in many situations.

For UWB signals using short pulses, the tendency of pulses belonging to different multipath reflections not to overlap in time (their direct resolvability) makes it reasonable to consider a simple, single-correlator baseband rake receiver design without the use of pre-rake techniques. Using the output of the correlator in Figure 3.1, which for known data (such as a training sequence) produces a "snapshot" of the channel multipath profile (as shown in Figure 3.5), it is possible to recover and combine data from different multipaths by sampling the correlator output at the appropriate times. This concept is illustrated in Figure 3.8. The output of the weighted sum operation in this receiver ideally would appear as the central peak shown in the lower part of Figure 3.7, without any of the other peaks.

3.3 Disadvantages of Short Pulse Width

Along with the advantages of using sequences of short pulses to form communication signals, there are certain real and perceived disadvantages. Here we discuss the "multipath-rich" nature of the "UWB channel" and the problem of synchronizing long pulse sequences.

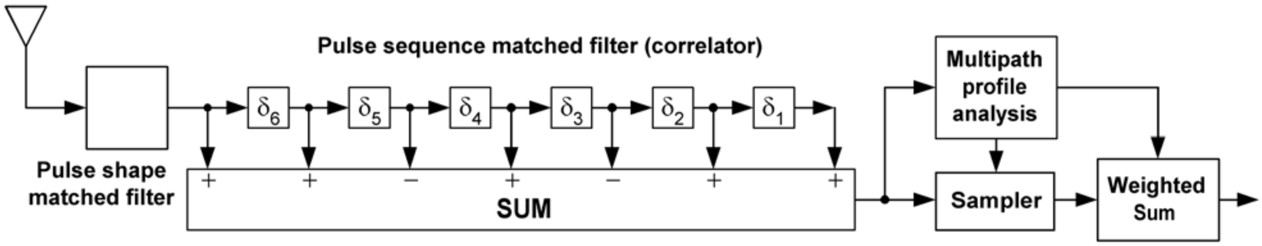


Figure 3.8 Concept of sampling correlator output to perform rake combining.

3.3.1 Large Number of Multipaths

Channel measurements using UWB signals show a large number of multipaths, so that the term "UWB channel" is sometimes used synonymously with "dense multipath channel." While there is a phenomenology associated with pulsed UWB signals that can result in a large multipath delay spread ("multipath persistence" as discussed below in Section 4), it is important to note the fundamental fact that the existence of multipath reflections is due to the particular scattering environment in which the signals operate. Thus, at least partially, the existence of a large number of multipaths in a particular situation is due to the reflective environment, such as a room in a home or office, and not due to the use of UWB signals themselves—it is just that the many multipaths are observable because of the structure of the UWB signal. This point is well made in Figure 3.9, which shows how a 5 GHz ± 625 MHz frequency scan using a network analyzer—not a UWB signal—through an inverse discrete Fourier transform (IDFT) develops a channel impulse response for an indoor environment that has a multipath resolution capability of 1/1.25 GHz = 0.8 ns, and there are very many, closely spaced multipath reflections.[67]

Although we have emphasized the distinction between *dense* multipath and *persistent* multipath, from the receiver complexity and power-consumption points of view[8,75] it makes little difference: there are a large number of multipaths to process if all or most of the available signal energy is to be captured.[76] Generally, there are up to $N_r = WT_d$ resolvable multipaths for a maximum delay of T_d and a signal bandwidth of W. It has been shown that the selection of L strongest multipaths yield a receiver error performance close to that for a receiver that processes

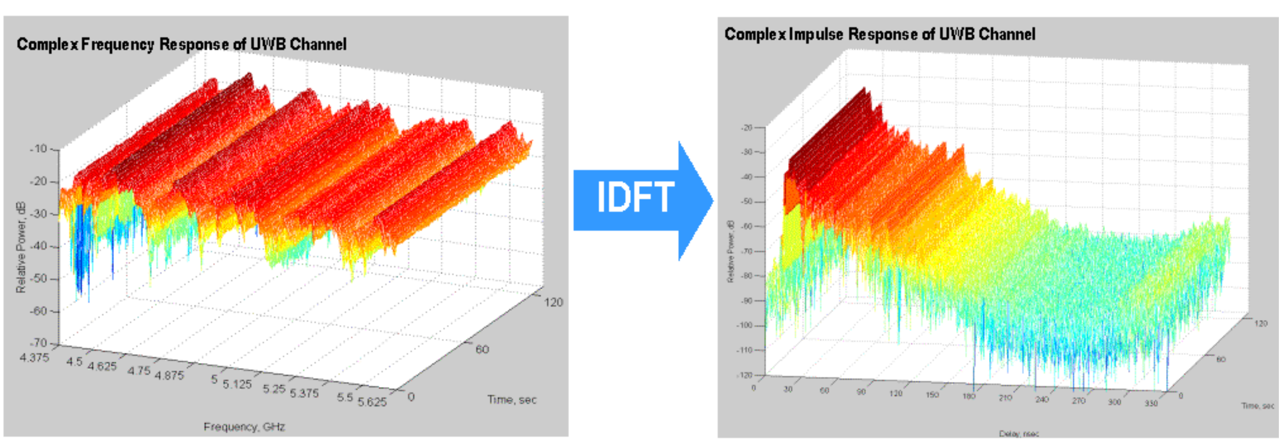


Figure 3.9 Calculation of channel impulse response from a frequency response (from ref. 67).

all the paths.[8,75,77] For example, analysis based on a transformation of the ordered multipath SNRs shows[77] that the probability of symbol error for M-ary phase-shift-keying (MPSK) achievable by a rake receiver is given by

$$P_{es} = \frac{1}{\pi}\int_0^{\Theta} d\theta \left[\frac{\sin^2\theta}{\delta_M\left(\beta/N_r\right)\cdot\left(E_s/N_0\right)+\sin^2\theta}\right]^L \prod_{n=L+1}^{N_r}\left[\frac{\sin^2\theta}{\delta_M\left(\beta/N_r\right)\cdot\left(E_s/N_0\right)\cdot\left(L/n\right)+\sin^2\theta}\right] \quad (3.6)$$

where $\delta_M = \sin^2\left(\pi/M\right)$, $\Theta = \pi\left(M-1\right)/M$, and β is a pulse shape factor. Plots of this expression are shown in Figure 3.10 for L =1 to N_r = 20, indicating that the performance of the receiver is close to optimal for L significantly less than N_r.

3.3.2 Long Synchronization Times

UWB signals based on short pulse waveforms typically embed information in position, polarity, and/or amplitude properties of pulse sequences to facilitate signal selection at the receiver. The selection is performed by matched filtering (correlation) to lock onto the signal in time and to enhance the receiver SNR in the presence of noise, multipath, and other waveforms. Additional encoding may be used for channelization, error correction, and scrambling. Essentially these signals utilize a form of spread-spectrum modulation since the information bit rate is much less than the signal bandwidth. The spreading requires signal acquisition, synchronization, and tracking at the receiver, which in the case of UWB signals must be done with very high precision in time, relative to the pulse rate. Achieving this high precision generally involves relatively long acquisition and synchronization times.[4]

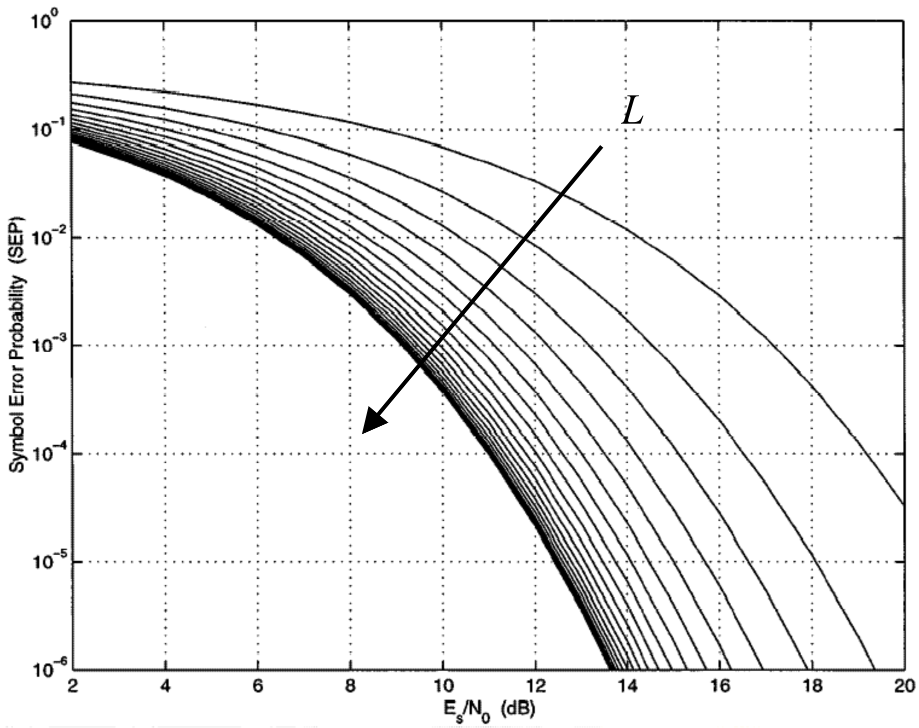


Figure 3.10 Performance of rake receiver parametric in L for N_r = 20 (from ref. 77).

For intermittent communications, such as packet radio, the overhead involved in acquiring and synchronizing each transmission of a UWB signal can be significant. To reduce the overhead, it is possible to implement a full-duplex scheme in which system timing is maintained by interleaving a low-rate, non-intermittent, low-power timing channel at each transmitter.[9] Another technique is to use a special beacon or preamble sequence especially designed for rapid acquisition.[78]

3.4 Applications of Short Pulse Width

The short pulse width of UWB communication signals is useful for non-communication purposes. Here we discuss the application of the pulse-width properties to localization.

3.4.1 Localization and Combined Communications and Localization

The potential for localization with resolution less than one meter using UWB waveforms is obvious from the bandwidth and pulse-width properties of the waveforms.[79] We focus here on the simultaneous achievement of communications and localization by the same system.

