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Abstract

An increasing transformation has been taken placed for the last decade in the design and applications of Ultra Wideband Technology, both in the area of radar and communications, particularly wireless communications. The transition from analog to digital cellular communications, the growth of third and fourth-generation radio systems and the user-driven need for WiFi, Bluetooth and wireless devices are pushing communications engineers to search into an frequency spectrum range and domain historically unexplored. In the area of radar, UWB finds extensive applications for remote fine resolution imaging and sensing based on high power systems. Ultra wideband technology has the potential to provide solution to today's spectrum allocation and licenses management costs, fine-range resolution, imaging, sensing and penetration and short-range wireless communication links and networking, among others. This report presents an overview of ultra wideband technology with focus on application to communications and/or radar. The report makes emphasis on accomplishments and their significance, identifies major developments that materially enhance the utility of UWB for communications and/or radar. It also addresses and identifies major obstacles, challenges and unanswered questions or capabilities required to significantly enhance utility of UWB for communications and/or radar.

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ON ULTRA WIDEBAND (UWB) TECHNOLOGY AND ITS APPLICATIONS TO RADAR AND COMMUNICATIONS

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Abstract

An increasing transformation has been taken placed for the last decade in the design and applications of Ultra Wideband Technology, both in the area of radar and communications, particularly wireless communications. The transition from analog to digital cellular communications, the growth of third and fourth-generation radio systems and the user-driven need for WiFi, Bluetooth and wireless devices are pushing communications engineers to search into an frequency spectrum range and domain historically unexplored. In the area of radar, UWB finds extensive applications for remote fine resolution imaging and sensing based on high power systems. Ultra wideband technology has the potential to provide solution to today's spectrum allocation and licenses management costs, fine-range resolution, imaging, sensing and penetration and short-range wireless communication links and networking, among others. This report presents an overview of ultra wideband technology with focus on application to communications and/or radar. The report makes emphasis on accomplishments and their significance, identifies major developments that materially enhance the utility of UWB for communications and/or radar. It also addresses and identifies major obstacles, challenges and unanswered questions or capabilities required to significantly enhance utility of UWB for communications and/or radar.

I. Brief Historical Overview

Ultra Wideband (UWB) communication has received a great deal of attention for the last ten years, especially in the area of wireless communications. Most of the research in the past had been restricted to military applications and now that the Federal Communications Commission (FCC) ([1],[L4]) and other international regulatory agencies have lifted some of their restrictions for commercial use, UWB has surged and is being referred as a promising emerging technology [2],[3],[4]. However, UWB has its origin more than a century ago. Hertz experimented with UWB in the late 1800s by generating a short-pulse and then Marconi with application to electromagnetic data communications. Marconi's early work of using modulated sinusoidal carrier has dominated RF radio design since the early 1900s that wide use of short-pulse technology has been seen with skepticism. In fact, the benefit of a large bandwidth and the capability of multiuser transmission systems provided by electromagnetic pulses were not considered at that time. It took more than 60 years before significant attention was given to UWB. Initially, transient analysis and time domain electromagnetic were studied with the purpose to understand the transient behavior of certain microwave networks by way of examining their characteristic impulse response [5], [6] . In the period parallel to this work, modern short-pulse transmission gained attraction in military applications in the area of radar, driven by the promise of fine-range resolution associated with large bandwidth. By the early 1990s, conferences and proceedings were documented and presented in books form. These papers are mostly motivated by radar applications and can be found in [7]-[10].

More recently, there has been a very rapid expansion of the number of private companies, research centers, publications and government agencies around the world involved with UWB. Today, UWB concepts and approaches are being applied to a variety of applications in both communications and radar, as illustrated in Figure 1 (below). In the following sections, we discuss basic UWB concepts and each application area.

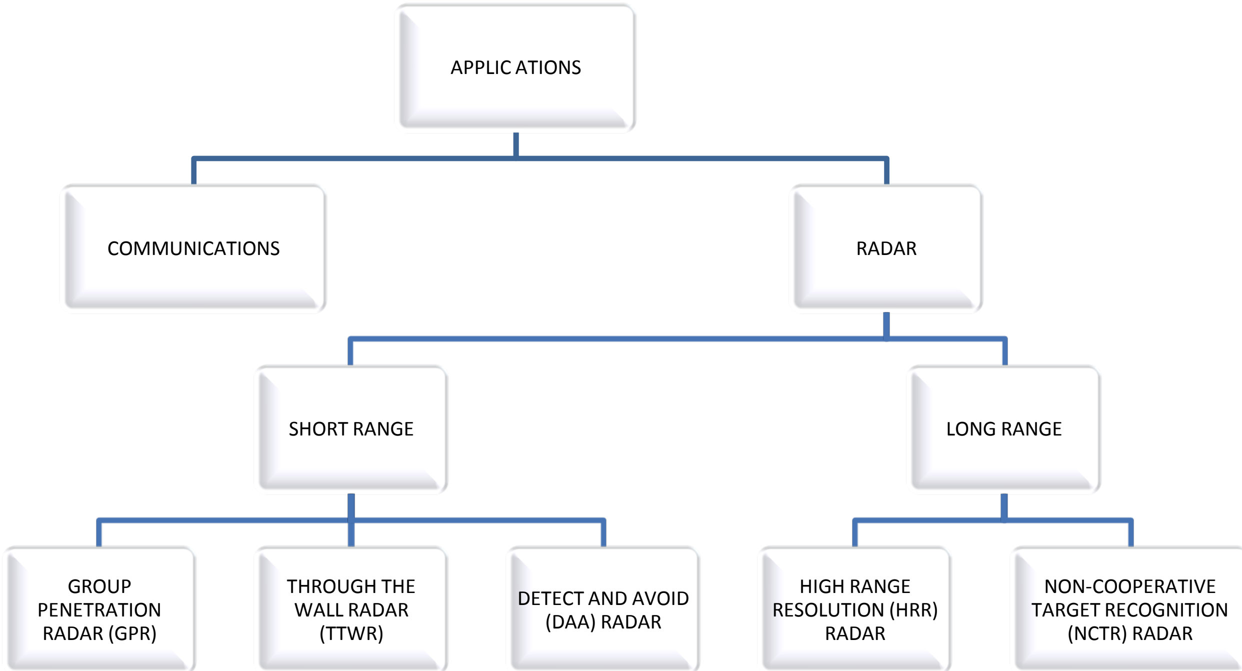

Figure 1. Ultra wideband applications in both communications and radar.

A. *Ultra Wideband Concepts*

The term *ultra wideband* was first adopted by the Defense Advanced Research Project Agency (DARPA) in ([43], [L3]). Based on DARPA's panel review, a signal was seen as an UWB signal if its fractional bandwidth was greater than 0.25:

$$Fractional\ Bandwidth = 2\,(f_h - f_l)/(f_h + f_l) \qquad (1)$$

Where f_h and f_l are the higher and lower -10 dB frequencies, e.g., the frequencies where the level of the power spectral density has decreased 10 dB from its peak value The prevailing definition has decreased the fractional bandwidth to a minimum of 20% or 0.20, as set by the FCC in [66]. The same ruling also states that a signal is recognized as an UWB if the -10dB signal bandwidth is 500 MHz or larger. The FCC has also permitted UWB devices to operate in the same spectrum occupied by existing radio services as long as the emission restrictions or spectral masks are met. These spectral masks are discussed in Section III.B below. Furthermore, FCC regulation 47 CFR Section 15 subpart 5(d) [L6] states that "Intentional radiators that produce Class B emissions (damped wave) are prohibited". Given these constraints and regulations, to better benefit from extremely large bandwidth, UWB systems employ nonsinusoidal waveforms that meet certain properties when transmitted from the antenna, more particularly narrow pulses. These are narrow impulse-like signals with specific characteristics called impulse or monopulse waveforms [60]. The time duration of monopulse waveforms is typically in the order of nanoseconds. Several non-damped waveforms have been proposed in the literature such as Gaussian monocycles, modified Hermite polynomial, Rectangular, Rayleigh, Laplacian and cubic monocycles [59]. The main objective of all these waveforms is to design a pulse with a nearly flat frequency spectrum over the bandwidth of the pulse and with no DC component. A fundamental characteristic of a monopulse is that it must have zero DC content so it can radiate effectively. In the following section below, we look at the Gaussian waveforms as the initial point for our analysis. Our analysis is based on conventional time-domain frequency-domain analysis strategies (Fourier transform relationships). Some parties in the UWB community argue that such techniques are not valid for UWB signals.

1) Waveforms

UWB systems based on impulse radio design are being considered as a low cost, power efficient and high data rate (~100 Mbps over distance at about 10 meters) wireless solution. We develop the general time-frequency relations of some common waveforms in this section and further discuss their significance for UWB systems in Section B.

a) Rectangular Pulse and Spectrum

As an illustration we begin with the simplest example of an impulse, the rectangular waveform. A rectangular waveform is defined as

$$\mathrm{r(t)} = \begin{cases} \mathrm{a}, & |\mathrm{t}| \leq \tau/2 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Where a is the amplitude of the pulse, normally chosen to be equal to the pulse width.

The equivalent Fourier Transform is then given by

$$R(\omega) = \frac{a}{\tau} \frac{\sin\left(\frac{\omega\tau}{2}\right)}{\left(\frac{\omega\tau}{2}\right)} \tag{3}$$

We can observe in the above relationship that by adjusting the pulse width τ, the bandwidth of the pulse is controlled. For example, a pulse with duration τ of 500 picoseconds can generate a center frequency of 2 GHz. Hence, the importance to look at impulse radio signals for UWB applications.

It can be easily shown that the energy of the rectangular pulse is equal to the squared product of its amplitude and pulse width, or

$$E_r = (a\tau)^2 \tag{4}$$

By selecting $a = \sqrt{(1/\tau)}$ the pulse is then normalized to unit energy.

In general, this is shown by the time-scaling property of the Fourier Transforms:

$$g(at) \leftrightarrow \frac{1}{|a|} G\left(\frac{\omega}{a}\right) \tag{5}$$

Furthermore, from equation (3) we can note that a DC term is present in this type of pulse, making wireless transmission of rectangular pulses impractical. Pulses based upon derivatives present an alternative approach. Gaussian pulses belong to this type.

b) Gaussian Pulse: Higher-order derivatives, Energy and Spectrum

One class of functions is called Gaussian waveforms because they are defined in a similar way to the Gauss function. The general zero-mean Gauss function is described by Equation (6), where σ is the standard deviation:

$$G(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-t^2/2\sigma^2} \tag{6}$$

The basis of these Gaussian waveforms is a Gaussian pulse, or

$$g_0(t) = A_0\, e^{-t^2/\tau^2} \tag{7}$$

where $-\infty < t < +\infty$, τ is a scaling factor and K_1 is a constant. From this Gaussian pulse, more waveforms can be created by taking higher order derivatives, a process equivalent to high-pass filtering of the Gaussian pulse. In general higher order derivatives are found by:

$$g_n(t) = \frac{d^n}{dt^n}\left(g_0(t)\right) \tag{8}$$

where n denotes the n-th derivative. For example, a Gaussian monocycle is defined as the first derivative of a Gaussian pulse, has the following form:

$$g_1(t) = A_1\left(-\frac{2t}{\tau^2}\right) e^{\frac{-t^2}{\tau^2}} \tag{9}$$

Similarly, a Gaussian doublet is defined as the second derivative of Equation (7 **)** and has the form:

$$g_2(t) = A_2\left(-\frac{2}{\tau^2}\right)\left(1 - \frac{2t^2}{\tau^2}\right) e^{\frac{-t^2}{\tau^2}} \tag{10}$$

Constants $A_0, A_1\ and\ A_2$ are useful parameters in order to determine the energy of the UWB. Let us consider an energy signal g(t). From Parseval's theorem, the total energy associated with g(t) is given by:

$$E = \int_{-\infty}^{+\infty} |g(t)|^2\, dt \tag{11}$$

When g(t) is a voltage signal, the amount of energy dissipated by this signal when applied to a network with resistance R is

$$E = \frac{1}{R}\int_{-\infty}^{+\infty} |g(t)|^2\, dt \tag{12}$$

Similarly, if g(t) is a current signal, we then get

$$E = R\int_{-\infty}^{+\infty} |g(t)|^2\, dt \tag{13}$$

Without loss of generality, we can easily calculate the Energy relationship for the three Gaussian pulses presented above, or E_0 [1]

$$\begin{aligned} E_0 &= \int_{-\infty}^{+\infty} A_0^2\, e^{\frac{-2t^2}{\tau^2}}\, dt \\ &= A_0^2\, \tau \sqrt{\frac{\pi}{2}} \end{aligned} \tag{14}$$

The resulting energy for $g_1(t)^2$ is

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1 Equation (48) provides the solution for the integration.

$$E_1 = \frac{A_1^2}{\tau} \times \sqrt{\frac{\pi}{2}} \qquad (15)$$

Employing a similar procedure, we now calculate the energy for $g_2(t)$

$$E_2 = \frac{3A_2^2}{\tau^3} \times \sqrt{\frac{\pi}{2}} \qquad (16)$$

We now express each of the above constants in terms of their energy level, or

$$A_0 = \sqrt{\frac{E_0}{\tau\sqrt{\pi/2}}},$$

$$A_1 = \sqrt{\frac{\tau E_1}{\sqrt{\pi/2}}}, \qquad (17)$$

$$A_2 = \tau \sqrt{\frac{\tau E_2}{3\sqrt{\frac{\pi}{2}}}}$$

We now derive the frequency domain representation of the Gaussian pulses. Using the definition of the Fourier Transform (Equation (50)(a)), $G_0(\omega)$ is given by

$$G_0(w) = \int_{-\infty}^{+\infty} A_0\, e^{-\frac{t^2}{\tau^2}} e^{-jwt}\, dt \qquad (18)$$

By completing the square and proper variable substitution, we obtain

$$G_0(w) = \int_{-\infty}^{+\infty} A_0\, e^{-\frac{\omega^2\tau^2}{4}} e^{-u^2}\, \tau du \qquad (19)$$

Or using Equation (48),

$$G_0(w) = \int_{-\infty}^{+\infty} A_0\, e^{-\frac{\omega^2\tau^2}{4}} e^{-u^2}\, \tau du \qquad (20)$$

which leads to

$$G_0(w) = A_0 e^{-\frac{\omega^2\tau^2}{4}}(\tau\sqrt{\pi}), \text{ or}$$
$$G_0(f) = A_0 e^{-(\pi f \tau)^2}(\tau\sqrt{\pi}) \qquad (21)$$

Using Equation (54), we obtain the solution for the higher derivatives, or

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[2] Differentiating Equation (48) with respect to "a" provides the solution for the energy of $g_1(t)$.

$$G_1(\omega) = A_1(j\omega)e^{-\frac{\omega^2\tau^2}{4}}(\tau\sqrt{\pi}), \text{ or}$$
$$G_1(f) = A_1(j2\pi f)e^{-(\pi f\tau)^2}(\tau\sqrt{\pi}) \quad (22)$$

Similarly,

$$G_2(\omega) = A_2(j\omega)^2e^{-\frac{\omega^2\tau^2}{4}}(\tau\sqrt{\pi}), \text{ or}$$
$$G_2(f) = A_2(j2\pi f)^2e^{-(\pi f\tau)^2}(\tau\sqrt{\pi}) \quad (23)$$

The time-frequency domain of the three Gaussian pulses and their spectral energy densities are shown in Figure 2 and Figure 3 respectively. The pulse widths were chosen to be 0.5 nanoseconds with unity energy. Important to our analysis is to observe how these three single pulses present significant spectrum difference when compared to a damped sine wave. We can also notice their large and uniformly distributed frequency spectrums with very little energy and, therefore, resemble noise-like signals. Similar to the rectangular pulse, the Gaussian pulse has a large DC component which in principle makes it impractical for wireless communications. However, higher-order Gaussian derivatives seem to present an alternative solution.