The military has developed a tactical communications/localization radio system using conventional signal waveforms in the UHF band in the form of the Enhanced Position Location Reporting System (EPLRS),[80] which provides a low-rate data capability in addition to position location and display at a central station. A satellite version, based on the Qualcomm OmniTracs vehicle tracking system, has also been used when LOS communications are not available.[81] For general applications, there is much interest in sensor networks that use wireless communications in order to collaborate.[82]

Using a time difference of arrival (TDOA) approach,[83] location with an accuracy of 3 cm has been demonstrated using UWB waveforms. As illustrated in Figure 3.11, ranging performed on beacon transmissions from the object to be located and distributed among the receivers or to a central location provide the localization solution, and data communications can be the payload on the various transmissions. A system using this technology is being developed to track the location of firefighters.[84]

In a variation on this technique, illustrated in Figure 3.12 (in which TOF denotes "time of flight" or propagation delay), the object to be located transmits UWB signals addressed to other terminals, which respond immediately to provide round-trip timing from which the distances to the other terminals can be measured.[85]

Using stationary receivers in known locations, low-power UWB RFID (RF identification) tag transmitters have been used to locate equipment in storage with an accuracy proportional to the inverse of the signal bandwidth.[14]

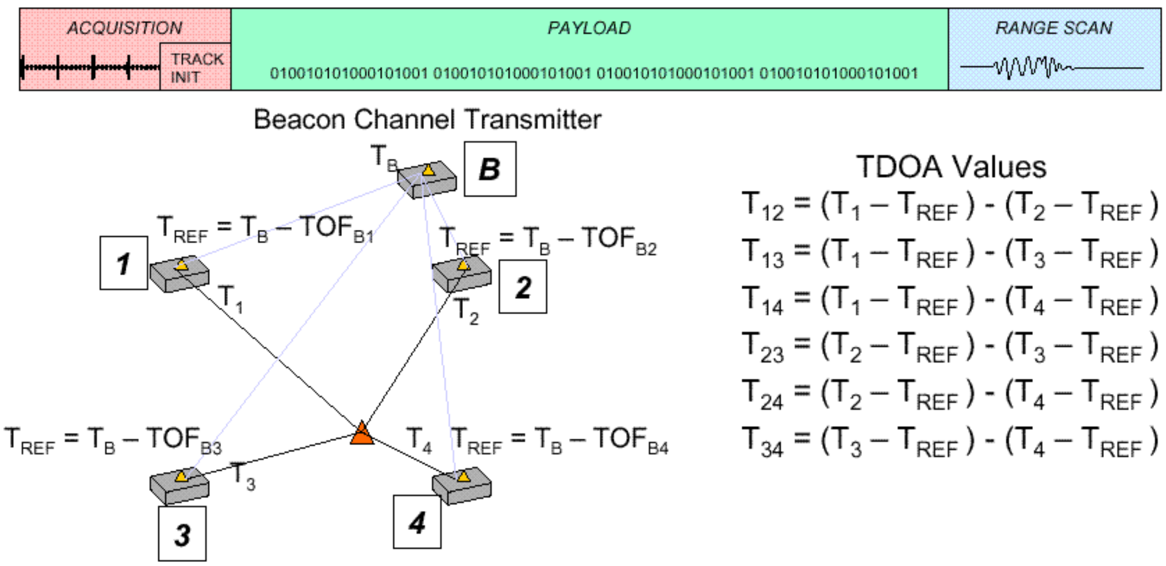


Figure 3.11 Example of combined communication and TDOA operations (ref. 83).

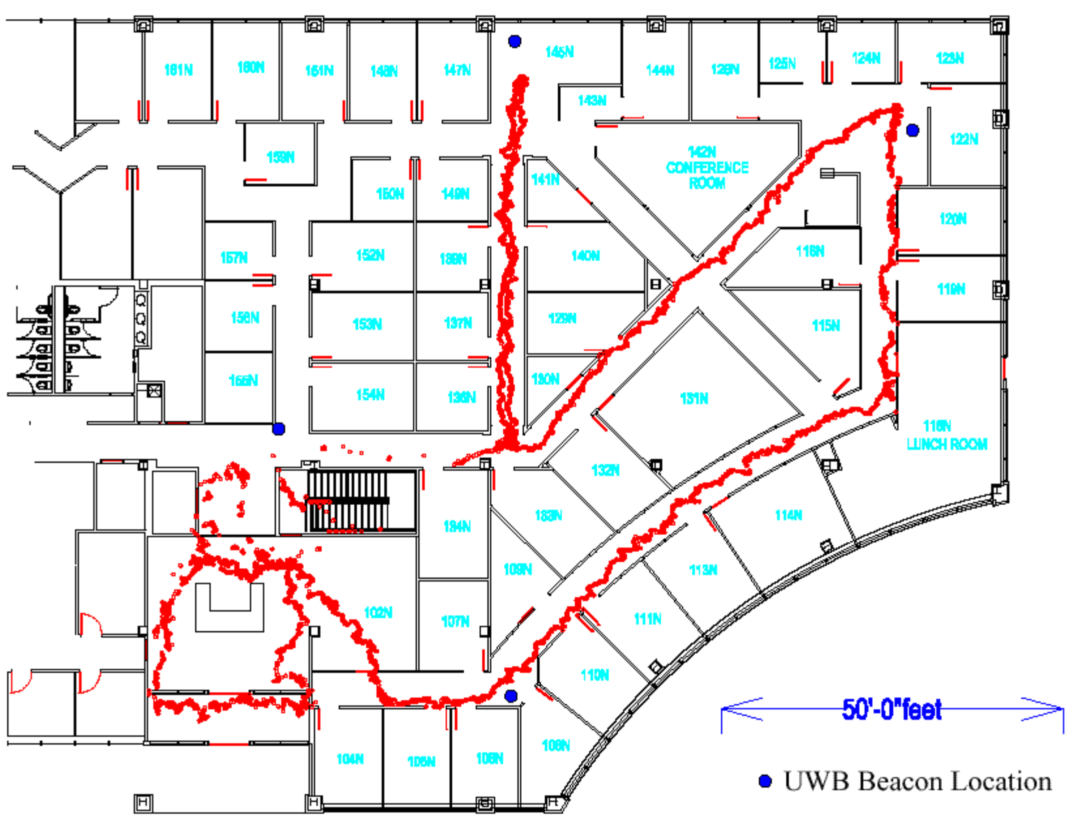


Figure 3.12 Example of indoor geolocation using responding terminals (beacons) (ref. 85)

4. Multipath Persistence Property of UWB Signals

We have mentioned previously, in Section 3.3.1, that it is common for UWB signals to be received with a large number of multipath reflections. While the existence of these reflections is due to the environment in which the system operates, the fact is that the reflections arrive at the receiver with less attenuation than for narrowband signals. In this section, we present examples of measurements showing this effect for UWB signals and discuss its physical basis, then discuss various implications of the effect for communication systems.

4.1 Background on UWB Multipath Propagation

Measurements of UWB pulsed signals have revealed an unusually long period of multipath reflection (reverberation) for these signals. Examples[33,2] of the multipath response to an UWB pulse are shown in Figures 4.1 and 4.2. Note in these examples that the multipath delay spread

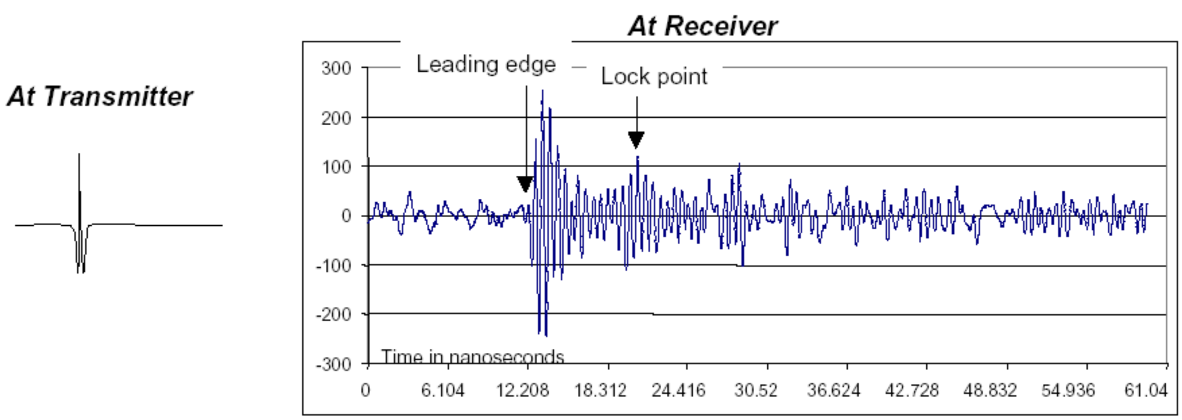


Figure 4.1 Example multipath response to UWB pulse (from reference 33).

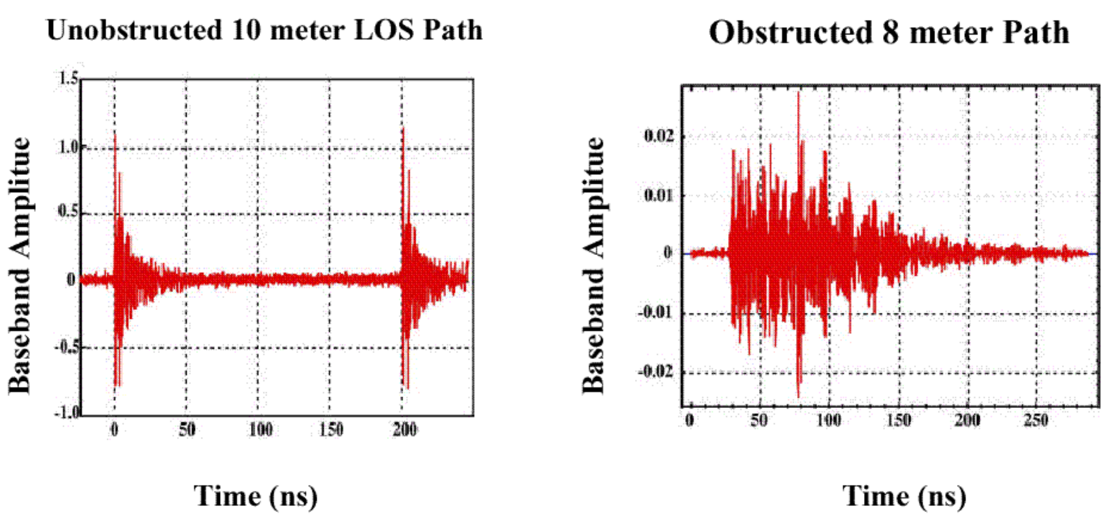


Figure 4.2 Examples of UWB multipath (from reference 3).

for LOS is on the order of 50 ns and that the NLOS delay spread is on the order of 150 ns. In addition to the duration of the reflections, which is a function of the reflection surface environment,[86] their density is notable.

4.1.1 Models for Multipath Delay Spread of UWB Signals

Various models for multipath delay power profiles have been proposed. A favorite analytical model features an exponentially decaying profile, beginning at the signal arriving on the shortest path, with the exponential profile populated by multipaths with Poisson arrivals. That is, the channel impulse response is modeled by[86,87,88]

$$h(t)=\sum_{k=0}^{N_p-1}\beta_k e^{j\theta_k}\delta(t-\tau_k) \tag{4.1}$$

where the parameters β_k, θ_k, and τ_k are generally randomly time-varying functions and N_p is a random number of detectable multipath components.[89],[90] The multipath power profile (MPP) is given by

$$\overline{\beta_k^2}=\mathrm{MPP}(\tau_k)=\overline{\beta_0^2}e^{-\tau_k/\gamma} \tag{4.2}$$

where γ scales the rate of exponential decay. The moments of the multipath delays are given by

$$\overline{\tau^n}\equiv\frac{\sum_k \beta_k^2\tau_k^n}{\sum_k \beta_k^2} \tag{4.3}$$

Using this definition of the moments, the RMS delay spread, denoted σ_τ, is defined as the standard deviation of the random multipath delays. The Poisson character of the arrivals is expressed by the following exponential condition probability density functions (pdfs) for the interarrival times:

$$p(\tau_k\mid\tau_{k-1})=\lambda\exp\{-\lambda(\tau_k-\tau_{k-1})\} \tag{4.4}$$

where λ is the Poisson arrival rate.

With the increased multipath density of wideband and UWB waveforms, a more detailed model for multipath arrivals, due to Saleh and Valenzuela[87], has been found useful. As illustrated on the left side of Figure 4.3, the S-V model characterizes multipaths as arriving in

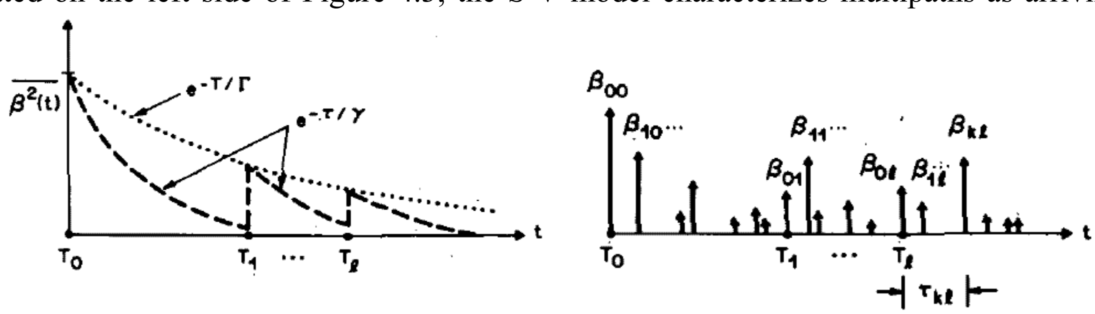


Figure 4.3 Saleh-Valenzuela model of multipath arrivals (from reference 86).

clusters, each with an exponential multipath intensity profile (MIP), and with the average strength of the clusters also decaying exponentially, with a particular realization shown on the right side of the figure. This double-exponential model assumes that the channel impulse response has the form

$$h(t) = \sum_{l} \sum_{k} \beta_{kl} e^{j\theta_{kl}} \delta(t - T_l - \tau_{kl}) \tag{4.5}$$

where the parameters β_{kl}, θ_{kl}, T_l, and τ_{kl} are generally randomly time-varying functions. The multipath power profile is given by

$$\overline{\beta_{kl}^2} = \overline{\beta_{00}^2}\, e^{-T_l/\Gamma}\, e^{-\tau_{kl}/\gamma} \tag{4.6}$$

where Γ scales the rate of exponential decay of the clusters and γ scales the rate of exponential decay of multipaths within a cluster. The Poisson character of the arrivals is expressed by the following exponential condition probability density functions (pdfs) for the interarrival times:

$$p(T_l \mid T_{l-1}) = \Lambda \exp\{-\Lambda(T_l - T_{l-1})\} \tag{4.7a}$$

and

$$p(\tau_{kl} \mid \tau_{k-1,l}) = \lambda \exp\{-\lambda(\tau_{kl} - \tau_{k-1,l})\} \tag{4.7b}$$

where Λ is the Poisson arrival rate for the (overlapping) clusters and λ is the Poisson arrival rate of multipaths within a cluster. Thus for the S-V model the following parameters are specified: Λ, λ, Γ, and γ. In addition to these parameters, for simulations and testing, a model for the probability distribution of the multipath amplitudes or powers is needed; this aspect of the modeling is discussed below in Section 4.1.2, as is the question of time resolution and receiver threshold as they affect the number of multipaths observed.

Fits of UWB signal data to the S-V model indicate that there is no single set of parameters that fits all situations. For testing of IEEE 802.15 UWB WPAN physical layer proposals, simulation of multipath environments using the S-V model is recommended by some researchers for the four "typical" scenarios whose parameters are listed in Table 4.1[91], while other researchers recommend a larger set of scenarios.[92]

Table 4.1 Parameters of the S-V multipath model for typical UWB scenarios (from ref. 91).

Model Parameters	Channel Model 1	Channel Model 2	Channel Model 3	Channel Model 4
Λ	0.0233/ns	0.4/ns	0.0667/ns	0.0667/ns
λ	2.5/ns	0.5/ns	2.1/ns	2.1/ns
Γ	7.1 ns	5.5 ns	14.0 ns	24. 0 ns
γ	4.3 ns	6.7 ns	7.9 ns	12 ns

4.1.2 Radiowave Phenomenology for UWB Multipaths

In addition to measuring and modeling for the arrival times and decay rates of multipath reflections, statistics have been compiled for the variation in the multipath amplitudes and powers. In many scattering situations, the received signal amplitude R has a Rayleigh distribution, which has the pdf[29]

$$p_R\left(x\right)=\frac{2x}{b}e^{-x^2/b} \tag{4.8a}$$

where b is the mean value of R^2. The pdf of $S=R^2$, which relates to the signal power, is found by transforming (4.9) to obtain

$$p_S\left(x\right)=\frac{1}{b}e^{-x/b} \tag{4.8b}$$

The exponential pdf in (4.8b) is corresponds to a special case of the pdf for b times a gamma random variable (RV) with parameter m, for the case of $m=1$.[87] The general case is given by[93]

$$p_S\left(x;m\right)=\frac{1}{b\Gamma\left(m\right)}\left(\frac{x}{b}\right)^{m-1}e^{-x/b} \tag{4.9}$$

where $\Gamma\left(\cdot\right)$ is the gamma function. Note that the mean of the distribution in (4.9) equals mb and its variance equals mb^2, so that normalizing the RV by m will create an RV with the same mean value for all m, namely b, and a variance that decreases with m, namely b^2/m. In this manner, Nakagami[94] developed a method for modeling the statistical variation of fading signal amplitudes that sometimes were Rayleigh-distributed, and sometimes had less variation. Transforming (4.9) by $S/m=r^2$, we obtain the Nakagami m-distribution's pdf:[87,95]

$$p_r\left(x;m\right)=\frac{2mx}{b\Gamma\left(m\right)}\left(\frac{mx^2}{b}\right)^{m-1}e^{-mx^2/b} \tag{4.10}$$

which is plotted on the right side of Figure 4.4, alongside the pdf for the square of the signal amplitude, S/m, which is shown on the left side.

With the foregoing review of fading amplitude statistical models in mind, we note that measurements of the amplitudes of multipaths from UWB pulse signals have been analyzed and were found *not* to be well modeled by the Rayleigh distribution. Instead, the statistical variation in the amplitudes relative to the MIP frequently have a Nakagami distribution[8] or a lognormal distribution[91,96]. For the lognormal distribution, the multipath amplitude in dB units has a Gaussian distribution about its mean value.

The experimental results indicating that the fading of the amplitudes of pulsed UWB signal multipath reflections tends to be less severe than Rayleigh fading appears to be due to the fact that the duty cycle of the signal is low and the various reflected pulses do not overlap in time. In the absence of any mutual interference among the multipaths, there still would be variation in their amplitudes at the receiver due to shadowing, which tends to induce a lognormal distribution of amplitudes.

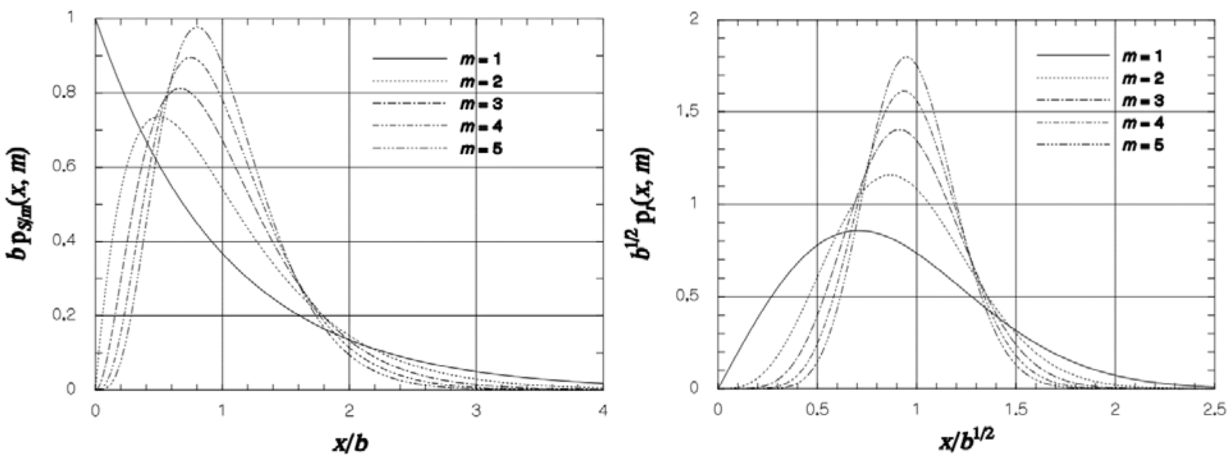


Figure 4.4 Nakagami *m*-distribution pdfs for *S/m* and *r*.

4.2 Advantages of Multipath Persistence

The fact that UWB signals produce many resolvable multipaths at the receiver has been discussed above in Section 3 in terms of the receiver processing required and of the potential for diversity gain. Here we discuss the potential advantages of the multipaths that are specifically related to their fading characteristics.

4.2.1 Low Fade Margins

When a radio communication signal is subject to "large-scale fading" (shadowing) or multipath-induced ("small-scale") fading, the received SNR is a random variable. Typically the link budget for the communication system uses average or median values of link quantities such as propagation loss in order to estimate the median received SNR. In dB, the margin on the link is the difference between the projected median SNR value and the SNR value required for acceptable link performance:

$$M_{dB} \equiv \text{Margin (dB)} = \text{SNR}_{\text{med}}\text{ (dB)} - \text{SNR}_{\text{req}}\text{ (dB)} \tag{4.11}$$

So, if the received SNR in dB equals $\text{SNR}_{\text{med}} + X$, where X is a random variable, then the probability that the received SNR is greater than or equal to the required value is given by

$$\Pr\left\{\text{SNR} \geq \text{SNR}_{\text{req}}\right\} = \Pr\left\{\text{SNR}_{\text{med}} + X \geq \text{SNR}_{\text{req}}\right\} = \Pr\left\{X \geq -M_{dB}\right\}$$

$$= \int_{-M_{dB}}^{\infty} p_X\left(x\right) dx \tag{4.12}$$

It is obvious from (4.12) that an infinite value of margin guarantees that the SNR will always meet the requirement, while a finite margin means that the requirement will be met only a certain percentage of the time. A link with zero margin will fail 50% of the time if the median value of X equals zero dB, which is the case with lognormal shadowing. For Rayleigh fading, the link will fail 63% of the time if there is zero margin; a margin of 10 dB is needed to achieve a link failure rate of 10% due to Rayleigh fading. Figure 4.5 shows the dependence of M_{dB} on the link

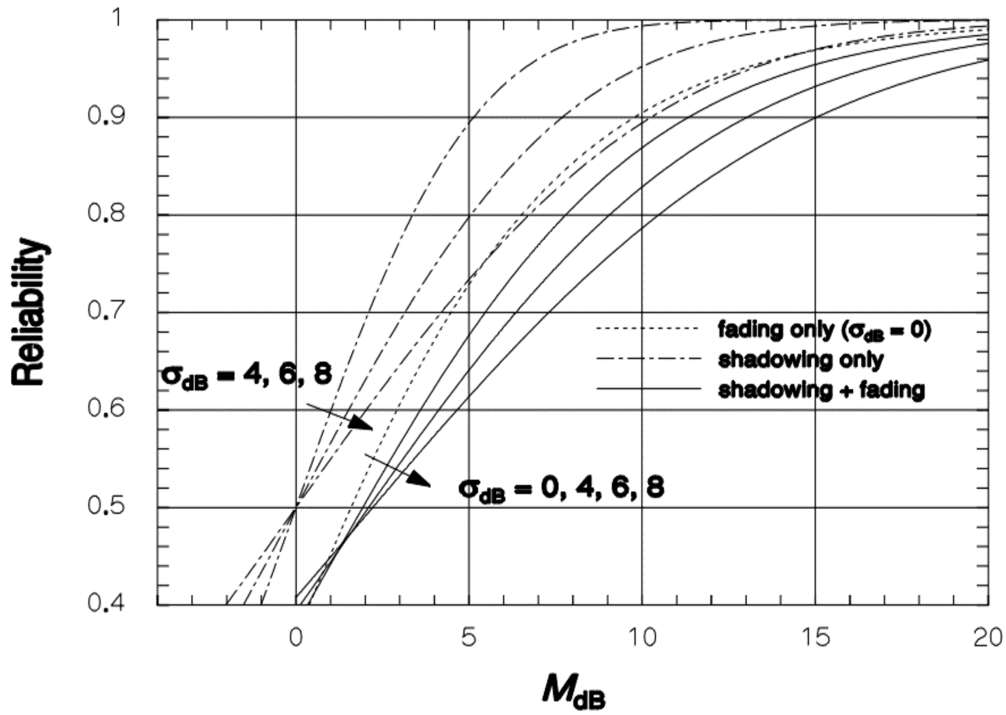


Figure 4.5 Link reliability vs. margin for shadowing, fading, and both (from ref. 97).

reliability for lognormal shadowing, Rayleigh fading, and a combination of the two types of fading.[97]

The concept of "fade margin" used in mobile radio communication systems traditionally has analog voice transmissions in view. It should be noted that the system performance of digital communication systems is evaluated in terms of bit error probability, and the required SNR or bit-energy-to-noise-density ratio (E_b/N_0) is given as a different amount depending on the channel; the required SNR under fading is, of course, higher—25 to 30 dB *with* Rayleigh fading compared with 9 to 14 dB *without* Rayleigh fading, depending upon the desired bit error rate. The practice is to state the required SNR under the assumed small-scale fading conditions and to calculate the margin for the link budget based on large-scale fading, usually lognormal.