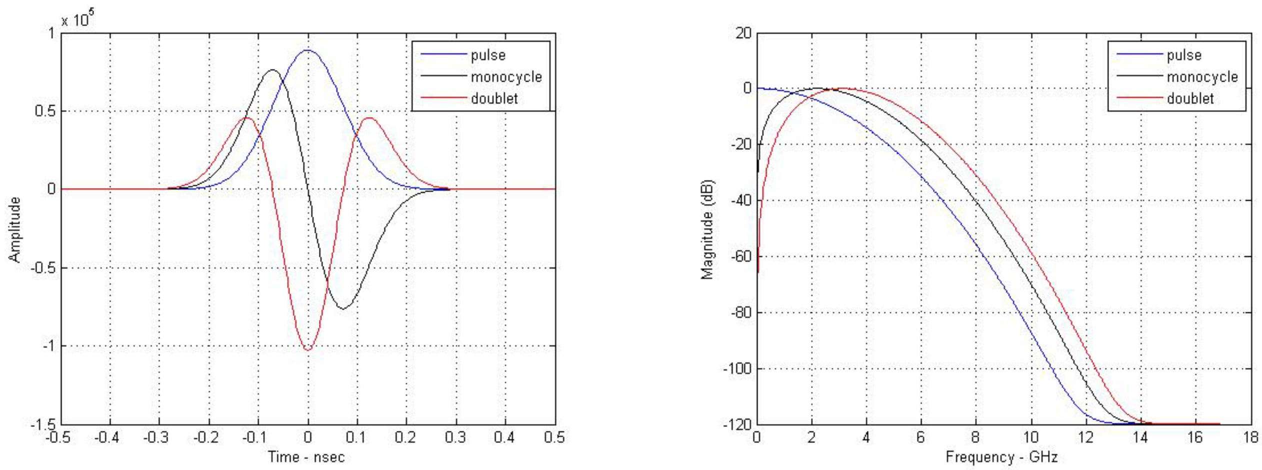


Figure 2. A Gaussian pulse, monocycle and doublet in the time and frequency domains.

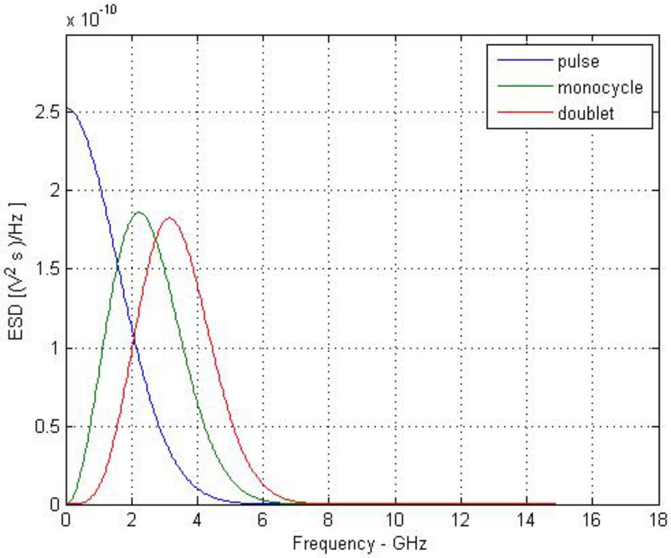


Figure 3. Energy spectral density for a Gaussian pulse, monocycle and doublet.

In the following Sections we derive the necessary parameters that account for pulse bandwidth, center frequency, maximum peak power, etc. that will help us to design pulses that meet or exceed the FCC mask emission limits. We are also interested in further analyzing the characteristics of rectangular pulses with the objective of understanding whether in reality they have a viable application. This is important from a practical point of view. A rectangular pulse is the simplest waveform that can be radiated from an antenna; therefore, we will explore in more details its time-frequency characteristics.

B. Communication Applications

In this Section we will look at the important components of a typical communication system and analyze its performance from a given set of UWB specifications. These specifications include bandwidth, channel capacity, noise, both thermal and man-made, modulation techniques and antenna characteristics for UWB signals. We will also look at the main attributes that UWB bring to wireless communications and possible research applications in UWB systems.

1) Unique UWB Attributes

Two important characteristics of an UWB system are its very large bandwidth and low average transmitted power. When combined with proper modulation schemes, these two characteristics offer several advantages over narrowband communications systems. Very large bandwidths (in the range 500 MHz -7.5 GHz) can be exploited to develop devices with high transmission capacity. In terms of power, UWB maximum output power of 75 nW/MHz is allowed by the FCC. This compares favorably since it is much lower than comparable narrowband radios, for example, IEEE 802.11b has a maximum output power of 100 mW, or 50 mW for IEEE 802.11a. This power restriction forces UWB systems to operate below the noise floor of a common narrowband receiver then enabling UWB signals to coexists with current radio systems with minimal or no interference. Furthermore, due to the large bandwidth of the signal, some interference would possibly change one part of the signal’s spectrum, leaving the remaining band unaffected. In this section, we discuss some of the key advantages of UWB signals that derive from these two main characteristics: a) Frequency Re-Use; (b) High Transmission Capacity; (c) Low Probability of Detection; and (d) Lower Sensitivity to Multipath Channels.

a) Frequency Re-Use

An important motivation to research and develop applications using UWB technology lies in one critical limitation imposed by regulatory agencies around the world: RF spectrum. Therefore, a starting point for understanding the appeal of UWB is to recognize the need to implement new technologies that can bring relief to the bandwidth crunch that exists today within the communication world. The portion of the RF spectrum commonly understood to have value for practical communication (about 100 MHz to about 10 GHz and more recently in the 60 GHz) applications has been fully allocated for decades and yet there is a growing demand for RF (wireless at least over short distance, a few km at most) communications, often with an attendant expectation of high data rate capability. This situation is shown in Figure 4 which presents the allocation of frequency bands in the USA. One response to the demand for short distance wireless RF communications is cellular telephone, small and relatively inexpensive user radios that communicate with cell towers (over short distances, a few km at most). A significant element in the cell telephone concept is frequency re-use (due to limited spectrum availability). Frequency re-use is a way to increase the capacity of the network by using the same frequency in a different area of the cellular network and is measured in function of the frequency re-use factor, the rate at which the same frequency can be used in the network. Because of frequency re-use and other advancements, i.e. code division multiplexing, cell telephone application has seen explosive growth in the last decade. Success of this application has led to other wireless voice and data services which are RF-based and designed to work over very short distances, on order of 1 to 10 meters. UWB can operate very efficiently in a relatively small footprint (10 meters or less) and as a result it can largely exploit the benefits of frequency re-use (based on the concept of spatial capacity as described above). Similar to the cellular concept, multiple UWB systems can be deployed together such that they cover a larger area and still deliver high transfer rates with a low power transmission signal.

Another way to re-use the same spectrum allocation is to implement different transmit and receive communication technologies within a common frequency band such that the transmission of information is not compromised. In other words, frequency re-use can be achieved by the assignment of unlicensed re-used of already licensed spectrum with the purpose to increase spectrum efficiency. By limiting the power spectrum density (max of -41.3 dBm/MHz over a 7.5 GHz bandwidth) and assigning specific bands (depending on the application), regulators have provided the opportunity to develop the necessary technology (UWB) that can co-exist with existent systems (narrowband systems) while ensuring sufficient attenuation to limit adjacent channel interference. Additional power spectral density limits have been placed below 2 GHz to protect critical applications such as global positioning system (GPS at 1.5 GHz) and digital cellular system (1.9 GHz). This is in-large one of the most important motivations for researchers to focus their attention in the development of UWB systems. As a result, interest of UWB radio access systems has grown rapidly over past few years. Figure 5 shows the required power spectral density and frequency band allocation for various narrowband and UWB applications as ruled by the FCC. But what can we say about the effect of narrowband radiators in UWB systems? This is indeed another important subject for researchers since UWB systems are most likely to suffer from the relatively high power emission of narrowband emitters. One particular approach would be to develop adaptive interference suppression techniques or more sophisticated antenna patterns that can behave like notched filters or stop-band filters and can have multiband flexibility.

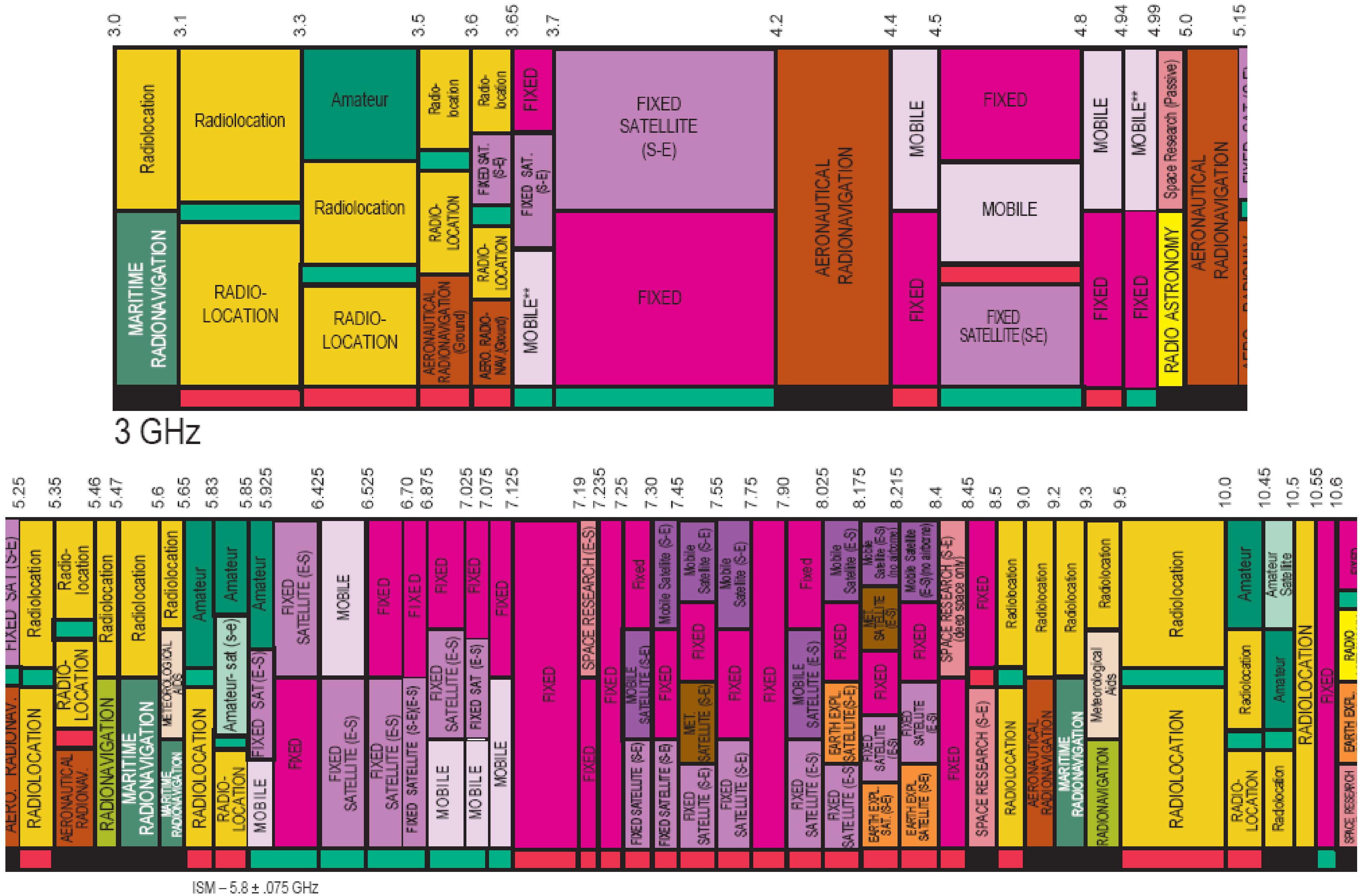


Figure 4. Frequency allocation spectrum in the band 3.1 GHz – 5.15 GHZ and 5.15 GHz - 10.6 GHz in the USA [76].

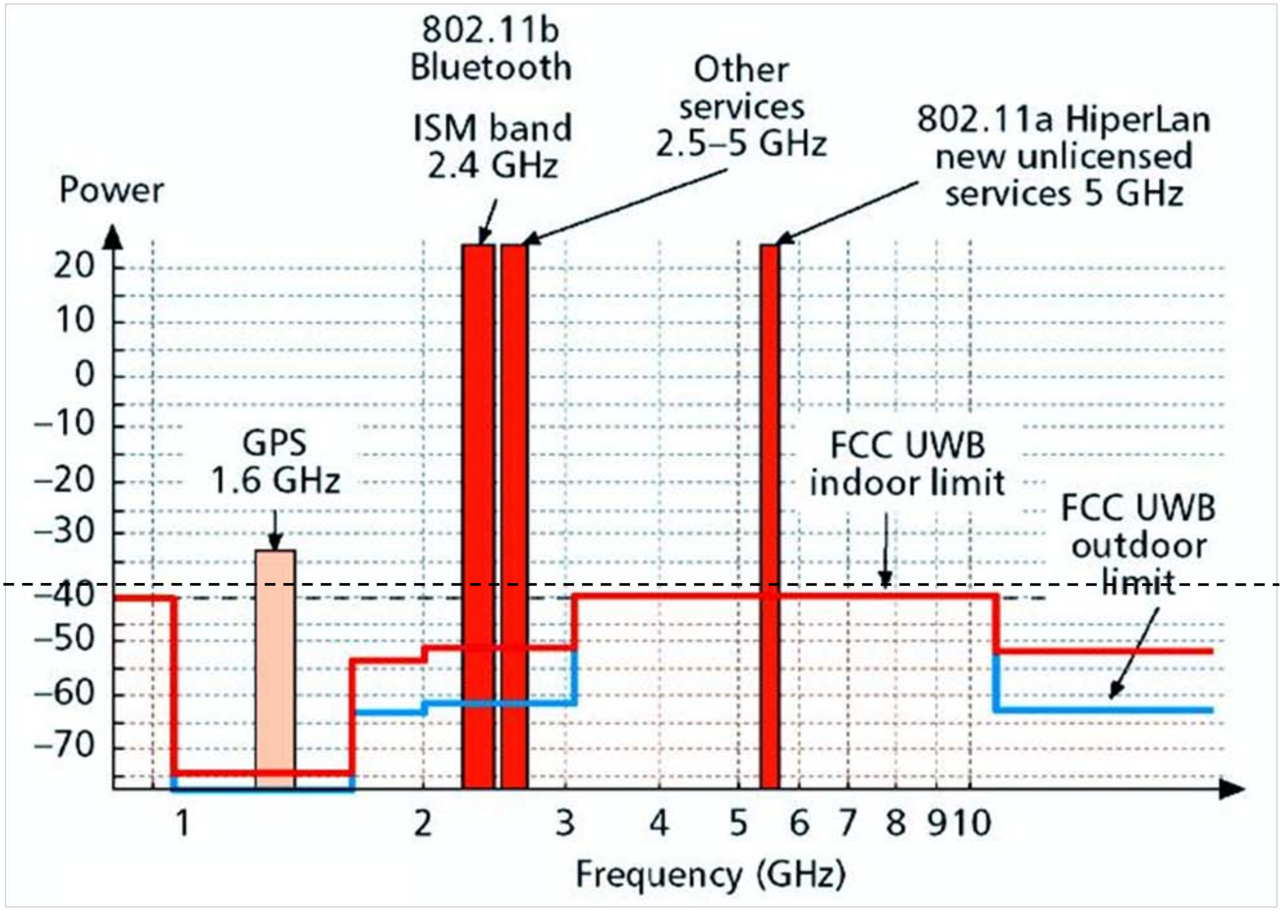


Figure 5. Frequency re-use principle as established by the FCC (from [77]).

To meet regulations and unlicensed spectrum allocation, there is a growing sense that a significant portion of interest in UWB communications is focused on very short range (wireless personal area network or WPAN) to (a) provide wireless connectivity that does not require a user license; (b) provide high transmission capacity over very short distances; and (c) provide the ability to co-exist with existing narrowband services (spectrum re-use issue). Furthermore, the past few years have witnessed extensive research and development in UWB applications operating in the 60 GHz band [68], [69]. Design of 60 GHz-UWB radio technology presents a unique opportunity to develop solutions that have low power transmission (similar to Bluetooth) and offer high data rate transmission at short distances. High definition video and multimedia streaming are just two of the many possible applications that are in need of high data rate.

b) High Transmission Capacity

One of the most important measurements to evaluate a communication channel is its transmission capacity. This is also one important characteristic that, when efficiently exploited, can enable the proliferation of multiple applications in video and audio wireless communication. One of the major advantages of UWB systems is its large bandwidth and hence the potential for high channel capacity. However, there are known limits, due to both physical limitations and regulations. For example, noise in the channel affects the received signal while the available bandwidth and power are under constrained imposed by regulatory bodies. Modulation efficiency and antenna characteristics are also important elements that will affect the performance of the wireless communication channel. These constraints can be summarized under three key limitations: noise (physical limitation), regulatory limits (primarily on power and bandwidth) and channel capacity and communication efficiency.

❖ *Noise*

Noise and interference in the channel impose a limitation in the performance of the communication systems. This limit is reflected in the ability to extract the desired information from the received signal. The efficiency of the system is then measured by the degree to which we are capable of recovering and detecting the source information. Noise is inherently related to the capacity of the channel and to its range of operation. It is well known the importance of the ratio of the power of the signal and the noise and its effect to the overall performance of the system. Ideally we wish to design either a very powerful system (high power on the information source) or a very effective and weak noise level system or both. Unfortunately, we are limited in either or both cases. When we refer to noise, we are more commonly referring to thermal noise or also known as additive white Gaussian noise (AWGN) and generated by electronic devices. There is also noise due to natural causes and man-made sources which vary with frequency as shown in Figure 6. Interference might arise from other users occupying part or the same frequency band. The noise-power density (watts/Hz) [62] can be expressed as

$$N_o\,(f,T) = hf\ \left[\frac{1}{e^{\left(\frac{hf}{k_bT}\right)}-1}+1\right] \qquad (24)$$

where

$h = 6.6260693\ x\ 10^{-34}\ J.s\ (Plank's\ constant)$ [L48]
$k_b =\ 1.3806505\ x\ 10^{-23}\ J\ K^{-1}$) (Boltzmann's constant) [L48], (25)
f is frequency in hertz and
T is the absolute temperature in Kelvin (K)

In many of the cases we deal in communications, the frequency is very small, therefore, we can derive the expression of the noise-power density when $f \to 0$ (f is small), or simply

$$\mathrm{N_o(T)} = \mathrm{lim}_{n\to 0}(\,N_o(f,T)) = \lim_{n\to 0}\left(hf\ \left[\frac{1}{e^{\left(\frac{hf}{k_bT}\right)}-1}+1\right]\right)$$

$$= \lim_{f\to 0}\left(hf\ \left[\frac{1}{1-e^{\left(\frac{-hf}{k_bT}\right)}}\right]\right) = \frac{\lim_{f\to 0}(hf)}{\lim_{f\to 0}(1-e^{\left(\frac{-hf}{k_bT}\right)})} \qquad (26)$$

$$N_o(T) = k_bT\ \text{(W/Hz)}$$

Noise power N is then the noise –power density multiplied by the bandwidth B, or

$$N = k_bT\ B \qquad (27)$$

We can now calculate the limitation due to thermal noise at room temperature (T=290 K) per 1-Hz of bandwidth, or

$$N =\ 4.00\ x\ 10^{-21}\ W$$

$$\text{N = -204 dBW or -174 dBm} \qquad (28)$$

For 1 MHz of bandwidth, then the power is -114 dBm.

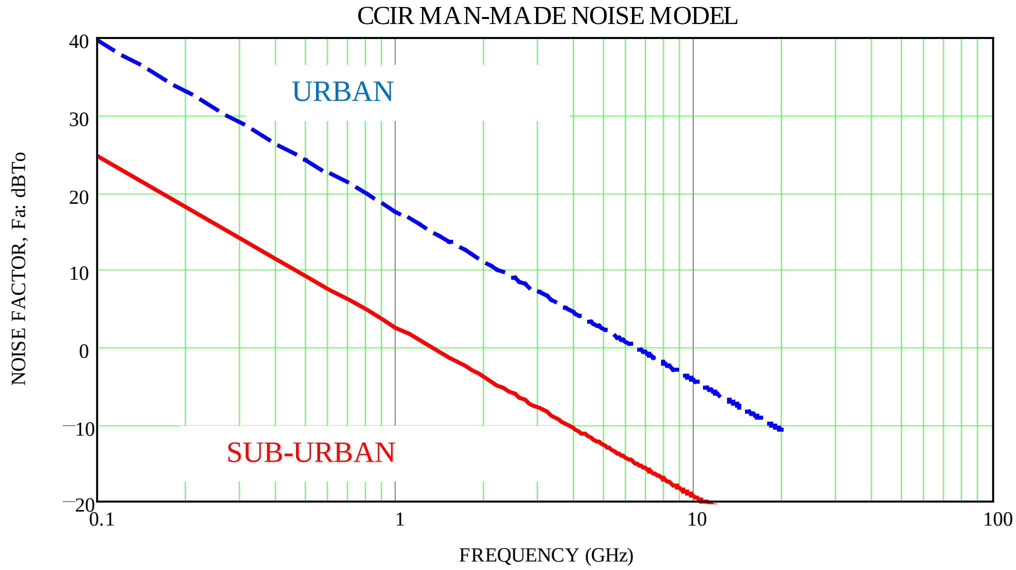


Figure 6. Man-made noise model.

❖ *Regulatory Limits*

Radiated power and frequency bands determine largely the communication links. In UWB there are regulatory constraints imposed in these two parameters. One is the power spectral limit measured in dBm/MHz, and the other is the frequency–band limit. Together they determine the maximum possible effective radiated power for an UWB signal at particular range of frequencies. This is the second limitation imposed for UWB systems and its specifications are determined by the various regulatory bodies across the world. We discuss these issues extensively in Section III below.

❖ *Channel Capacity: Shannon's capacity*

One of the most fundamental performance measurement of any communication system is its ability to transmit and receive the information with minimum error (or error free) at a given rate of information transmission. This is referred as the information capacity. For UWB systems, there are two important characteristics in the signals: low power and high bandwidth. In this Section, we analyze the capacity of UWB systems and also we look at the range of these UWB radio signals. An estimate of the capacity for low-power UWB radio signals can be obtained from one fundamental theorem: Shannon's capacity theorem ([63], [L49]).

The channel capacity per unit time (bits per second) is given by

$$C = B\log_2\left[1+\frac{S}{N}\right] = B\log_2\left[1+\frac{S}{N_oB}\right] \tag{29}$$

where S denotes the power of the signal, N is the noise, N_o noise-power density and B the bandwidth of the system. The term S/N or SNR is also known as the signal-to-noise ratio which compares the level of the radio signal power to the power of the channel noise. From Equation (29) we can easily observe that the capacity of the channel increases logarithmically (and monotonically) as a function of the SNR (in this case 10log10(S/N)). Thus, for a fixed bandwidth B, the capacity of the radio signal increases with an increase in the radiated signal power. Figure 7 shows the capacity (in bps) normalized by the bandwidth B (in Hz) as a function of the SNR (dB) in an idealized situation.

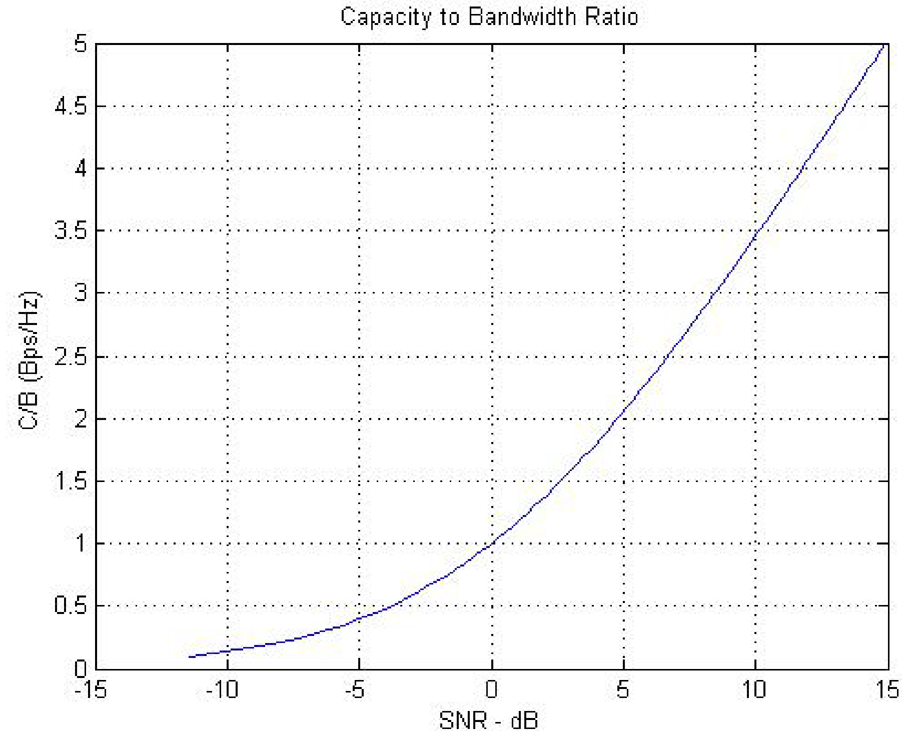
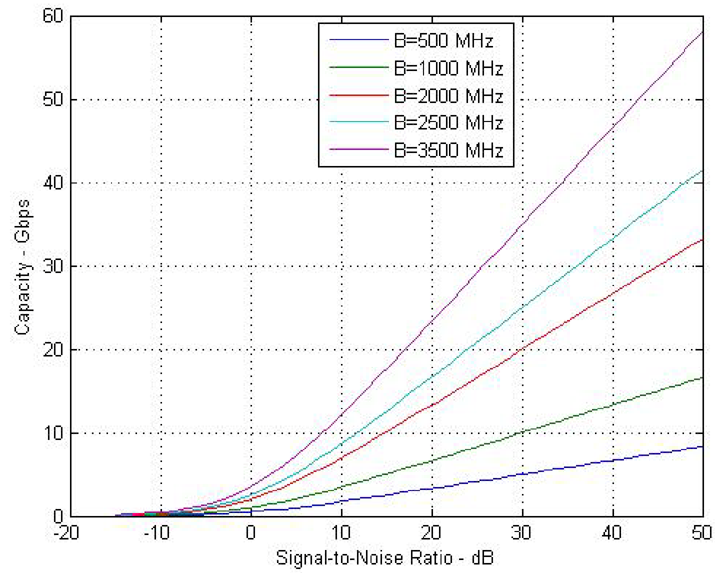
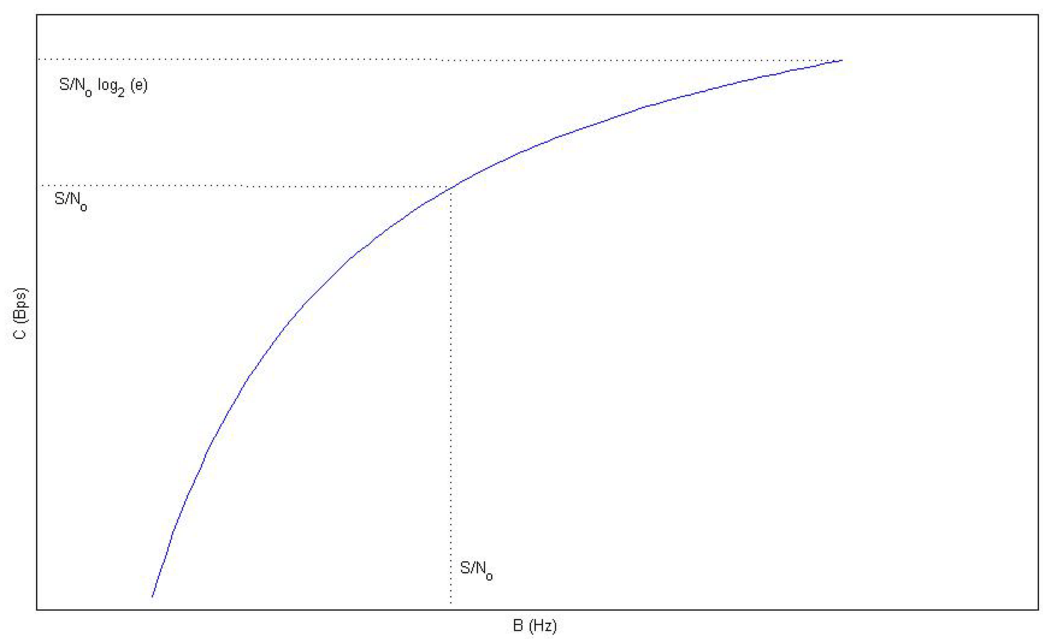


Figure 7. Ideal normalized channel capacity as a function of SNR for an AWGN channel.