With this background on fade margins, it is clear that a reduction in small-scale fading variability will have a profound effect on the link budget. As discussed in the previous section, multipath components of UWB pulsed signals, because of their low duty cycle, tend not to overlap and thus tend not to interfere with one another to the same degree as for conventional CW signals. It is reported that the total received energy of an UWB signal varied only by about 5 dB as the receiver was moved around in a room, and did not experience the deep fades that are common for narrowband signals. For this reason, it is conjectured that the link budget for UWB systems can afford to include a much smaller margin to allow for small-scale fading.[98]

4.2.2 Low Power

Going along with smaller fade margin requirements for UWB pulsed signals due to the properties of the multipath components is a smaller power requirement. Several dB less margin in the link budget translates into significant reduction in the transmitted power in Watts. Contributing also to low power requirements for UWB signals is their low duty cycle and the various system gains that are available—processing gain from pulse coding and diversity combining gain.

4.3 Disadvantages of Multipath Persistence

In addition to the disadvantage of UWB receivers having to process large numbers of multipath reflections that was discussed above in Section 3.3.1, there are other propagation phenomena that are associated with the fact that the multipaths persist for UWB waveforms. Here we discuss the scatter in angle of arrival (AOA) that has been observed for these waveforms.

4.3.1 Scatter in Angle of Arrival

There is a great variety in the AOAs of the multipath components of a UWB waveform, as reported in the literature.[13,99,100,101,102] In part, this result is due to the variety of scattering environments that are associated with the measurements. For example, measured TOAs and AOAs of pulsed UWB signals transmitted from a single location and received at different NLOS locations on the same floor of a building are shown in Figure 4.6.[102] In some of the receiving locations there is a very weak correlation between TOA and AOA, while in other locations there is a definite direction from which the pulses appear to be arriving. Even for the presumably same reflecting source—giving rise to a particular multipath cluster of arrivals—there is a fairly wide distribution of AOAs about the mean value that tends to have a double-exponential (Laplacian) probability distribution of the form

$$p_A(\theta) = \frac{1}{\sigma\sqrt{2}} e^{-\sqrt{2}|\theta|/\sigma} \tag{4.13}$$

with the parameter σ taking values from 20° to 40° in the test environments reported.[99,100,101,102] An example fit of AOAs relative to a cluster mean value of AOA is shown in Figure 4.7. A comparison of S-V multipath model and Laplacian distribution parameters from different buildings is shown in Table 4.2.[99]

In the indoor propagation environment it is not surprising that there is such a dispersion of arrival angles because of the many objects, including furniture, that are typically placed throughout a building. In outdoor situations as well it is the general case that multipath signal components arrive from various directions (not only in the so-called plane of propagation in which path profiles are often visualized).[103] What we are concerned with here is the apparent “richness” of AOA scatter for pulsed UWB signals due to the resolvability and non-mutually interfering properties of these waveforms (affecting also the measurement process),[99] and possibly due to other factors, such as the ability of wideband pulses to penetrate various building materials with less attenuation than narrowband signals.

The research in the area of AOA for communication signals in multipath environments is still progressing. It may be some years before AOA measurements can be reliably exploited for localization purposes to enhance the solution based on time measurement alone.

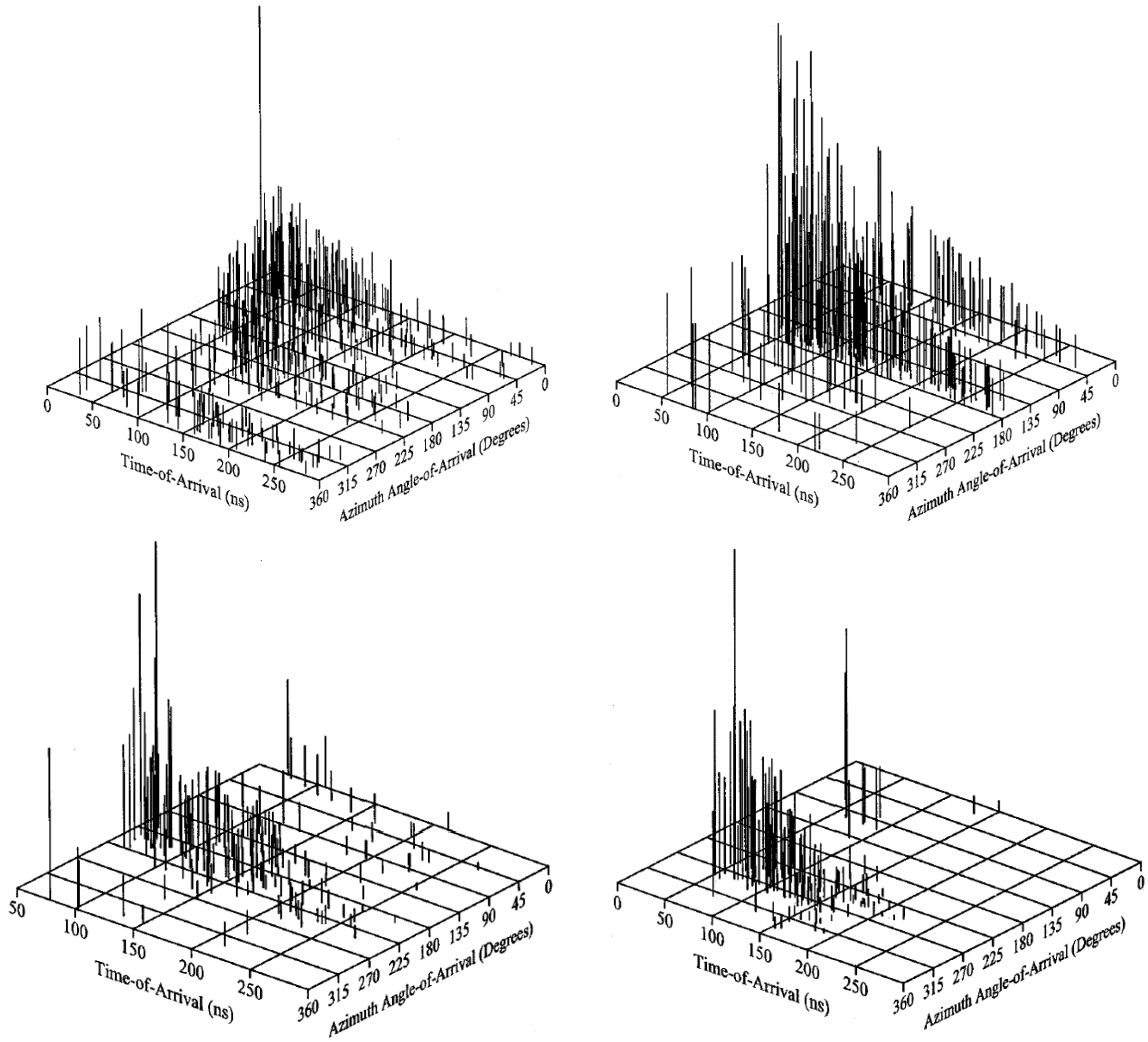


Figure 4.6 Multipath TOA vs. AOA for different indoor locations (from ref. 101).

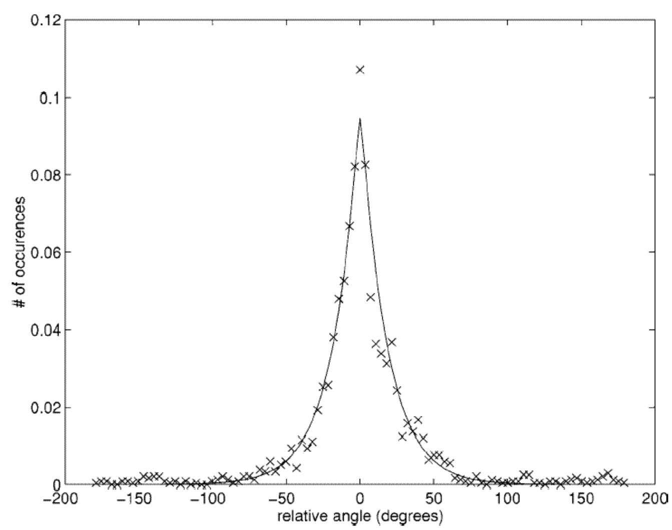


Figure 4.7 Example of AOA distribution about the mean for individual clusters (from ref. 100).

Table 4.2 Comparison of multipath and AOA parameters in different buildings (ref. 99).

Parameter	Ref. 99	Ref. 101 A	Ref.101 B	Ref. 86
Γ	27.9 ns	33.6 ns	78.0 ns	60 ns
γ	84.1 ns	28.6 ns	82.2 ns	20 ns
$1/\Lambda$	45.5 ns	16.8 ns	17.3 ns	300 ns
$1/\lambda$	2.3 ns	5.1 ns	6.6 ns	5 ns
σ	37°	25.5°	21.5°	—

4.4 Applications of Multipath Persistence

The numerous resolvable multipath components of received pulsed UWB signals can be combined to effect diversity gain, as discussed above in Section 3.2.2. Here we note from the literature how the persistence of UWB multipaths, the phenomenology of which was discussed above in Section 4.1.2, has found application in a practical system.

4.4.1 NLOS Communications Indoors and on Ships

Tracking of expensive equipment and critical inventory items is often performed using RF identification (RFID) techniques,[104] both passive (such as bar codes) and active. Active techniques utilize radio transponder "tags" that are placed on the item to be tracked, and that emit a signal suitable for localization when paged by a search radio device.

Usually, localization of a radio signal's source is best done under LOS conditions, and multipath components are a "nuisance" rather than an aid to the localization solution. For that reason, it has been difficult to use conventional RFID techniques aboard ships because radio transmissions aboard ships and in other situations involving metal containers feature many reflections. However, recently it has been found using the system illustrated in Figure 4.8[14] that UWB signals propagate well aboard ships, into corners, "through cracks between containers," and around objects, so that reasonably accurate positions can be determined. The signal used in the system of Figure 4.8 was a pulsed UWB waveform with 400 MHz instantaneous bandwidth.