On the other hand, for the purposes of UWB systems the bandwidth is greatly increased which means that the channel capacity should linearly increased by increasing the bandwidth B. In this case we plot the capacity of the channel as a function of the SNR (in dB). In an ideal situation, the capacity grows largely as we increase the bandwidth (and the SNR) of the system. Figure 8 (a) shows this situation using different bandwidths: 500 MHz, 1000 MHz, 2000 MHz, 2500 MHz and 3500 MHz, which are typical UWB bandwidths. If we were to compare the capacity of UWB systems with other existing radio systems, the difference would be enormous; the occupied bandwidth of GSM is 200 KHz [64], for 3G W-CDMA (UMTS) is 5 MHz [64] and 16.6 MHZ in IEEE802.11a (WLAN) [65].



(a)



(b)

Figure 8. (a) Ideal normalized channel capacity for several UWB bandwidths as a function of SNR for an AWGN channel.

(b) Channel Capacity as a function of bandwidth with a fixed ERP.

Figure 8 (a) is an ideal case, but in reality, the capacity cannot grow infinitively large as we increase the bandwidth, it has a limit as shown in Figure 8 (b). Note in Equation (29) that as B approaches infinity ($B \rightarrow \infty$), the capacity approaches an asymptotic value

$$\lim_{B\to\infty} C = \lim_{B\to\infty}\left(B\log_2\left[1+\frac{S}{N_o B}\right]\right)$$

$$= \lim_{B\to\infty}\left(\frac{\log_2\left[1+\frac{S}{N_o B}\right]}{\left(\frac{1}{B}\right)}\right) = \frac{S}{N_o \ln(2)} \quad (bits/s) \tag{30}$$

We are also interested in looking at the limit imposed by the channel capacity so we can obtain the maximum possible communication efficiency in an AWGN with unconstrained bandwidth. The smaller the ratio, the better a system will perform in the presence of white noise. For this purpose, we define the energy per bit E_b. Since C is the capacity of the channel in bits/sec and S the radiated power in W (or J/sec), then it follows that $S = E_b$C. Hence, we can express Equation (29) as

$$C = B\log_2\left[1+\frac{S}{N_o B}\right] = B\log_2\left[1+\frac{E_b C}{N_o B}\right] \tag{31}$$

which results in

$$\frac{E_b}{N_o} = \frac{2^{C/B}-1}{C/B} \tag{32}$$

We now look at three possible cases:

- C/B = 1
- C/$B \to \infty$
- $C/B \to 0$ (will give the best communication efficiency)

Case 1: it is straight forward and gives $\frac{E_b}{N_o} = 1 \; or \; 0 \; dB$

Case 2: In this case it will grow exponentially as C/$B \to \infty$ or $\frac{E_b}{N_o} \approx \frac{2^{C/B}}{C/B}$

Case 3:

$$\lim_{\frac{C}{B}\to 0}\frac{E_b}{N_o} = \lim_{\frac{C}{B}\to 0}\frac{2^{\frac{C}{B}}-1}{\frac{C}{B}}$$

$$= \frac{\lim_{\frac{C}{B}\to 0}\left(2^{\frac{C}{B}}\ln(2)\right)}{\lim_{\frac{C}{B}\to 0} 1} = \ln(2) \; or -1.59 \; dB \tag{33}$$

This (-1.59 dB) is the best possible communications efficiency in an AWGN channel with unconstrained bandwidth. The problem we currently has is that we do not know how to achieve this limit and extensive research has and is being done based on numerous modulation techniques, but with less efficient results. Figure 9 depicts the relationship capacity/bandwidth versus $\frac{E_b}{N_o}$.

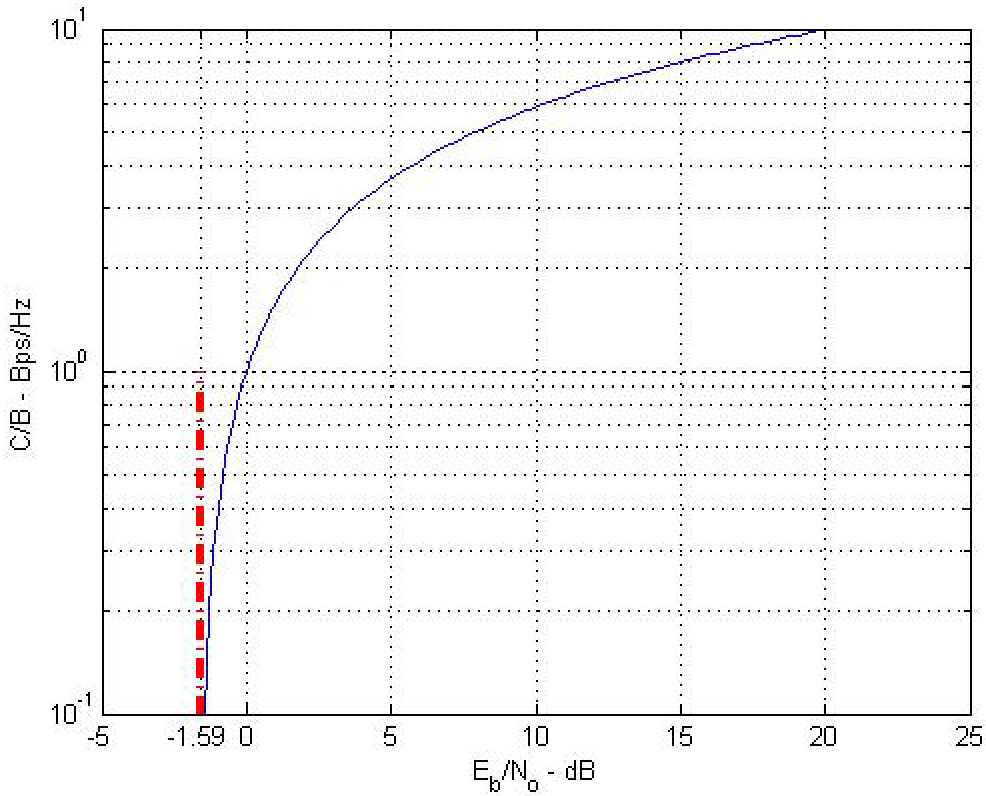


Figure 9. Communication efficiency limit: channel capacity/bandwidth ratio versus $\frac{E_b}{N_o}$.

From a practical point of view, we are looking for small, low power and inexpensive set of hardware (transmitter, receiver, antenna) that can achieve a high transmission capacity given the availability of a high bandwidth (as in the case of UWB systems). We have already shown that channel capacity increases with channel bandwidth with an ever increasing demand for more transmission capacity. We look now at the relationship between channel capacity and range.

If we consider a radio signal source that radiates power in all direction with equal intensity S_t (or effective radiated power ERP), and an antenna located at a distance r, then the received power density $S_d$will be

$$S_d = \frac{S_t}{4\pi r^2} = \frac{ERP}{4\pi r^2} \qquad (34)$$

In other words, S_d is the power density from an isotropic antenna, S_t is the transmitted power and r is the range from the antenna (radius of sphere). Normally S_d is either peak power or average power depending on how S_t is specified. A receiving antenna captures a portion of this power and it is determined by the effective area A_{rx} of the receiving antenna. We can now express C as a function of the bandwidth and the range as

$$C = B\log_2\left[1+\frac{S_d A_{rx}}{N_o B}\right] = \mathrm{B}\log_2\left[1+\frac{ERP\ A_{rx}}{k_b TB}\ \frac{1}{4\pi r^2}\right] \quad (35)$$

Consider an UWB system with a low power transmitter (ERP of 1 µW) and a receiver attached to a small aperture antenna (capture area of 1 in^2) in a moderately noise environment (receiving noise temperature = 5000 K). Using Equation **(32**) we can plot the relationship between channel capacity and the range for this particular case.

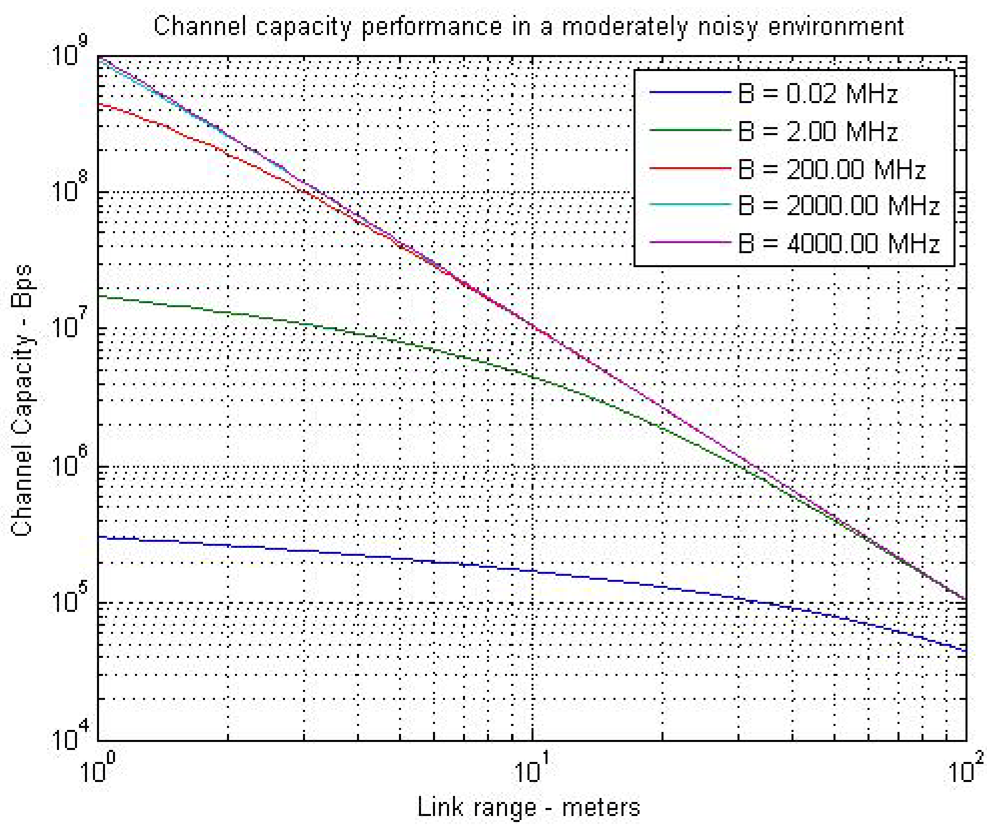


Figure 10. Channel capacity as a function of link range for various bandwidths:

ERP = 1 µW; A_{rx}= 1 in^2; T = 5000 K

Figure 10 above illustrates the point that in general (not requiring UWB per se), it is theoretically possible to achieve a very substantial transmission capacity (measured in Mbps) over short ranges (a few meters) with a minimal hardware set (ERP = 1 µW; A_{rx}= 1 in^2; T = 5000 K) --- it should be noted that traditional narrowband transmission techniques do not get close to this capacity. As mentioned before, much of the work on coding theory has been motivated by the prospect of finding a coding technique that allow operation near the channel capacity; therefore, it is important to know how close UWB approaches get to this upper bound on channel capacity.

By putting together all the limitations discussed above, both natural and regulatory, we can establish a more realistic link budget for our UWB communication link and address its fundamental limitations. It is clear to observe that we are primarily limited by the communication efficiency limit imposed by nature (most efficient modulation). Shannon's theorem tells us the communication efficiency limit but does not specify how to achieve this limit. One possible research topic is the application of coding techniques to UWB signaling for the purpose of achieving high channel capacity. An associated issue is the impact of non-Gaussian noise (as would be experienced for signals at frequencies below 30 MHz) on the channel capacity.

c) Low Probability of Detection and Intercept

UWB signals have very low power levels that can easily be considered as noise relative to narrowband signals, hence they have an inherent immunity to detection and intercept. Eavesdroppers attempting to discriminate between noise and data will have to be very close to the transmitter (sub meter range) and will have to have access to selected coding schemes and modulation techniques. UWB pulses are very short and modulated with codes unique to each transmitter and receiver pair. The addition of handshaking protocols and encryption techniques provide further immunity to intercept and detection making UWB technology attractive for the development of highly secure communication systems that are critical especially for military operations.

d) Lower Sensitivity to Multipath Channels

The effect of multipath in narrowband signals is significant when compared to UWB signals. The out-of-phase effect caused by the addition of LOS and NLOS (non-line-of-sight) continuous waveforms, i.e. narrowband signals, can cause signal degradation up to -40 dB. On the other hand, very short duration pulses, i.e. UWB nanosecond pulses, are less sensitive to multipath effect because such "narrow" pulses have an extremely short collision window between the LOS and NLOS (reflected) pulses. However, lower sensitivity to multipath channels does not mean immunity. Research on UWB channel modeling has shown that in completely NLOS environment, the impulse radio signal can become significantly distorted due to frequency dispersion and the modulation scheme [67]. Successive multiple reflections through a large number of objects and scatterers in close proximity tend to distort the signal.

UWB Attributes	Advantages	Disadvantages	Applications
Large Fractional Bandwidth	• High Transmission Rate • Frequency Re-use (spectral efficiency) • More energy per bit is transmitted.	• Potential interference to and from existing radios.	• Short range high rate PAN. • Indoor localization
Low Power Transmission	• Low probability of detection and Intercept.	• Short range capabilities	• Low power communication
Short Pulses	• Lower Sensitivity to multipath	• Long synchronization time	• NLOS communication

2) General Architecture

We start with a generic structure of a communications system in which a source of information is communicating with an information sink via a channel as illustrated in Figure 11. The goal of the communications system is to transmit, from the source to the sink, as much information as possible while achieving the greatest fidelity. To that end, one important concept has been developed, *coding* and first introduced by Shannon [63]. The objective of the source encoding is to compress the source signal (reduce the bit rate), that is, to minimize the average number of bits required to represent a source symbol. The objective of the channel encoding is to maximize the information rate that the channel can sustain to transmit reliably and efficiently. The metric by which *reliability* is measured is commonly referred to as the bit error probability or bit error ratio[3] (BER). The communications system is also

[3] An error ratio is "the ratio of the number of bits, elements, characters, or blocks incorrectly received to the total number of bits, elements, characters, or blocks sent during a specified time interval. The most commonly encountered ratio is the bit error ratio (BER) - also sometimes referred to as bit error rate."

composed of other fundamental components that are critical to the success of transmission. These components are encompassed under what we called the *link*. The link refers to the communication path from the modulator (and the transmitter), through the channel, to the receiver and demodulator. We will look in more details at the encoder, the link and the decoder in the following sections as applied to UWB systems.

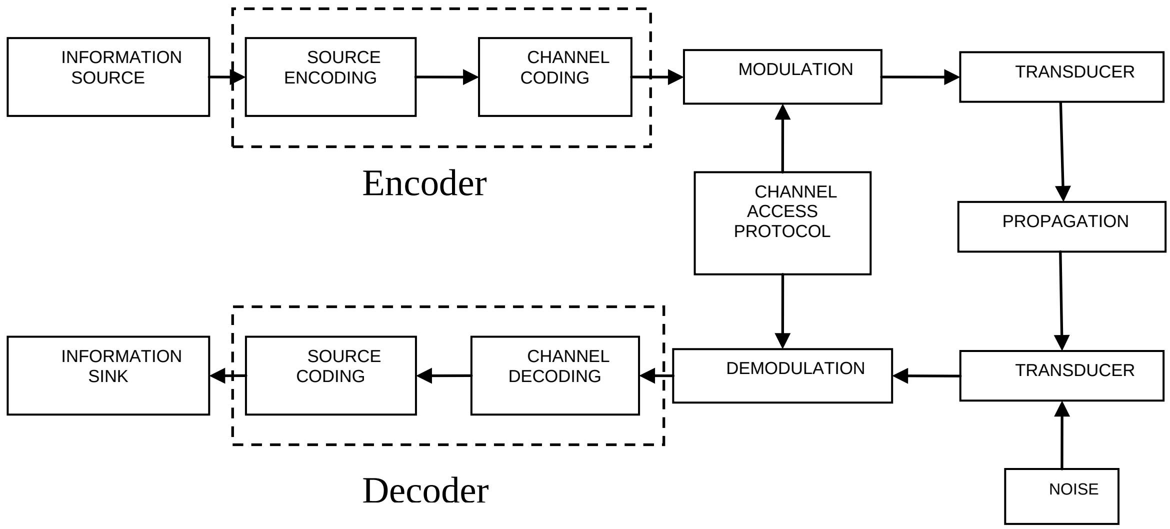


Figure 11 Generic architecture of a communication system.

a) Modulation

There are two common UWB modulation types that are used in UWB systems. One type of modulation is based on a single-band processing (there is no intermediate frequency used) or impulse radio (IR) systems. The second type of modulation is based on multiband processing and do have carriers, such as Multiband UWB and Orthogonal Frequency Division Multiplexing (OFDM) (supported by the Multiband Group -WiMedia Alliance).

In the single-band systems, information bits are modulated directly into the amplitudes, phases, or position of the pulses. The modulation techniques employ in single-band UWB systems include pulse amplitude modulation (PAM), on-off keying (OOK), pulse position modulation (PPM), and phase-shift keying (PSK). Additionally, in a single-band UWB system multiple users share the same UWB spectrum simultaneously; therefore, sharing of the spectrum by multiple users required the use of multiple access techniques. Four access modulation schemes are used in the impulse radio category: (1) time-hopping pulse position (TH-PPM) modulation; (2) time-hopping pulse amplitude (TH-PAM) modulation; (4) time-hopping phase shift keying modulation: and (4) direct-sequence pulse amplitude (DS-PAM) modulation (favored by UWB Forum).

❖ *Pulse Amplitude Modulation (PAM)*

Pulse amplitude modulation for UWB systems can be represented using two antipodal Gaussian monocycle pulses. Pulses sent individually can have the form (see Section A.1)b) above for more details):

$$G(t) = \frac{-A_j t}{\sqrt{2\pi\sigma^2}}\, e^{-t^2/2\sigma^2} \qquad (36)$$

where A_j is either 1 or -1 depending on the bit transmitted. Figure 12 shows a binary PAM pulse shapes for “1” and “0” bits. In Equation (37), σ is related to the pulse width T_p by $\sigma = T_p/(2\,\pi)$ [73]. In general, an M-ary PAM signal is made out of a sequence of modulated pulses with M different amplitude levels and can be modeled as

$$\tilde{x}(t) = \sum_{k=-\infty}^{+\infty} a_m(k)\, G\left(t - kT_f\right) \qquad (37)$$

where $a_m(k)$ is the amplitude of the k^{th} pulse, which depends on the M-ary information symbol m, where $m \in \{0,1,2,\ldots,M-1\}$, and T_f is pulse repetition time ($T_f > T_p$) and $A_j = +1$ (in Equation (36)). Figure 13 shows a 4-ary PAM signal. PAM signals are simple to generate but are very sensitive to channel noise which can change the amplitude and cause false detection.

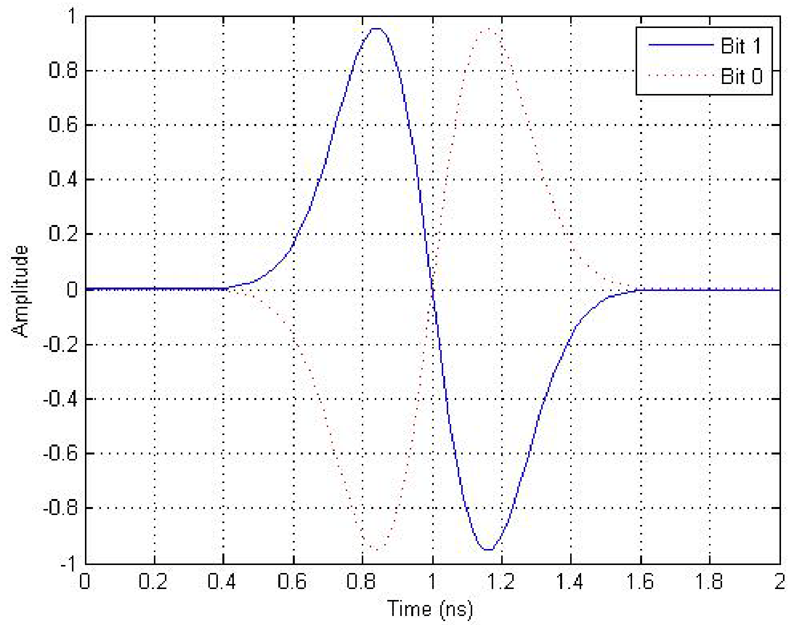


Figure 12. Binary PAM pulse shapes for "1" and "0" bits.

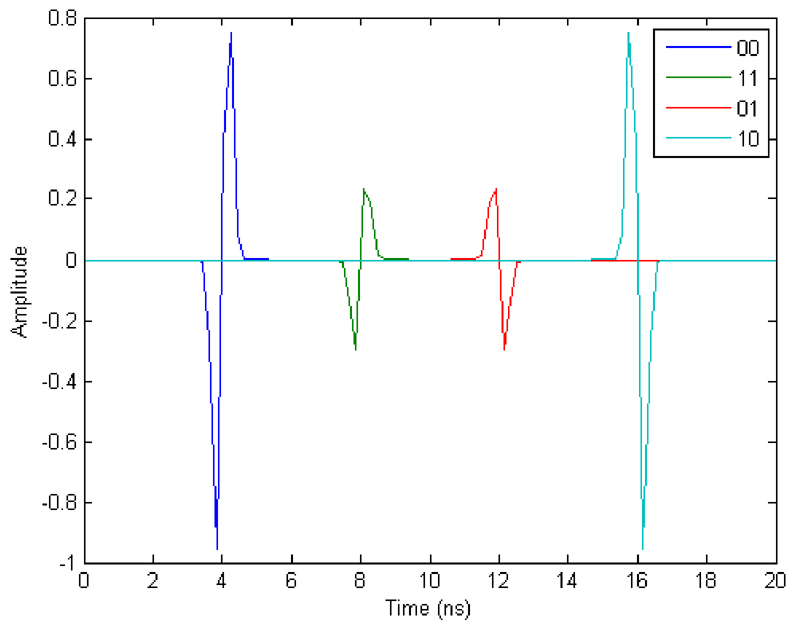


Figure 13. Four-ary PAM signal.

The PAM symbol error probability [70] is

$$Pa(\gamma) = \frac{M-1}{M}\, erfc\left(\sqrt{\frac{3\gamma}{M^2-1}}\right) \qquad (38)$$

where $\gamma = E_{avg}/N_o$, E_{avg} is the average symbol energy and N_o is the noise. The corresponding bit error ratio as a function of average SNR per bit is

$$P_b = \frac{M-1}{M\, log_2(M)}\, erfc\left(\sqrt{\frac{3\log_2(M)}{M^2-1}\frac{E_b}{N_o}}\right) \qquad (39)$$

The average bit energy, E_b, is related to the average symbol energy E_{avg}, by $E_{avg} = (\log_2 M)\ E_b$. Figure 14 shows the bit error performance as a function of SNR for M=2,4, 8 and 16 PAM.

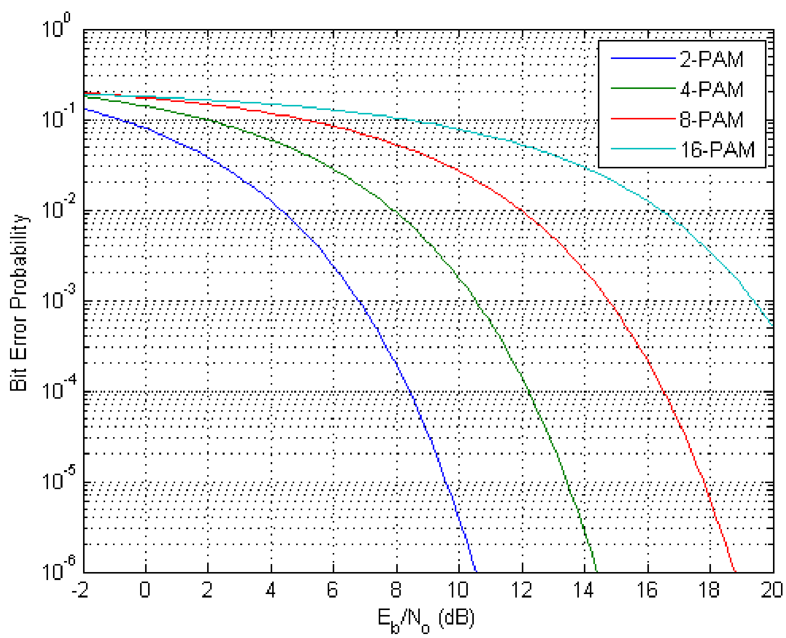


Figure 14. Probability of bit error versus E_b / N_o for M-ary PAM (M=2,4,8,16).

The probability of error increases as M increases making the modulation more depending on higher SNR per bit. This is clear since the average symbol energy now has to be shared with more bits. For example, a fixed P_b of 10^{-6} binary PAM requires 10.6 dB SNR, while 4-ary PAM requires 14.6 dB. Similarly, 8-ary PAM requires 19.2 dB which is 8.6 worse than binary PAM at $P_b=10^{-6}$. The modulation efficiency loss is approximately 4 dB for M=4, and approaches 6 dB for every factor of 2 increases in M.

❖ *On-Off Keying (OOK)*

On-off keying is a special case of binary PAM and pulse amplitude (1 or 0). In other words, a pulse is transmitted if the information bit is 1; otherwise, the pulse amplitude is absent (zeros amplitude). An OOK signal is modeled as

$$\tilde{x}(t) = \sum_{k=-\infty}^{+\infty} a(k)\, G\left(t - kT_f\right) \quad (40)$$

This modulation is one of the simples one to implement, but it has very poor performance and noise and interference can easily cause false detection.

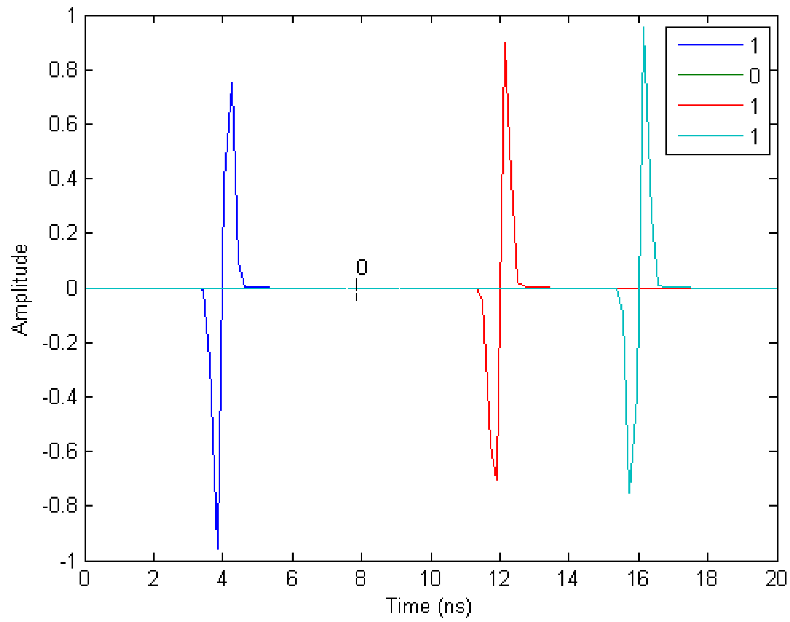


Figure 15. OOK signal.

❖ *Pulse Position Modulation (PPM)*

Pulse position modulation is one of the most used techniques in UWB systems. Pulse position modulation was first introduced by Time Domain Corporation in the late 1980s [71], [L50]. In PPM pulses are generated at high rates, in the million to ten millions of impulses per second. Another unique characteristic is that pulses are not evenly spaced in time, but randomly spaced (pseudo noise) in time intervals. This pseudorandom process reduces the discrete lines on the power spectral density of the PPM signal more than those of the PAM or OOF. This is a very important characteristic especially given the restrictions by the FCC EIRP limited mask. PPM is also less sensitive to noise than is PAM or even PSK signals because information is carried in the time shift of the pulses. UWB systems built using PPM have demonstrated both short and long range data links and positioning measurements within few centimeters [71]. The M-ary PPM signal can be modeled as [72]

$$\tilde{x}(t) = \sum_{k=-\infty}^{+\infty} G\left(t - kT_f - m(k)T_d\right) \quad (41)$$

where $m(k) \in \{0,1,2,\ldots,M-1\}$ is the k^{th} M-ary symbol, T_f is the pulse repetition time and Td is the modulation delay, which shifts the pulses that represent each M-ary symbol. A 4-ary PPM signal is shown in Figure 16.

Performance analysis can be developed based on the autocorrelation characteristics of the pulse. For example, if the goal is to implement a standard PPM system with orthogonal signals, then an optimal modulation delay can be obtained by setting the autocorrelation function of the Gaussian pulse to zero [73], or

$$R\left(T_{d\_opt}\right) = \int_{-\infty}^{+\infty} G(\tau)G\left(T_{d\_opt} - \tau\right)d\tau = 0 \quad (42)$$

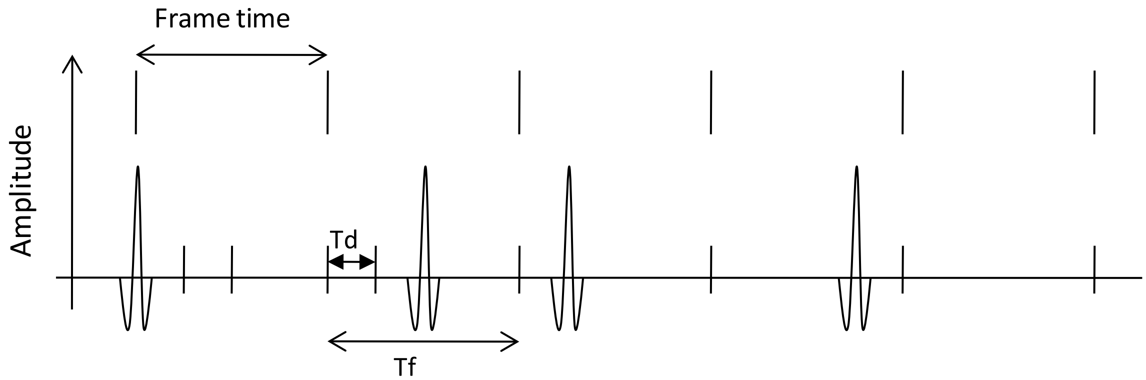


Figure 16. Four-ary PPM signal.