It is notable that the shipboard environment is especially difficult for RF operations. Using another UWB pulsed system as well as network analyzer measurements, a survey of the container ship on which the RFID system was tested[105] found that the delay spread of multipath components was about 1 microsecond for multipath amplitudes down 6 dB from the peak and 3 microseconds down 20 dB from the peak. The large delay spread observed was attributed to the combination of the shipboard reflective environment and the non-fading of the UWB pulses. An example shipboard test path is shown in Figure 4.9 and the received digital sampling oscilloscope trace for this path is shown in Figure 4.10.

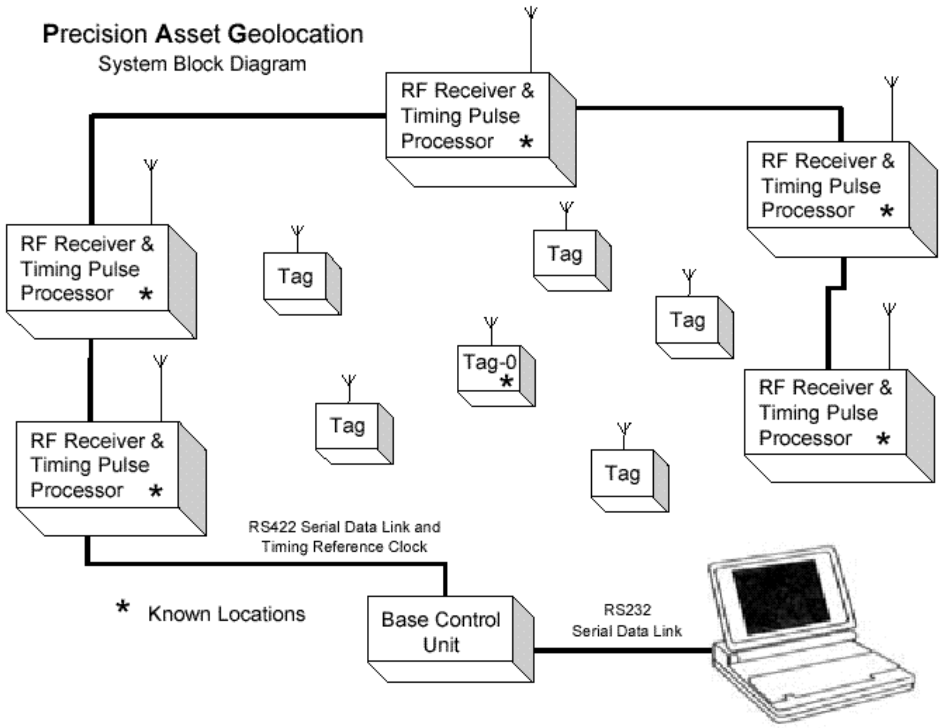


Figure 4.8 Precision asset location system using UWB signals (from ref. 14).

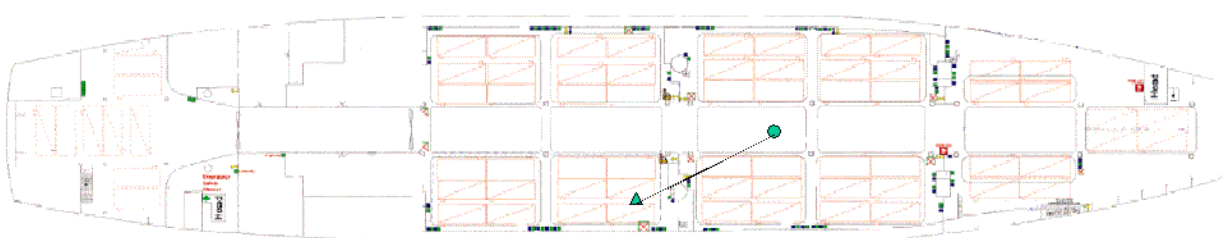


Figure 4.9 Shipboard transmission path through bulkhead (from reference 105)

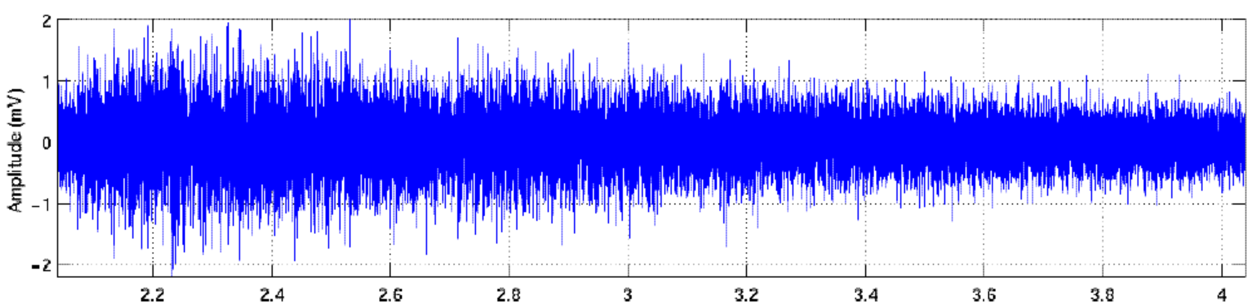


Figure 4.10 Digital sampling scope view of signal received for path of Fig. 4.9 (ref. 105).

5. Carrierless Transmission Property of UWB Signals

We have discussed the carrierless (baseband) aspect of pulsed UWB waveforms to some extent previously in Section 1.3, primarily in regard to the effect on spectrum. Here we focus on the effect of carrierless operation on the type of hardware that is used.

5.1 Background on UWB Transmission

In this Section, we provide a brief survey of the configurations of radio components that are involved in transmitting and receiving UWB carrierless waveforms, including antennas, based on the open literature.

5.1.1 Transmitter and Receiver Configurations

The earliest radio transmissions by Marconi were UWB in the sense that Marconi's spark-gap transmitter in effect generated short pulses and occupied a relatively large bandwidth, but means for using spreading gain to enable multiple access were not available. Soon after the potential of radio as a medium for communication was understood, efficient methods for sharing the medium were sought and found that involved heterodyning and narrowband, tunable transmitters and receivers. An example superheterodyne receiver diagram[106] is given in Figure 5.1 that features double conversion to reject harmonic images of the signal that are unwanted byproducts of the heterodyning (multiplication) operations. With the proliferation of narrowband wireless devices today and the continual development of new devices for the wireless market, the trend is for the transmitters and receivers to become smaller and simpler. For example,[107] Figure 5.2 shows a typical digital heterodyne receiver using a surface acoustic wave (SAW) filter and a "one chip" receiver based on direct conversion to baseband that does not require the SAW filter. As such advances in digital processing became cheaper and more efficient, the use of UWB waveforms in radar and communication applications also has become feasible.[33]

Ideally in carrierless (baseband) transmission, as illustrated in Figure 5.3, the radio system can operate without local oscillators and the sometimes complex filtering needed to

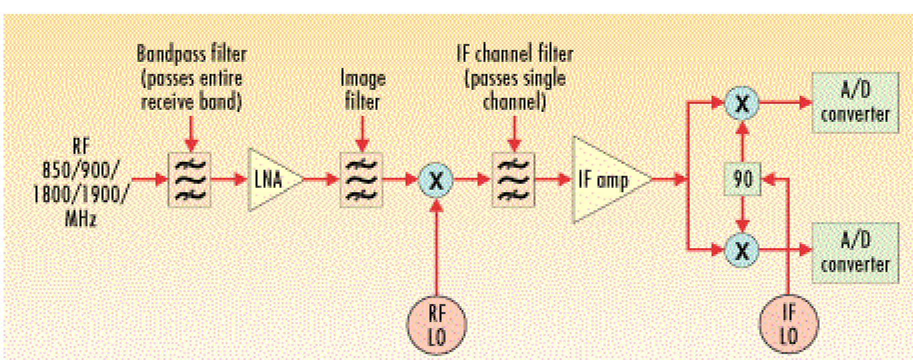


Figure 5.1 Double-conversion superheterodyne receiver (from reference 106).

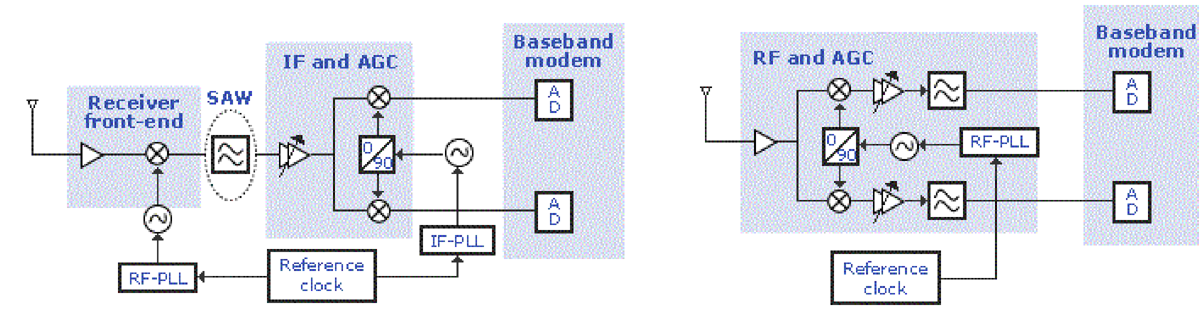


Figure 5.2 Typical digital heterodyne receiver (left) and single-chip direct conversion receiver (right) that integrates RF and IF without a SAW filter (from ref. 107).

Figure 5.3 Concept of UWB baseband system implementation (from reference 108).

control emissions and spurious radiations that accompany heterodyning. It is almost, but not quite, as simple as utilizing the same kind of transmissions as those that are unintentionally emitted by the printed circuit board of digital devices, with the antenna connecting directly to the integrated circuit containing the baseband processing logic.[108]

5.1.2 Antenna Configurations

"Classical" antenna theory and practice is well understood and well developed for sinusoidal transmission and reception. Predicting and determining antenna radiation patterns for UWB signals is not as familiar to engineers because the effect of the antenna on the radiated signal is more critical—all antennas differentiate the input signal one or more times, depending on the antenna, and while derivatives of sinusoids are simply phase shifts of sinusoids, the whole shape of UWB waveforms can change due to the antenna.[109] While existing antennas can radiate UWB baseband waveforms, they will not necessarily do so efficiently or with the desired pattern because of the wide bandwidth required. For that reason, it is recommended that antennas intended for UWB applications be specially designed for the waveform.[109] The theory for such a design is basically known, but sometimes is controversial.[110,111,112]

One approach starts from a basic conical antenna shape, used for generating reference fields and waveforms,[113] and calculates a modified conical radiating surface for delivering the desired time waveform shape at a specified distance; a comparison of the far-field waveforms generated by this method and using other antennas is given in Figure 5.4,[112] in which it is assumed that an ungrounded antenna is charged to a certain level, then grounded; the current discharging through the antenna generates a narrow pulse waveform. (Note: 100 time units in Figure 5.4 equals 1 ns.)