It has been shown that the optimal modulation delay is independent of pulse width but optimal BER performance and higher data rates will be achieved if the modulation delay is smaller than the pulse width. Additionally, as the order of the derivative increases, the minimum bit error ratio is reached for lower values of Td, thus a better BER performance is achieved [73] Table 1 shows optimal time shift values as a function of the pulse width for PPM modulation in an AWGN channel (from [73]).

Table 1. Optimal time shift values for Td for PPM modulation.

Pulse Signal	**Optimal Td**
Second Derivative	$0.292683.T_p$
Third Derivative	$0.243902.T_p$
Fourth Derivative	$0.219512.T_p$
Fifth Derivative	$0.195122.T_p$

Pulse shape modulation (PSM) is an alternative to PAM and PPM for UWB system implementation. The idea is to use different pulse shapes to represent information bits. Modified Hermite polynomial functions, wavelets, Rayleigh, Laplacian and cubic monocycles [59] have been proposed in the literature as pulse sets for PSM systems since all exhibit orthogonal property which is desirable for optimum detection. This particular feature is an area worthwhile for research since it will possibly allow alternative multi-access techniques.

❖ *Phase Shift Keying (PSK)*

In binary PSK (BPSK) for UWB systems, data is determined by the polarity of the pulses. Impulses are sent individually, for example, with a positive polarity if the information bit is 1, and a negative polarity if the bit information is 0. A BPSK signal can be modeled as

$$\tilde{x}(t) = \sum_{k=-\infty}^{+\infty} a(k)G\left(t - kT_f\right) \quad (43)$$

where a(k) is equal to 1 or -1 depending whether the information bit is 1 or 0 respectively. For an M-ary PSK system, a(k) can take values in the set

$$\left\{\frac{2\pi}{M}\,(i-1) + \varphi\right\}_{i=1}^{M} \quad (44)$$

where φ is an arbitrary phase. BPSK modulation approach and PPM are two of the most common modulation techniques used in UWB systems. People also refer to BPSK modulation for UWB systems as a Bi-Phase Modulation (or BPM); however, since phase is associated with a delay in a typical narrowband communications system, the term in UWB can be confusing. When compared to PPM, BPM is based on polarity (antipodal modulation), while PPM is based on delay and possibly orthogonality. Two important features make BPM more attractive than either PPM or PAM. PPM sends millions of delay pulses, but those instances in times in which pulses are not transmitted are under used or "wasted". In one cycle in which PPM pulses are delayed, i.e. a delay by one pulse width, then BPM can send twice as many pulses resulting in twice the information. BPM signals have zero mean due to the change in polarity, thus there BPM signals have fewer discrete lines on the power spectral density, minimizing violation of the FCC power spectral density template. Other benefits related to BPM modulation, according to McCorkle [74] are:

> Biphase presents several other key benefits. First, it exhibits a peak-to-average power ratio (PAR) of less than 8 dB. Thus, an implementation using biphase does not require any external snap-recovery or tunnel diodes or power-amplifier circuitry. Instead, it can be driven directly from a low-voltage high-speed CMOS IC.
>
> Finally, for reasons of clocking, biphase modulation has reduced jitter requirements. In PPM, the clocking path must include elements to accurately control arbitrary time positions on a fast (pulse-to-pulse) basis. This control requires a series of wide-bandwidth circuits where jitter accumulates. But a biphase system needs only a stable, low-phase-noise clock as the pulses occur on a constant spacing. Synchronization circuits can be narrowband so that they do not add significant jitter. As a result, less power and real estate are needed to implement the required circuits.

The error probability of pulse polarity modulation is expressed as (conventional BPSK, from [71])

$$P_{BPM} = \frac{1}{2}\, erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \qquad (45)$$

which is also a valid approximation also when M=4. The error probability for an M-ary PSK is closely approximated by (from [75])

$$P_{BPM} \approx\; erfc\left(\sqrt{\log_2 M \frac{E_b}{N_o}}\, \sin\left(\frac{\pi}{M}\right)\right) \qquad (46)$$

The probability of error for M-ary PSK is shown in Figure 17. When compared with the probability

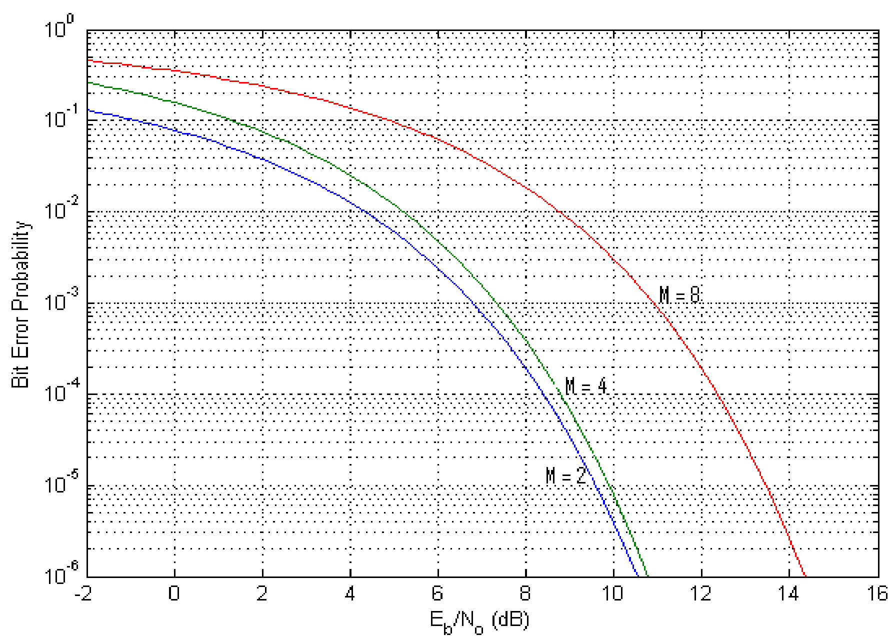


Figure 17. Probability of bit error versus E_b / N_o for M-ary PSK (M=2,4,8).

of error for M-ary PAM, we can see that for M=4 or 8, PAM requires more than 4 dB of SNR to achieve the same probability of error of 10^{-6}.

II. Advancement and Regulatory Efforts for Ultra Wideband Technology

An interest in the applications of UWB for commercial use has increased over the past several years, especially after the period 2002 - 2004 when the FCC approved the First Report and Order (RO) and a revisited version of RO for commercial use of UWB technology under strict emission power limitations which are discussed in Section III.B below. For the regulation of UWB around the world, there are many organizations that set recommendations and rules for UWB applications. To better understand the global effort on UWB technology and its advancement, we classify such effort into four different groups: (A) Regulatory Bodies; (B) Standardization Organizations; (C) Research & Development Centers and (D) Industry or Global Public Organizations. When possible, we will establish relationships among these groups and their common efforts. Figure 18 shows the four groups considered in this paper:

A. Regulatory Bodies: are those organizations that control, regulate or manage the use of Radio Frequency (RF) spectrum and telecommunications media in any given country. Telecommunications media include radio, television, wire, satellite and cable.

B. Standardization Organizations: are those entities "whose primary activities are developing, coordinating, promulgating, revising, amending, reissuing, interpreting, or otherwise maintaining standards that address the interests of a wide base of users outside the standards development organization" [44].

C. Research & Development Centers: are those organizations dedicated to the advancement of a technology (UWB technology) throughout research and development. R&D Centers include universities, industry laboratory centers and government research centers.

D. Industry and Public Organization (IaPO): are those organizations that promote the standardization of a given technology, i.e. UWB technology, foment its advancement, organize forum and develop technical specifications. Generally, IaGPOs are non-profit organizations whose members include industry (private companies), research laboratories and academic leaders.

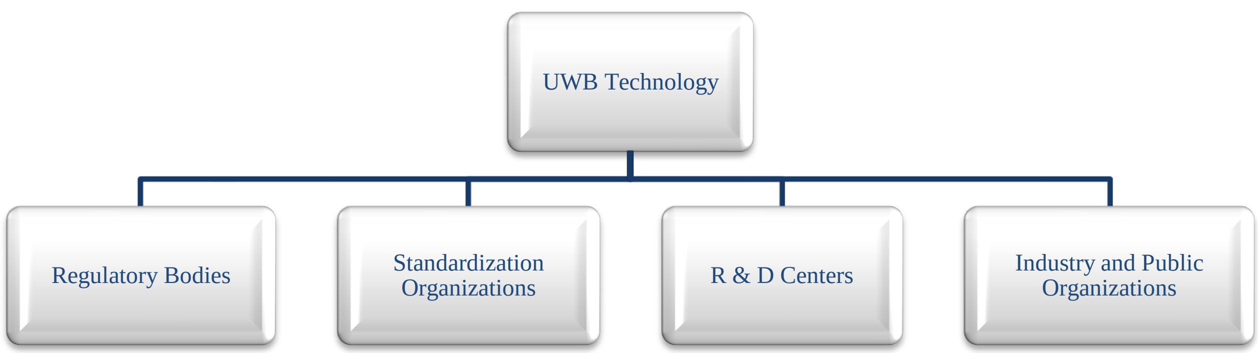


Figure 18. Classification of effort in UWB technology around the world.

A. Regulatory Bodies

In this section we will discuss the progress made on UWB technology and effort toward its regulation and standardization as carried out by regulatory bodies across different regions of the world and by some of the international standardization organizations. In presenting our findings, we have classified regulatory bodies under three categories or world regions: (1) USA, (2) Europe, and (3) Asia-Pacific (include China, Japan, Singapore, etc.) Figure 19 illustrates the structure of the regulatory bodies and those standardization organizations considered in our discussion.

1) USA – Federal Communications Commission (FCC)

In the USA the process towards the regulation of civilian UWB applications was initiated in the late 1990's by the FCC. In September 1998, the FCC released the Notice of Inquiry (NOI) about UWB technology ([45],[L7]) with the purpose to investigate the possibility of permitting the operation of ultra-wideband radio systems on an unlicensed basis. The inquiry called for input to help evaluate UWB technology and to determine standards and operating requirements necessary to prevent interference to existent radio services. The request was open to all interested parties. Following the process of inquiry, the FCC published the first draft for UWB regulations. This document, called Notice of Proposed Rule Making (NPRM) ([46],[L8]), was released in May 2000. In this report, the FCC expressed the possibility that UWB devices could be operated on radio frequency spectrum already allocated to other radio services without causing interference, however, it made clear that further testing and analysis were needed before the risk of interference was better understood. The issue about co-existence arose and is discussed in Section III.C.2) below. Again, the FCC requested comments from interested parties. Extensive comments and reply comments to both documents can be found in [L9].

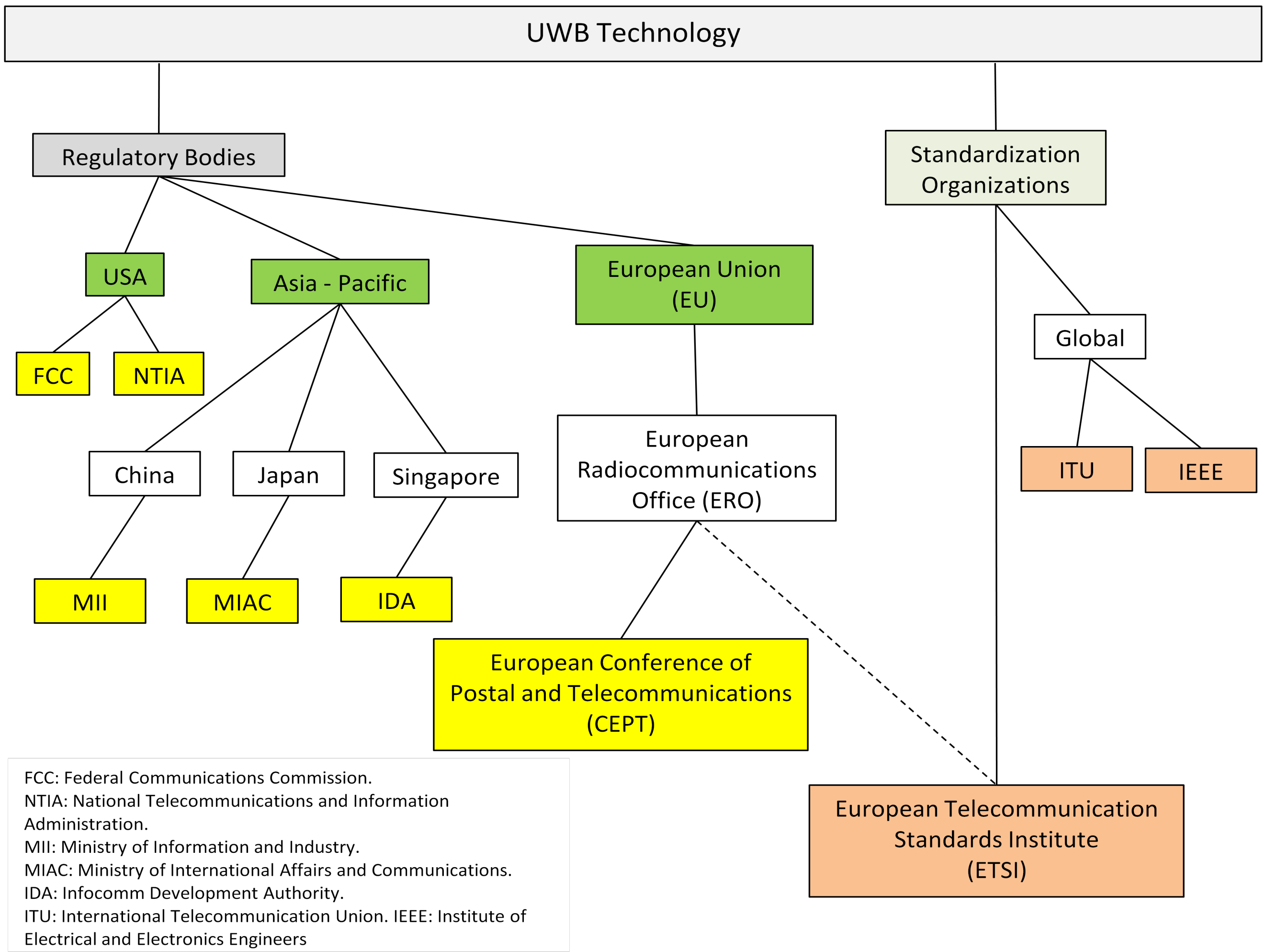


Figure 19. Structure of regulatory bodies and standardization organization for some regions of the world as they pertain to UWB technology.