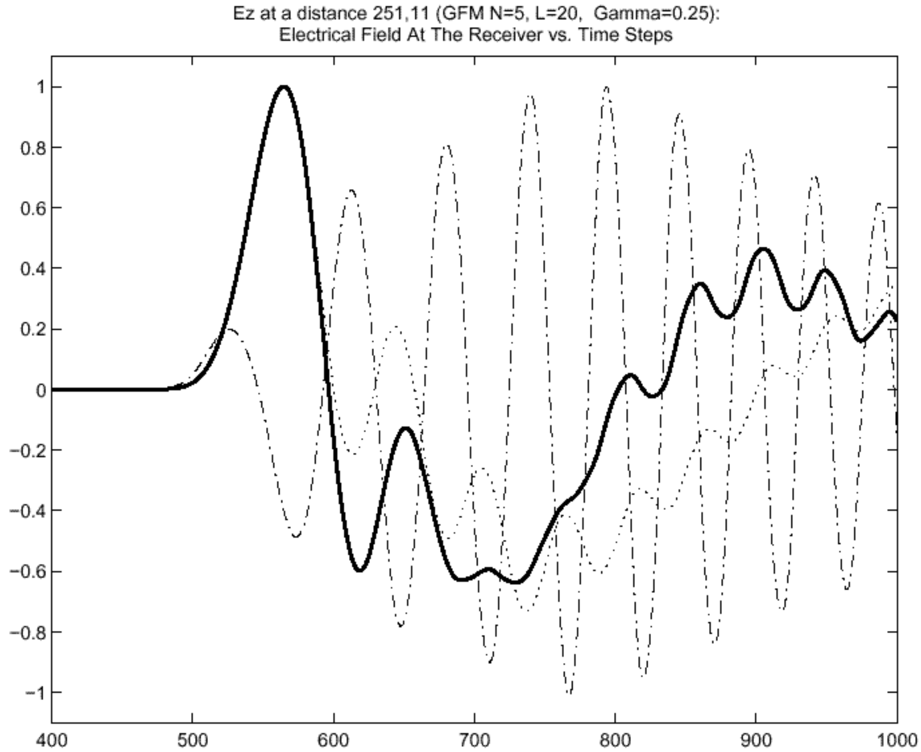


Figure 5.4 Example time domain waveforms generated by antenna charging and discharging: modified conical (solid-line), conical (dot-dash), and wire (dotted) (from ref. 112).

Generally, it is not desirable to generate UWB pulses by direct excitation of an antenna in which the shape and bandwidth of the pulse depends on the antenna configuration[114] because inadvertent or intentional bending of the antenna, or bringing it near a metal surface, can change the center frequency of the waveform and cause significant interference to existing systems. Instead, the pulse shape should be determined by the transmitter circuitry before it reaches the antenna. This philosophy of antennas for UWB signals is dominant because of the FCC restrictions on UWB emissions, so the emphasis in antenna design and selection is in finding configurations that match the pulse generation circuitry well and have sufficient bandwidth. Several UWB antennas based on these considerations are commercially available[115] or are included with UWB chip sets.[116] Typically in these cases, the antenna is similar in size and appearance to antennas that are etched on printed circuit boards.[117]

An exception is a 4-cm dual-monopole "large current radiator" antenna system for an UWB geolocation system[79] that is driven by a bridge circuit in order to preserve the shape of the impulse. A photograph of this antenna system is shown in Figure 5.5 and its performance is shown in Figure 5.6 in comparison with that of a 6-cm electric dipole, which differentiates the pulse shape. The respective effects of the two antennas compared in Figure 5.6 on the waveform shape is consistent with their frequency response characteristics, in view of the fact that the Fourier transform of the derivative of a finite-energy waveform is given by[118]

$$F\left\{\frac{d}{dt}x(t)\right\} = j\omega F\left\{x(t)\right\} \tag{5.1}$$

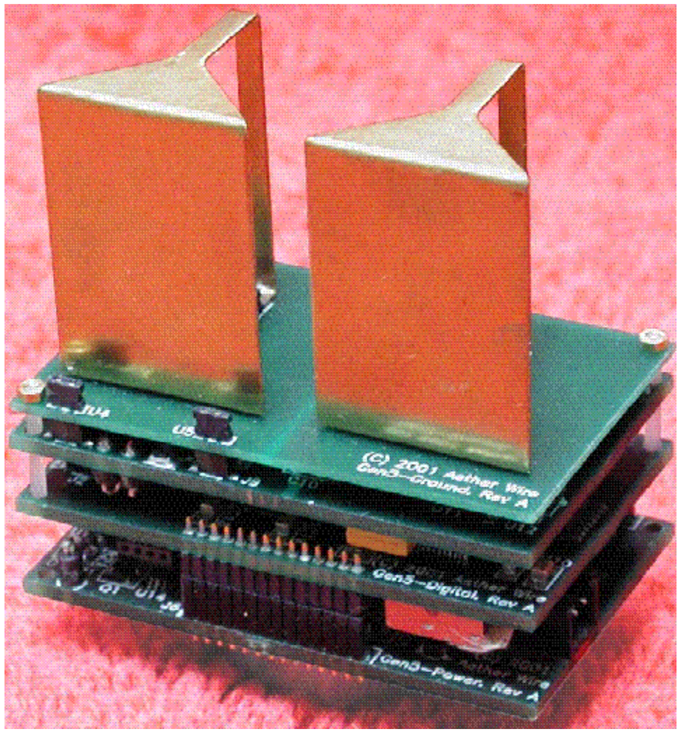


Figure 5.5 Large current radiator UWB antenna system (from reference 79).

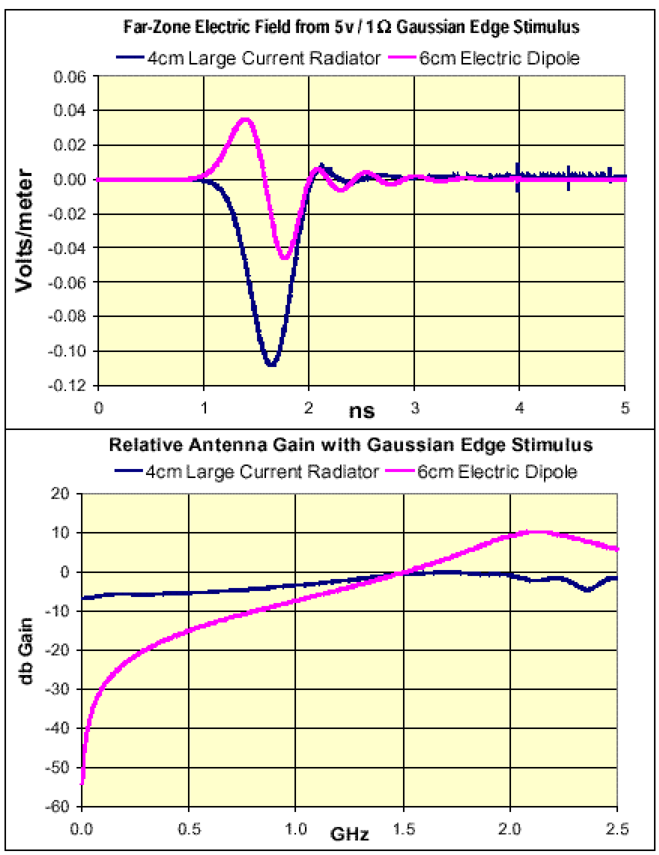


Figure 5.6 Performance of antenna system of Figure 5.5 (from reference 79).

5.2 Advantages of Carrierless Transmission

Certain implementation advantages accrue to carrierless transmission. Here we summarize them briefly under the headings of hardware simplicity and hardware size.

5.2.1 Hardware Simplicity

Since heterodyning, tuning, and IF filtering are not required for carrierless transmission, UWB transceivers can be built with much simpler RF architectures than narrowband systems with fewer components and the low-power transmissions do not require a power amplifier.[33] The UWB baseband (carrierless) functionality has been described as having the following advantages:[108]

- The transmitter needs no D/A converter.
- The receiver A/D converter operates at the bit rate, as opposed to the Nyquist sampling rate.
- The A/D converter does not need to be high resolution, since the information is not embedded in signal phase.
- No digital pulse shaping filter is used.
- No equalizer is needed to correct carrier phase distortion.
- With low order modulation such as antipodal signaling (as in BPSK), the transmission is reliable enough in many instances to do without forward error correction (FEC) and the corresponding decoder at the receiver.
- Low-power, small, mature CMOS technology can be used.

The relevance of these potential advantages depends on the particular application and the particular operational scenario.

5.2.2 Small Hardware

Because UWB carrierless operation uses fewer RF components, the size of the hardware is primarily a function of the integrated circuit technology that is used. Existing UWB baseband processing chips using CMOS technology are comparable in size to chips for other communication system components, such as cellular telephone handsets.

5.3 Disadvantages of Carrierless Transmission

The potential and realized advantages of carrierless UWB transmission are naturally offset by certain disadvantages or costs. The seriousness of a particular "disadvantage" depends on the state of the art, the application envisioned for the technology, and economic factors. Here we focus on the consequences of using carrierless transmission in terms of the relatively more complex signal processing that must be used to accomplish multiplexing and beamforming, and on the uncertainty involved with the antenna form factor that can be achieved.

5.3.1 Complex Signal Processing

For narrowband systems using carriers, frequency-division multiplexing is very straightforward, and the development of a communications or other narrowband device need only consider the band of frequencies directly affecting itself, with due care to minimize interference to out-of-band systems by emission control techniques including filtering and waveshaping. For carrierless transmission and reception, every narrowband system in the vicinity is a potential interferer and also every other carrierless system. Thus the carrierless system must rely on relatively complex and sophisticated signal processing techniques to recover the communications data from this noisy environment.

5.3.2 Inapplicability of Super-resolution Beamforming

For narrowband radio systems, adaptive beamforming using multiple antennas is being investigated as a means of spatial reuse of time and frequency resources in cellular communication systems. A beam is formed by phasing the different antennas so that the combined signal's carrier is coherent when sent to, or received from, a particular direction. Achieving narrow beams with small numbers of antennas is possible using "super-resolution" beamforming based on unequally-spaced antennas.

Since the theory of beamforming and super-resolution beamforming is based on the phase relationships among sinusoidal waveforms, it does not directly apply to UWB systems using pulses. However, there are methods for discriminating between coded pulse trains arriving from particular directions[119] that makes use of the fact that the TDOA of the coded pulse train between two antennas is dependent on the angle of arrival.

5.3.3 Antenna Form Factor

UWB pulse transmissions utilize antennas in the "current mode" as opposed to the "resonant mode." At present, the design of broadband nonresonant antennas that fit the form factor (size and shape) of the rest of the hardware is a challenge.[33] Examples were given in Section 5.1.2 of UWB antennas that are relatively small and use various emissions techniques, not necessarily optimal. The "disadvantage" of antenna form factor in connection with UWB consists of the fact that it is largely unknown due to the relative novelty of UWB transmission for most communication applications.

The high RF frequencies and large bandwidth of UWB systems render them eligible for small antennas, with perhaps a tradeoff between size and efficiency/gain.[120] For conventional (narrowband) radios, transmission fractional bandwidth in term of the antenna Q (quality factor) is theoretically related to antenna size[120,121] by the following expression:

$$\frac{1}{B_{rel}} \approx \frac{1}{6\pi^2\left(V/\lambda^3\right)} + \left[\frac{1}{6\pi^2\left(V/\lambda^3\right)}\right]^{1/3} \tag{5.2}$$

where V is a spherical volume enclosing the antenna and λ is the center frequency. For example, a relative bandwidth greater than 25% corresponds to a ratio of V/λ^3 greater than about 73%.

The quantitative extension of these classical results to extremely wideband systems is not an exact science, although the tradeoffs still dictate the same general trends.

5.4 Communication Applications of Carrierless Transmission

The potential for high-rate transmission using UWB waveforms follows from the bandwidth of the signal. Some communication applications for UWB making use of the high-rate potential were described in Section 2.4. Here we consider applications that specifically make use of the carrierless transmission property of UWB waveforms for communication purposes.

5.4.1 Smart Sensor Networks

The potential for low-power, simple hardware using carrierless transmission makes UWB technology an attractive alternative for distributed sensor networks. Several projects are ongoing to determine the feasibility of using UWB for networks of small, inexpensive sensors of various types. Among these is a focused project at the Rutgers WINLAB to perform system-level prototyping aimed at validating UWB in context of Infostations and/or sensor network applications.[122] Currently this project is examining MAC layer architecture and issues for the networking as well as channel propagation characteristics.

The concept of low-power sensor-radios that can organize themselves for collaborative signal processing and multihop connectivity is being studied under the "smart dust" project at Berkeley, and the same general objectives are being pursued under a short-range "communication in the background noise" UWB sensor-radio project.[123] The Berkeley UWB sensor-radio is designed to work below 960 MHz with a variety of antenna types and generates carrierless pulses by switching baseband circuit components. The radios transmit packets of monopulse waveforms that encode PN-code spread data in the amplitudes of the pulses; as illustrated in Figure 5.7, at the receivers the incoming signal is sampled during the expected pulse-arrival time window only to save power and the samples are processed by matched filters. The very high sampling rate is accomplished using an array of simple A/D converters instead of a fast single A/D converter in order to minimize power consumption.

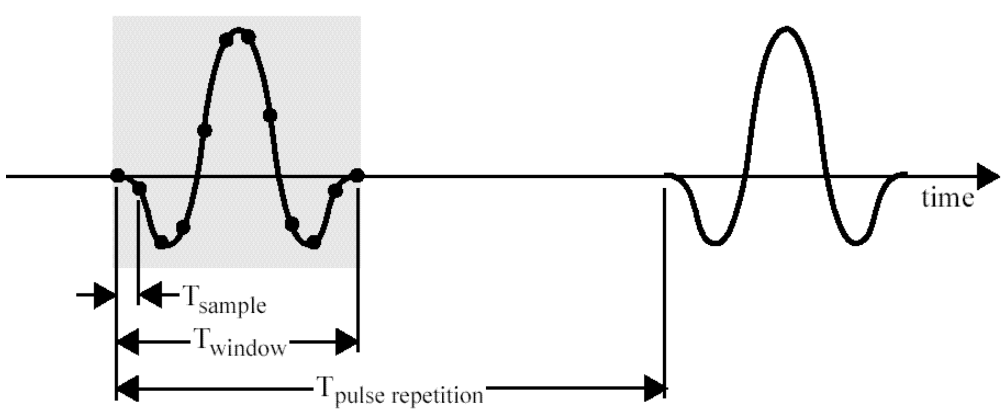


Figure 5.7 Receiver sampling of carrierless pulse transmissions (from reference 123).

The Aetherwire UWB sensor-networking concept[10] utilizes a Gaussian doublet (as illustrated previously in Figure 1.10) for the basic chip waveform and features burst packet communications among radios that can be clustered by means of an ad hoc routing algorithm and geolocated using the timing of pulse arrivals. As illustrated conceptually in Figure 5.8, this networking capability can be exploited to locate and get multihop communications from the sensors, using very low power.

Military sensor network applications in which UWB waveforms are being considered include joint naval warfare sensor network applications[124] "information warfare" sensor networking, the latter described in an SBIR proposal as follows:[125]

> We propose to develop an information warfare sensor network based on Time-Modulated Ultra-Wideband radio. TM-UWB radio has several characteristics which make it ideal for low cost covert recovery of wideband data. The only signals transmitted by UWB radio are pulses generated pseudo-randomly in time. The Fourier transform of a perfect impulse is constant at all frequencies. The pulses we are currently using are ½ nanosecond in duration and the energy extends approximately from .5 to 4 gigahertz. The energy content in any conventional frequency band is far below the noise, making TM-UWB transmission very difficult to detect unless you know the specific pseudo-random sequence of the pulses. With TM-UWB there is no carrier frequency, there is no up conversion and no down conversion required, and the output stage is a single transistor which creates a binary pulse, all resulting in decreased radio size and complexity. The duty cycle of the pulses is approximately 1/500, resulting in low power consumption because 99.8% of the time, nothing is being transmitted. During phase I we will demonstrate UWB communication at 5 miles with at least two simultaneous channels. We will also evaluate several innovative system concepts related to the IW sensor network, including ad hoc network protocol and range measurement capability.

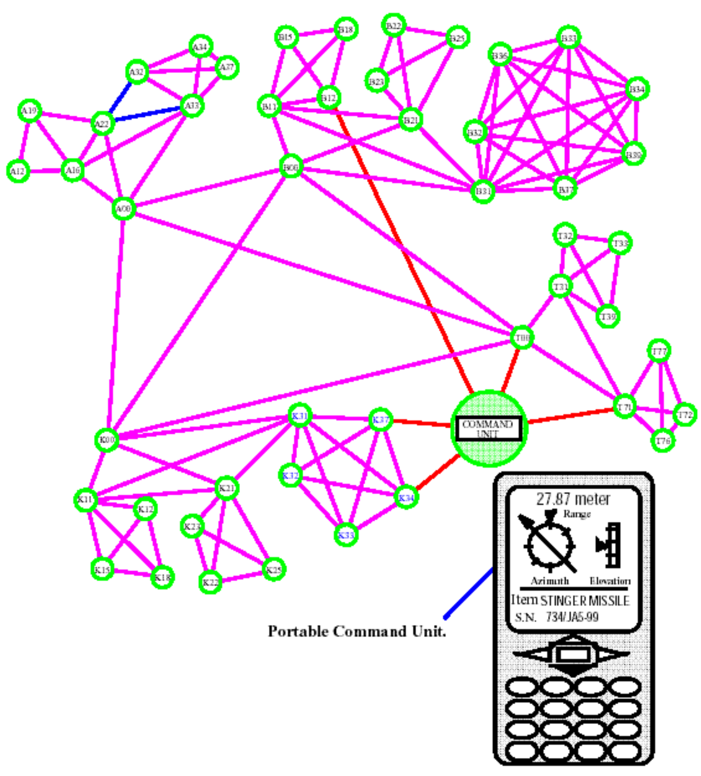


Figure 5.8 Combined network clustering and geolocation (from ref. 10).

6. Summary and Assessment

In this section, based on the material in Sections 1 to 5, we perform an assessment of the current status of UWB technology with respect to the desired performance of communication systems in the NETEX environment.

6.1 Synopsis of the NETEX Requirements

The objective system characteristics for the NETEX program, as cited previously in Section 1.1.2, can be summarized as requiring a communications networking system (potentially using UWB technology) that is "robust" in "complex and hostile" environments and that is compatible with existing spectrum allocations.

The keys to the technical (*i. e.*, performance) requirements are the words "robust" and "environment," for the following reasons:

- All communication systems (waveforms, modulations) with the same capacity will perform about the same in an ideal environment.
- All systems are subject to the same physical effects of non-ideal environments, such as urban land-mobile and indoor propagation channels.
- Margin (excess power) and/or special processing techniques are needed to overcome the effects of non-ideal environments.
- Some systems have properties that facilitate the use of special processing to make them "robust" in a particular situation.
- The question is therefore whether UWB has such properties with respect to the NETEX environment.

In the context of considering the use of UWB technology, the spectrum allocation problem is included in the consideration of the coexistence of UWB systems with other systems that may be operating in the same area, both in terms of interference *to* those other systems from the UWB system and in terms of interference *from* those other systems to the UWB system.

6.2 Synopsis of Potential NETEX Applications and Environment

Any assessment of the potential of a particular technology to fulfill the objectives of a particular application must be conditioned on the scenarios that are implied by that application, including the environmental factors that apply.

6.2.1 NETEX Application Scenarios

As implied by the discussion of NETEX program goals in Section 1.1.2, the objective system is a radio communications network that can be configured rapidly and operate successfully in complex and hostile environments. The scenarios implied by these descriptions of the desired operational characteristics of the objective system include the following:

- Urban combat or search and rescue operations
    - Mobile ad hoc communications network, possibly integrated with sensors
    - Geolocation of ad hoc network nodes
- Ad hoc networks for asset tracking in difficult environments such as aboard ship

6.2.2 NETEX Environmental Factors

The main environmental factors cited in the description of the objective system are implied by the following:

- "Complex and harsh" physical locations, including dense urban terrain
    - Multipath and clutter
    - Non-line of sight (NLOS) communications including transmission through building exterior and interior walls
- A hostile electromagnetic environment where jamming and interception attempts are assumed
    - Desirability of emitting as little power as possible and/or transmitting with low duty cycle
    - Desirability of using waveforms with high processing gain

6.2.3 NETEX Program Approach and Goals

The relative importance of the various properties of UWB systems cited in Section 1.1.1 and the issues related to their potential deployment are apparent from the NETEX program's approach and goals, which are stated as follows:[126]

Approach:

- Gain a thorough understanding of the effect of UWB system operation on military radio frequency (RF) receivers
- Characterize UWB systems and channel properties through a series of hardware tests and system simulations
- Modify emerging ad-hoc routing and multiple access protocols to utilize the unique capabilities of UWB systems
- Integrate UWB communications and sensors systems into an interoperating net

FY02 Goals:

- Establish and publish UWB Electromagnetic Interference (EMI) test methodology
- Perform a series of EMI tests of UWB systems against wide range of military RF receivers
- Develop UWB channel models and conduct UWB interference simulations

FY03 Goals

- Complete EMI tests of UWB systems against wide range of military RF receivers
- Identify the spectral masks and modes of operation of UWB systems that will not cause undesired operation of other devices
- Develop an improved UWB physical layer (improvement of >20dB in signal to interferer ratio, an increase of >20dB in receiver sensitivity or code gain, and an order of magnitude reduction in size and power)
- Develop ad-hoc networking and multiple access protocols to take advantage of the unique properties of UWB

6.3 Assessment

In this section, we conclude by assessing the validity of the various claimed advantages, disadvantages, and applications of UWB technology, as outlined in Table 1.1, with respect to the potential NETEX application scenarios and environmental factors. Given these scenarios and factors, the various claimed advantages, disadvantages, and applications have different degrees of relevance and importance—that is, significance to the NETEX program. In the following assessment, we discuss them in reverse order of significance.

6.3.1 UWB Advantages/Disadvantages/Applications of Lesser Significance

In the category of "lesser significance" we place the claims listed below for UWB that are listed in Table 1.1 and that were discussed individually in previous sections of this report.

- UWB technology's very wide bandwidth property offers the advantage of high-rate communications (cited in reference 3 and elsewhere) such as a high-rate WPAN.
    - Assessment: The claim that the use of UWB waveforms can provide high-rate communications is valid. The actual capacity that is realized will be a function of the modulation scheme and of the power and bandwidth limitations that are placed on UWB emissions to prevent interference to critical existing systems.
    - Rationale: This aspect of UWB technology is included among those of lesser significance to the NETEX program because the emphasis of the program is not on high rate communications *per se*. Also, the short range of WPANs (up to 10 meters) is not consistent with NETEX objective systems.