Adopted on February 14, 2002 and later released on April 22, 2002, Revision of Part 15 of the Commission's Rule Regarding Ultra-Wideband Transmission System, First Report and Order (RO) ([1],[L1]) gave the permission to commercialize UWB technology if it meets a series of radiation mask limits. These mask limits (discussed below) were the results of studies from the two previous Notices, inputs from interested parties and more importantly from studies carried out by the NTIA. As a part of the process, three reports were produced by the NTIA. The first report characterizes UWB signals and can be found in [L10]. The second report addresses the compatibility of UWB with respect to selected federal systems [L11] and the third focuses on the compatibility and interference issues with respect to GPS receivers and can be found in [L12]([L13] is an addendum).

In February 2003 and at the end of 2004, the FCC released Memorandum Opinion and Order and Further Notice of Proposed Rule Making (MO&O and FNPRM)([47],[L15]) and Second Report and Order and Second Memorandum Opinion and Order ([15],[L14]) respectively. One important ruling that came out of the MO&O and

FNPRM report is that the FCC proposed to eliminate the definition of an UWB transmitter (47 C.F.R § 15.503(d))[4] and in its place, the FCC would permit "the operation of any transmission system, regardless of its bandwidth, as long as it complies with the standard for UWB operation set forth in Subpart F of 47 C.F.R. Part 15"[5]. In the Second Report and Order, the FCC decided not to change the existing UWB rules until the FCC had more experience with UWB devices. Instead and alternatively, the FCC decided to make changes to the general provisions of unlicensed devices. More specifically, the FCC decided to permit the use of peak emission levels, similar to UWB devices, for wideband emissions in the 5925 - 7250 MHz, 16.2 – 17.7 GHz and 23.12 – 29.0 GHz bands [15].

2) *European Union*

In Europe, the European Conference of Postal & Telecommunications Administration (CEPT) is responsible for examining public policy and appropriate regulatory issues regarding post and electronics communications, including the use of radio spectrum. It also promotes and helps to realize harmonization of the radio spectrum among all its members[6]. It is important to mention that CEPT is an independent organization which cooperates with the European Union (EU) [L20], the European Free Trade Association (EFTA) [L21] and other intergovernmental organization as well as any other organizations involved with posts and electronic communications ([48][L18]).

CEPT originally formed three committees, one on postal issues, Comité européen de Réglementation Postale (CERP) and two on Electronic Communication matters: the European Radiocommunications Committee (ERC) and the European Committee for Regulatory Telecommunications Affairs (ECTRA). In September 2001, these two committees were merged into a single body, the Electronic Communication Committee (ECC). ECC is then the Committee that brings together the radio and telecommunications regulatory policies of the 48-member countries and is supported by the European Radiocommunications Office (ERO). ERO is the distribution point for all ECC documentation and also provides detailed information about the work of the ECC via its web site at [L22]. In addition to these three groups, in 1988 CEPT created the European Telecommunications Standard Institute (ETSI) [L25] to manage all its telecommunication standardization activities. ETSI is officially recognized by the European Commission as a European Standard Organization. ETSI has a Memorandum of Understanding (MoU) with CEPT in which both bodies "will develop deliverables embracing all necessary aspects of electronics communications" ([51], [L32]). UWB issues are under the Technical Committee EMC (Electro Magnetic Compatibility) and Radio Spectrum Matters (TC-ERM)[L29] in task group 31a/b ([L30][L31]). TC-ERM is the technical committee responsible for coordinating and supporting the needs and interests of all ETSI members on radio spectrum matters and allocations.

The groups within CEPT involved with UWB and related radio spectrum matters include the following working groups (WG):

a) WGFM: Frequency-Management Short-range Device Maintenance Group (SRDMG) [L26].
b) WGSE: Spectrum Engineering. Two task group exists under WGSE, SE21 (unwanted emissions) and SE24 (short-range devices) [L27].
c) WGRR: Regulatory Affairs [L28]. This group is responsible to draft the final regulations for UWB.

In 2004 and later in 2005, the European Commission (EC) mandated the European Conference of Postal & Telecommunications Administration (CEPT) to identify and develop harmonized standards for UWB applications for the countries of the European Union([50],[L23],[49],[L24]). In March 2004, the ECC responded to the first mandate by establishing Task Group 3 (TG3)[L33]. Task Group 3 main tasks include:

- To study the possible use of UWB at fixed locations, or connected to a fixed outdoor antenna.

---

[4] (d) <u>Ultra-wideband (UWB) transmitter</u>. An intentional radiator that, at any point in time, has a fractional bandwidth equal to or greater than 0.20 or has a UWB bandwidth equal to or greater than 500 MHz, regardless of the fractional bandwidth [L16].

[5] Subpart F refers to Part 15 Sections 501, 503,505, 507,509, 510, 511, 513, 515, 517, 519, 521, 523 and 525 [L17].

[6] Currently 48 countries are members of CEPT [L19].

- To consult with relevant European organization, particularly ETSI, and
- To study the technical requirements for mitigation techniques to be allowed under the genetic regulation for UWB devices.

Figure 20 shows the structure of CEPT working groups on UWB technology.

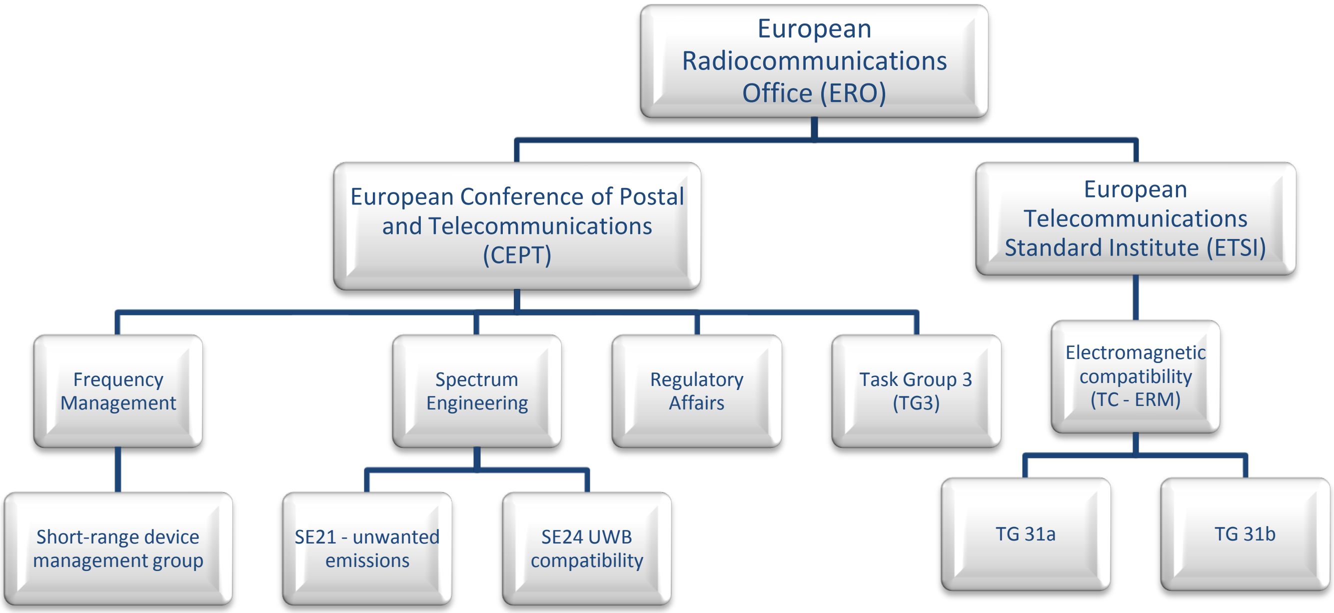


Figure 20. Structure of CEPT working groups on UWB technology.

At its meeting in Cascais in October 2005, the Electronic Communications Committee (ECC) of the European Conference of Communications and Postal Administrations (CEPT) approved the uses in Europe of devices using UWB technology in bands below 10.6 GHz but restricted to indoor operations. In March of 2006, ECC approved the use of UWB for Europe in the 6 to 8.5 GHz band ([12],[L39], [52],[L40]). In February 2007, the final decision allowing the use of UWB stated ([13],[L38]): "The Member States shall, as early as possible and no later than six months following the entry into force of this Decision, allow the use of the radio spectrum on a non-interference and non-protected basis by equipment using ultra-wideband technology provided that such equipment meets the conditions set out in the Annex to this Decision and it is either used indoors or, if it is used outdoors, it is not attached to a fixed installation, a fixed infrastructure, a fixed outdoor antenna, or an automotive or railway vehicle." Investigation and final report on the use of UWB in outdoor locations and infrastructures have not been released yet, but considerations are being studied. Radiation limits of UWB devices will be described in Section III.B below.

3) Asia-Pacific

a) Japan

The regulatory body that sets policy on UWB in Japan is called the Ministry of International Affairs and Communications (MIAC)[L34]. In March 2004, it published its first report on the limit of UWB emission and addressed the issue of interference. On limit of emission, it set the limit of UWB to be the same as that set by the FCC, and for the other, it set a slightly more restrictive limit. In August 2005, the Ministry of International Affairs and Communications adopted the use of UWB communications with unlicensed spectrum with initial allocation between 3.4-4.8 GHz and between 7.25-10.25 GHz for indoor devices. "The allocation requires the implementation of Detection and Avoidance (DAA) for the 3.4-4.8GHz band to ensure co-existence with existent systems and new services such as 4G and no DAA for the higher band (7.25-10.25GHz). The emission limits from 3.4-4.75GHz and from 7.25-10.25GHz is -41.3dBm/MHz, and is the same as what the U.S. Federal Communications Commission (FCC) ruled" [14].

b) Singapore

Singapore is another important country in the Asia region that in February 2003 initiated a UWB program through its regulatory body: the Infocomm Development Authority (IDA) [L35]. In its first phase, a two-year effort, the IDA set the following objectives:

- Aim to encourage technical UWB experimentation through the introduction of trial regulations.
- Gather experimental data to determine regulations that would enable commercial deployment.
- Create an ecosystem of UWB players and users.

Main focus was to exploit the UWB technology in three important areas:

i. Consumer and business data communication systems.
ii. Trough-wall or ground probing radar imaging systems.
iii. Asset tagging, tracking and vehicle collision avoidance systems.

In December 2007, the Infocomm Development Authority adopted the use of UWB and issued the Technical Specification document for Ultra Wideband (UWB) Devices ([35],[L36]).

c) China

Another important country in the region, China, has been rather slower in setting regulatory rules on UWB technology. Since 2006 Intel representatives have been working closely with China's Ministry of Information and Industry (MII) [L37] to understand the regulatory changes needed to support wireless technologies including UWB. MII is a regulatory body in charge of the "manufacture of electronic and information products, the communications and software industry, as well as the promotion of informatization of the national economy and social services" [L37] in China. MII issued a public call for comments on their first draft UWB regulation effective thru September 30, 2008. It has proposed uses of UWB transmission in the frequency range band 4.224 – 4.752 and 6.336 – 8.976 GHz. Devices using UWB technology which have UWB transmission in the band 4.224 – 4.752 GHz are restricted for indoor applications only and are required to implement DAA. Devices using UWB technology which has UWB transmission in the band 6.336 – 8.976 GHz can be used indoor and outdoor.

B. Standardization Organizations

1) International Telecommunication Union - Radiocommunication Sector (ITU-R)

The International Telecommunication Union (ITU) [L45] is the impartial international organization in which governments and the private sector work together on matters related to telecommunication networks. In July 2002 the Study Group 1 (SG1) [L46] of the Radio Sector of the ITU (ITU-R) decided to form Task Group 8, or ITU-R TG 1/8 to study the possible introduction of UWB technology and the compatibility between UWB and other communication services . Task Group 8 was then divided into four working groups:

- Work Group 1 (WG1): to work on UWB characteristics issues.
- Work Group 2 (WG2): to work on compatibility issues between UWB and other radio communication services.
- Work Group 3 (WG3): to work on spectrum management.
- Work Group 4 (WG4): to work on measurement techniques.

2) European Telecommunications Standard Institute (ETSI)

In 1988 CEPT created the European Telecommunications Standard Institute (ETSI) [L25] to manage all its telecommunication standardization activities. ETSI is officially recognized by the European Commission as a European Standard Organization. ETSI has a Memorandum of Understanding (MoU) with CEPT in which both bodies "will develop deliverables embracing all necessary aspects of electronics communications"([51],[L32]).

In March 2003, the European Commission issued a mandate to the European Standardization Organizations to develop a work programme for harmonized standards covering UWB applications. ETSI then assigned UWB issues under the Technical Committee EMC (ElectroMagnetic Compatibility) and Radio Spectrum Matters (TC-ERM)[L29] in task group 31a/b ([L30][L31]). TC-ERM is the technical committee responsible for coordinating and supporting the needs and interests of all ETSI members on radio spectrum matters and allocations.

a) ETSI – Task Group 31 a/b (TG31a/b)

The task of TG31a is to investigate and develop generic and specific ETSI radio standards for Short Range Devices (SRD) and Ground- and Wall- Probing Radars using UWB technologies [L43]. The work of TG31a has concentrated in developing a set of standards and technical requirements designed to fit in a modular structure to cover all radio and telecommunications terminal equipments within the scope of the R&TTE Directive (see Annex D in [55]). In February 2008, ETSI issued the most recent ETSI Deliverables: EN 302 066-1 [57] and EN 302 066-2 [56].

EN 302 066-1 provides a generic set of technical requirements covering different types of UWB technologies used for short range devices. Similarly, EN 302 066-2 provides a generic set of technical requirements for Ground- and Wall- Probing Radar imaging systems applications (discussed in Section III.C.1)b) below). For communications applications, power density emission limits are the same as those published by the ECC and discussed in Section III.C.1)b) below. The only difference is in the band 2.7 – 3.8 GHz. ETSI has broken this band in two sub bands: 2.7 – 3.4 GHz with a maximum mean power density of -70 dBm/MHz and 3.4 – 3.8 GHz with a maximum mean power of -80 dBm/MHz.

The task of TG31b is to create and update standards and other technical documents for short-range devices in the field of automotive radar applications. TG31b also investigates spectrum parameters for use in automotive radar systems in order to ensure the efficient use of the radio spectrum, considering global harmonisation [L44].

In June 2008, ETSI published TS 102 754 [58] which include the Detect-and-Avoid (DAA) mitigation technique specifications for UWB to protect:

- Radio services in the band 3.1 – 3.4 GHz.
- Broadband wireless access services in the band 3.4 – 4.2. GHz.
- Radio location services in the band 8.5 – 9.0 GHz.