- UWB technology's very wide bandwidth property supports multiple-access communications (cited in reference 4 and elsewhere).
    - o Assessment: The claim that the wide bandwidth of UWB waveforms can support multiple-access communications is valid. Theoretical estimates of the multiple-access capacity for certain forms of UWB signaling are given in the literature.
    - o Rationale: This aspect of UWB technology is included among those of lesser significance to the NETEX program because the emphasis of the program is not on high-capacity multiple-access systems *per se*.
- UWB technology's carrierless transmission property offers the advantage of hardware simplicity and small hardware (cited in references 2, 4, and 10, among others).
    - o Assessment: The claim that carrierless transmission using UWB pulse waveforms requires simpler and smaller hardware is partially valid. The state of the art for conventional narrowband systems is such that very complex signal processing functions can be performed in very small packages. Also, there is some real-time signal processing complexity involved in realizing the potential of UWB waveforms, and the state of the art in UWB antennas is not advanced for the relatively high power systems contemplated by the NETEX applications.
    - o Rationale: This aspect of UWB technology is included among those of lesser significance to the NETEX program because the emphasis of the program is not on terminal size *per se*.
- UWB technology's carrierless transmission property has the disadvantage of not supporting super-resolution beamforming (cited in reference 13).
    - o Assessment: The claim that carrierless UWB systems do not support super-resolution beamforming is partially valid—although with UWB pulsed systems there is no carrier and therefore no carrier phase for fine resolution in terms of phase coherency, there is certainly the potential at least for the baseband equivalent of coherency using pulse sequences.
    - o Rationale: This aspect of UWB technology is included among those of lesser significance to the NETEX program because the program is not on beamforming *per se*, at least at this time.

6.3.2 UWB Advantages/Disadvantages/Applications of Greater Significance

In the category of "greater significance" we place the claims listed below for UWB that are listed in Table 1.1 and that were discussed individually in previous sections of this report.

- UWB technology's very wide bandwidth property offers the advantage that its lower frequencies penetrate walls and the ground (cited by references 2 and 4, among others), enabling, among other things, indoor localization applications (cited by references 2 and 3, among others).
    - o Assessment: Experience with UWB waveforms in ground- and wall-penetrating radar applications supports the validity of the claim that these waveforms have a

greater penetration capability that is related to the frequency-dependence of the penetration of materials by RF signals. However, as discussed in Section 2.2.4, the realization of this potential advantage is system- and scenario-dependent, and it may be argued that the multipath persistence property of UWB pulse waveforms, wherein UWB pulses are less subject to fading, has something to do with the penetration (NLOS) effects that have been observed.

- o Rationale: Although geolocation of ad hoc network nodes is a desired capability for NETEX objective systems, this aspect of UWB technology is not included among those of highest significance to the NETEX program because it is system- and scenario-dependent. Also, recent advances in massively parallel processing and "assisted" schemes may make indoor geolocation using GPS a robust and viable solution.[51, 52]

- UWB technology's very short pulse width property has the disadvantage of producing a very large number of multipath components (cited in reference 8 and elsewhere).
  - o Assessment: The claim that UWB pulse signals result in a very large number of multipath components is valid, having been observed by many researchers. It is therefore a necessary task of UWB (and any high-rate system) receivers to deal with the multipaths at least by extracting a particular path for processing.
  - o Rationale: This aspect of UWB technology is not included among those of highest significance to the NETEX program because, strictly speaking, it is not really "about" UWB waveforms *per se* but about the environment—any wideband signal will be subject to a lot of multipaths in the same situation.
- UWB technology's very short pulse width property has the disadvantage that pulse coding of signals involves relatively long synchronization times (cited in references 4 and 10, among others).
  - o Assessment: The claim that UWB pulse signaling involves relatively long synchronization times has some validity; for packet radio networks, synchronization time limits data capacity. The use of coded pulse trains for extraction of multipaths and data processing introduces overhead as well. However, as mentioned in Section 3.3.2, schemes have been devised to minimize the need for repeated synchronization in UWB packet networks.
  - o Rationale: This aspect of UWB technology is not included among those of highest significance to the NETEX program because it is rather dependent on the implementation scheme—in this case, packet radio.
- UWB technology's multipath persistence property has the disadvantage that there is a significant scatter in the angle of arrival (cited in reference 14 and elsewhere).
  - o Assessment: The claim that UWB multipaths "persist" because they often do not interfere with each other is valid, having been demonstrated by various researchers, and it does appear to be true that a side effect of the persistence is a significant degree of scatter in angle of arrival. This phenomenon adds to the challenge of correctly tracking multipaths.

  - Rationale: This aspect of UWB technology is not included among those of highest significance to the NETEX program because angle of arrival has not been identified in particular as a signal parameter marked out for exploitation.

6.3.3 UWB Advantages/Disadvantages/Applications of Highest Significance

In the category of "highest significance" we place the claims listed below for UWB that are listed in Table 1.1 and that were discussed individually in previous sections of this report.

- UWB technology's very wide bandwidth property offers the advantage of potentially high processing gain (cited in reference 2 and elsewhere) that can be applied to low-power, stealthy communications (cited in references 2, 4, and 8, among others).
  - Assessment: The claim that UWB signals offer potentially high processing gain that can be used to lower emitted power is valid, but depends somewhat on details of the particular UWB waveform that is under consideration. The fact that the wide bandwidth of UWB signals coexists with a very large number of other RF signals and can be extracted only by the appropriate receiver is inherently a stealthy mode of operation. The amount of processing gain (the ratio of bandwidth to bit rate) depends on the specific pulse modulation and coding scheme that is used. The amount of power needed by a UWB system is not only scenario-dependent but also is influenced by the potential for diversity gain (see below) in addition to the processing gain.
  - Rationale: Although stealth per se has not been articulated as a property of the objective system, the low power aspect of UWB technology is of the highest significance to the NETEX program because the objective system is intended to operate in the same bands as the existing communications infrastructure.
- UWB technology's very wide bandwidth property has the disadvantage of causing interference *to* existing systems (cited in references 3 and 5, among others) and of being subject to interference *from* existing systems (cited in references 3, 4, and 5, among others).
  - Assessment: The claim that UWB systems will cause interference to existing systems is obviously valid since the UWB signals will occupy the same bands as existing systems. However, it is the amount and kind of interference, as measured by effects on the operation of the existing systems, that is important and that needs to be assessed—in detail for particular UWB waveforms, existing systems, and scenarios. Therefore, ongoing efforts under the NETEX program are concerned with the potential effects of UWB interference on military receivers. For general applications, the FCC has restricted the emissions of UWB signals to levels and bands that will avoid significant interference with the operation of GPS (see Section 2.3.1). Concern continues to be expressed for potential interference to critical aviation systems.
  - Rationale: This aspect of UWB technology is of the highest significance to the NETEX program because the objective system must not disrupt existing communication systems, except perhaps during restricted operations for emergency

purposes. It is also desirable in most NETEX scenarios for the presence of the UWB system to be not only unobtrusive but also difficult to detect.

- UWB technology's very short pulse width property offers the advantage that multipath components of UWB signals can be resolved directly (cited in references 2 and 4, among others.
  - Assessment: The claim that multipath components of short UWB pulsed signals can be resolved is valid, and it is the single fundamental physical fact about UWB technology that makes the technology differ from other technologies. (See the discussion in Section 3.2.1.) Not always, but frequently the different reflections do not overlap in time—this effect has been observed indoors, and very likely will be at least as pronounced outdoors. As a result, the pulses do not interfere with each other and individual paths tend not to fade, unlike continuous-wave (CW) signals, whose multipath components always overlap and tend to incur fading. Multipath components of spread-spectrum (SS) encoded CW signals can be isolated by correlators using the property of the SS code, but there remains interference from the rejected multipaths that can be strong. For UWB pulsed signals, a correlator is not needed for the purpose of extracting a multipath component (but would be used for timing), and the extracted component will have only a small amount of residual interference.
  - Rationale: This aspect of UWB technology is of the highest significance to the NETEX program because it is a fundamental, enabling property of the technology.
- UWB technology's very short pulse width property offers the advantage of providing for diversity gain from combining multipath components (cited in reference 9 and elsewhere).
  - Assessment: As discussed in Section 3.2.2, the claim is valid that multipath components of UWB pulsed signals can be combined to realize a diversity gain. The fact that the resolution in time of the multipaths is possible makes the construction of a coherent, multipath-combining "rake" receiver for UWB pulsed signals much easier than for CW signals, although the number of resolvable multipaths can be large. The total power collected from the multipath components at the receiver can be higher than predicted by free-space propagation. In situations that give rise to fluctuations in the individual multipaths, the extraction and combining of them fulfills the role of "diversity" signal processing to obtain robust (reliable) signal reception.
  - Rationale: This aspect of UWB technology is of the highest significance to the NETEX program because it is a fundamental, enabling property of the technology.
- UWB technology's very short pulse width property supports low-power combined communications and localization (cited in reference 11 and elsewhere).
  - Assessment: The claim that the short pulse width of carrierless UWB signals supports combined communications and localization is of course valid, and prototypes have been demonstrated by several developers. Various military

systems in the past have combined communications and localization; for the most part those systems were primarily one kind of system or the other in terms of application and/or performance, and the localization and communication functions were more often separable than integrated. In contrast, UWB waveforms seem to be equally exploitable for localization and communication purposes. Further, in the applications envisioned for the NETEX program, the ad hoc networks that are involved can base their organization and operation on position and distance information, so that the two functions are fully integrated.

 - o Rationale: This aspect of UWB technology is of the highest significance for the NETEX program because it illustrates the full potential of the technology.

- UWB technology's multipath persistence property offers the advantage of low fade margins (cited in references 11 and 13, among others).
  - o Assessment: As discussed in Section 4.2.1, the claim is valid that UWB pulsed waveforms can require low fade margins, due to the infrequent interference of individual multipaths with each other for many environmental situations, leading to the "persistence" of the individual multipaths. The design of the pulse-coded waveform must take into account the multipath delay spread in order to exploit this property of short pulses. With low fade margins come the advantages of correspondingly low power and higher link reliability, both of which are enhanced by diversity combining of the multipaths.
  - o Rationale: This aspect of UWB technology is of the highest significance to the NETEX program because it shows the practical impact of the technology on communication system operations: a lower fade margin permits lower power.
- UWB technology's multipath persistence property offers the advantage of requiring less transmitter power (cited in reference 11 and elsewhere).
  - o Assessment: The claim of lower required power for UWB communication systems is valid in terms of lower required margins based on the persistence or anti-fading property of UWB pulsed waveforms, as well as in terms of the processing gain obtainable because of the system's wide bandwidth. Both of these elements in the link budget (margin, processing gain) can be traded for transmitter power.[127]
  - o Rationale: This aspect of UWB technology is of the highest significance to the NETEX program because it shows the practical impact of the technology on communication system operations.
- UWB technology's multipath persistence property supports NLOS communications, such as indoors and aboard ships (cited in reference 15 and elsewhere).
  - o Assessment: Based on reports on several experimental systems, the claim appears to be valid that UWB waveforms propagate significantly higher amounts of usable signal energy to receivers in NLOS path (through-the-wall) situations and reverberating environments, such as may occur in indoor and shipboard scenarios. The physical explanation for this phenomenon varies somewhat, depending on the

specific scenario, but the underlying propagation mechanism is at least in part due to the fact that the UWB pulses tend not to overlap and therefore persist.

- Rationale: This aspect of UWB technology is of the highest significance to the NETEX program because it shows how the technology applies to the "extreme" environments in which the objective NETEX system must operate.

- UWB technology's carrierless transmission property supports smart sensor network applications (cited in reference 10 and elsewhere).
    - Assessment: The claim that carrierless UWB waveforms support smart sensor network applications is valid in the sense that short-range, self-organizing and self-localizing networks are feasible based on using these waveforms for signaling. However, it remains to be seen how small UWB sensor nodes—including antennas—can be made for this application. To this date, the research in this area is incomplete.
    - Rationale: This aspect of UWB technology is of the highest significance to the NETEX program because it typifies the challenges to implementing the technology in relevant applications.

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