3) Institute of Electrical and Electronics Engineers (IEEE)

The Institute of Electrical and Electronics Engineers [L47] is “the world's leading professional association for the advancement of technology” and a leading developer of global industrial standards in several industries. The IEEE established the 802.15.3a Study Group to define a new physical layer for short-range and high-data-rate applications. It was not created specifically as an UWB standard group, however, technical requirements pointed very much to the use of UWB technology. By 2003, the number of proposals ended with only two multiband OFDM (orthogonal Frequency-division multiplex) and the DS-CDMA (direct-sequence code-division multiple access) proposal. Since December 2003, the standardization process stalled since none of the two proposal reached the 75% of the votes required for a proposal to become a standard. By early 2006, one of the two proponents of the standard was willing to move forward with a joint proposal, the other was not and had sufficient vote to block forward progress. Finally, in February 2006 the task group decided to eliminate any further attempt to create an IEEE standard.

C. Research and Development Efforts on Ultra Wideband Technology

Time-domain electromagnetic studies have been conducted since early 1962, when different transient phenomena in microwave networks were studied [5],[6],[36]. In the 1960s, the so-called ultra wideband technology was developed for military radar applications [37]. By the late 1960s, both Lawrence Livermore National Laboratory and Los Alamos National Laboratory had already performed original research on pulse transmitters, receivers and antennas. LLNL had already established a laser-based research diagnostic program and in the 1970s began expanding it into a pulse diagnostics effort. The first commercial ground penetrating radar (GPR) was invented in 1974 [38]. In 1975, a technology named baseband radar or free space time domain reflectometer[7] was introduced

[7] “Sub nanosecond baseband or video pulses drive a high fidelity transmitting antenna which, in turn, radiates a differentiated version of the incident signal. The radiated pulse reflects off a target and returns to a similar receiving antenna where it is fed to a range-gated tunnel-diode receiver and display network; in essence, the system is a free-space time domain reflectometer” [39].

with applications in pre-collision sensing, collision avoidance and docking. Beginning in the late 1980s, small companies started basic research and development on communications and positioning systems. Some of these companies include Multispectral Solutions, Pulson Communications (later to become Time Domain Corporation) and Aether Wire. At the same time, extensive research in micropower impulse radar was being carried out at the Lawrence Livermore National Laboratory (LLNL). In the mid-1990s, the Ultra Wideband Radio (UltRa) Laboratory [L51] at the University of Southern California was formed and began lobbying the FCC to allow UWB technology for commercialization. In May 2001, a team of researchers from the University of Southern California, the University of California at Berkeley, and the University of Massachusetts at Amherst were awarded a Multidisciplinary University Research Initiative (MURI) Grant from the Department of Defense. On the initial phase, the focus of this effort was on Short-Range Ultra-Wideband Systems.

Currently, there exist 31 companies with 90 FCC certifications from Canada, Germany, Italy, Sweden, Taiwan, United Kingdom and US with applications areas that include [16] :

- Ground Penetrating Radar (GPR): 7 companies with 38 certified devices
- High-speed Wireless: 15 companies with 28 certified devices
- Real-time Tracking: 3 companies with 9 certified devices
- Automotive Radar: 3 companies with 5 certified devices
- See-through Wall Radars: 1 company with 3 certified devices
- UWB Test Equipment: 3 companies with 3 certified devices
- UWB Radars: 2 companies with 2 certified devices
- Low-speed Wireless (e.g., audio): 1 company with 2 certified devices

A list of semiconductor companies involved in the development of UWB solutions is included in Table 2 [78].

Table 2. Semiconductor companies involved in UWB technology.

Semiconductor Companies	Website Link
Alereon	www.alereon.com
Artimi	www.artimi.com/
Broadcom	http://www.broadcom.com/careers/wireless_design_center.php
Cambridge Silicon Radio	http://www.csr.com/pr/pr193.htm
Focus Enhancements	http://www.focussemi.com/products/uwb_radio_module.html
Fujitsu	http://www.fujitsu.com/us/services/edevices/components/input/uwb.html
General Atomics	www.ga.com/uwb
Infineon	http://www.infineon.com/cgi-bin/ifx/portal/ep/channelView.do?channelId=79492&pageTypeId=17099
Intel Corporation	http://www.intel.com/technology/comms/uwb/
Mindtree Consulting	www.mindtree.com/
NEC Electronics	http://www.necel.com/usb/en/wusb/uwb.html
NXP Semiconductor	www.nxp.com/products/connectivity/uwb/index.html
Realtek Semiconductor (Wionics)	http://www.wionics.com/
Staccato Communications	www.staccatocommunications.com
Synopsys	http://www.synopsys.com/products/designware/wiusb_solutions.html
Texas Instruments	http://focus.ti.com/docs/solution/folders/print/302.html
Tzero	www.tzerotech.com
Wipro	http://embedded.wipro.com/reusablframeworks/uwb/
Wisair	www.wisair.com/
WiQuest Communications	www.wiquest.com

Commercial leading companies include:

(1) Consumer Electronics: Philips Electronics and Samsung Electronics.

(2) Personal Computing: Intel, Texas Instruments and Microsoft.

(3) UWB Developers: Multispectral Solutions, Pulse~Link, Staccato Communications, Time Domain Corporation and Xtreme Spectrum.

Internationally, several centers around the world have formed laboratories or projects aimed to develop UWB technology for both commercial and military applications. The Scientific and Research Center of Ultra-Wideband Technologies of the Moscow Aviation Institute [19], [L52] was created in 2007 to explore ultra wideband technology in radars operating at short distance with applications to medicine, guidance systems and transport safety systems. Another important research center exploring and developing applications for UWB is Philips Research Center . Projects currently being pursued by Philips Research are aimed at developing the technologies needed to realize high-speed data and audio/video streaming. Part of Philips' research focuses in ultra-wideband technology to enable low-cost, short-range connectivity with data rates ranging from 100 to 400 Mbit/s and beyond. This research is part of Philips' vision of "Ambient Intelligence" viewed as "people living easily in digital environments in which the electronics are sensitive to people's needs, personalized to their requirements, anticipatory of their behavior and responsive to their presence" [L54].

Also in Europe, there are two more important centers dedicating substantial effort to UWB technology: Nokia Research Center (Lausanne, Switzerland) [L55] with open collaboration with École Polytechnique Fédérale de Lausanne (EPFL) [L56], and the Swiss Federal Institute of Technology (ETH Zürich) [L57] and IBM Research, Zurich Research Laboratory [L53].

In the Asia-Pacific region, China has been investing substantial efforts in UWB technology since 2000. China's Hi-Tech Research Development Program (HTRDP), [L58] also known as the 863 program, has been very supportive of UWB research. HTRDP awarded the first grant for UWB research to Southeast University[8] and since has continuously increased budget support for this effort. Other universities in China are engaged in key technologies and system level solutions. With support from the 863 program, two high-speed UWB demo systems have been developed by Southeast University and jointly with the University of Science and Technology of China and Tsinghua University[9], respectively. The National Natural Science Foundation of China (NSFC) [L59], which is another important research funding provider of Chinese government, also initiated a UWB key project in 2004. This project was jointly taken by Harbin Institute of Technology, Nanjing University of Posts and Telecommunications, and Guilin University of Electronic Technology [23].

China Communications Standards Association (CCSA) [L60] is not a research institution, but a unified standard organization that carries out standardization activities in the field of Information and Communications Technology across China. Established in 2002, CCSA has been involved in UWB technology applications with three main goals: study the effect on interference and protection between UWB and other wireless technology, get UWB PSD values in UWB and other wireless technology co-existence, and give reference for China UWB spectrum. Four fields in this area include, UWB and IMT-2000 FDD[10], UWB and IMT-Advanced [11], UWB and GSM and UWB

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[8] Southeast University, located in the city of Nanjing, Jiangsu Province, is one of the top 10 universities in scientific research and development in China.

[9] Tsinghua University located in Beijing, ranks as the top university in China and is one of the most famous comprehensive universities in China.

[10] International Mobile Telecommunications-2000 (IMT-2000) is the global standard for third generation (3G) wireless communications, defined by a set of interdependent ITU Recommendations.

[11] International Mobile Telecommunications-Advanced (IMT-Advanced) systems are mobile systems that include the new capabilities of IMT that go beyond those of IMT-2000. Such systems provide access to a wide range of telecommunication services including advanced mobile services, supported by mobile and fixed networks, which are increasingly packet-based.

and TD-SCDMA [12].

Figure 21. Research & Development on UWB at government, university and industry centers in three areas of the world.

More specific information on the research and development at these centers and companies will be discussed in the following sections.

1) *Government and University Research Centers*

In this section, we discuss some of the most relevant work currently being developed at companies and research centers in the United States and other countries. We concentrate on those that have a more established history on UWB technology.

a) USA

❖ *Ultra Wideband Radio Laboratory (UltRad), University of Southern California, Los Angeles, CA*

Under the leadership of Dr. Robert Scholtz, UltRad has focused his research on the problems and issues that are associated when designing radios whose radiation has very large fractional bandwidth, i.e., ultra-wideband (UWB) radio systems. Consideration are being given to the considerable changes in conceptual design from narrowband to UWB radios, and applicable to all aspects of radio design, from propagation characterization and modeling, to antenna design, circuit design, and system design and architecture. Major topics include modeling UWB channels (especially for short range mobile and dense multipath links), antenna design for UWB links, co-existence with interference, energy capture for highly time-spread UWB signals, rapid sync acquisition techniques, low-power implementation issues, and compliance with expected FCC regulations.

Most recently, UltRad along with researchers from the University of California at Berkeley, and the University of Massachusetts at Amherst formed a Multidisciplinary University Research Initiative (MURI) to explore deeper into UWB technology. Some of the most important areas that MURI has been studying include the following:

[12] Time Division-Synchronous Code Division Multiple Access, or TD-SCDMA, is a 3G mobile telecommunications standard, being pursued in the People's Republic of China by the Chinese Academy of Telecommunications Technology.

i. Algorithm and System Architecture Studies: work in this area focuses on UWB acquisition and tracking, channelized UWB receivers, UWB frequency domain processing and capacity limits of UWB Impulse radios. More particularly, MURI has looked at design challenges driven by synchronization, channel estimation, multipath and tracking hardware imperfections. UWB systems have been considered for very high data rate applications, e.g. WPAN (Wide Personal Application Network) with at least 110 Mbps data rate. Channel measurements have demonstrated the present of delay spreads far beyond 30 ns resulting in significant inter-symbol interference (ISI). This poses a challenge to the way receivers are designed, which in many cases, ISI is ignored assuming AWGN. MURI has had two important goals in the study of channel capacity: they want to understand the impact of channel uncertainty on capacity of various UWB modulations and to design ways to mitigate the effect of channel uncertainty on performance.

ii. Antennas and Propagation: most important topics include simulation of UWB antennas and circuits, antennas for UWB, optimal waveform studies and UWB synthesizer. Challenges in this research include the study of antenna geometries for UWB with the goal to determine:

- Pulse shapes optimal for generation, radiation & reception.
- Simple "canonical" pulse shapes suitable for generation through hardware.
- Effects of spectrum control to meet FCC regulation.

There seem to be more questions than answers to most of the issues related to antenna and UWB systems. In antenna radiation and reception, MURI has been trying to understand three important issues: (i) what happens when a short pulse is transmitted and received by antennas; (ii) how "link loss" is defined and calculated and (iii) what the optimal generator waveform is in order to maximize received voltage amplitude, or received energy. Analysis of radio link loss for transient radiation and reception has been based on three methods:

- Rigorous electromagnetic analysis: full-wave analysis of antennas and T/R effects.
- Comparison with narrowband Friis formula.
- Closed-form approximation for dipoles with Gaussian pulses.

Solutions to these problems, including the effects of T/R antennas and loads have been obtained using variation methods and numerical electromagnetic solutions.

iii. Circuit Design: some of the challenges looked in this area deal with the digital UWB receivers and the limitations imposed by the need for high speed, high dynamic range ADC and wideband low noise amplifiers. MURI has been researching on the design of UWB low noise amplifiers in CMOS, low power integrated UWB transceivers and CMOS implementation design for UWB acquisition, tracking and detection.

❖ *Lawrence Livermore National Laboratory (LLNL), Livermore, CA*

Using an experimental license, Livermore has developed numerous UWB systems in frequency bands ranging from 200 MHz to 100 GHz. The work at LLNL has been mainly directed at developing UWB devices for the government at frequencies that operates above and below the limits set by the FCC designated for commercial devices, i.e. 3.2 – 10.6 GHz. Concentration has been given to short pulse UWB systems. One of the most significant contributions that came from LLNL is an invention derived from laser research called micropower impulse radar (MIR). In the last decade Livermore researchers have been applying their expertise in MIR to develop new types of UWB-based sensing, imaging, and communication devices that are portable, rugged, energy-efficient, and resistant to detection and interception. Some of the transmitter designed with MIR can emit millions of pulses per second with a width pulse as short as 50 picoseconds. MIR technology has made possible the design of extremely accurate systems for motion detection and localization. Currently, under the direction of Steve Azevedo, extensive research is concentrated on radar and radio projects which fall into three areas: sensors, imagers and communications. Through modifications of MIR motion sensors, some applications include search and rescue under rubble, measurement of explosive velocities up to 3800 m/s , proximity for rockets and cluster bombs, cargo container intrusion sensing, inspection of bridge decks and other. Equipped with high gain antennas, LLNL has developed portable detectors capable of sensing motion caused by breathing and heartbeats up to 100 meters away. As a medical device, MIR sensors have been considered to improve combat casualty care. The idea is to monitor a soldier's vital signs and relay the information to a central command post. In response to the military's need, LLNL has developed rugged, low-power motion sensors that avoid detection and interception. An interesting device being considered provides security within a confined area. It is equipped with an omnidirectional antenna that can generate a protective "bubble": all motion outside the bubble and limited motion inside the bubble are ignored, but any penetration of the bubble triggers an alarm.

Livermore engineers are also developing systems that monitor the status of shipping containers before they arrive to the port. The project target inexpensive devices that can last at least 10 years. The unit shall be able to detect any intrusion, monitor radiation levels and be able to transmit all the information to a computer on the ship. Networking of these devices using UWB communications is part of the research being carried out at LLNL.

With growing concern with the safety of bridges in the US, LLNL is investing efforts to develop suitable MIR sensors that can generate images. One particular project, the High-Performance Electromagnetic Roadway Mapping and Evaluation System (HERMES), scans the bridge deck, generates a set of images and pinpoints needed repairs. UWB pulses with frequencies ranging from 1 to 5 GHz are used; they are able to penetrate to a depth of up to 30 centimeters. Echoes generated from the surface are recorded and compiled into a three-dimensional map of the deck.

Additional work in UWB systems using MIR sensors and technology is being extended to devices such as radio used in police, military, and intelligence operations. LLNL engineers are currently developing for The Department of Energy (DOE) a network of walkie-talkies to serve as a backup to typical narrowband units. LLNL is also exploring video and data communication over short distances.

b) Europe

❖ *The Scientific and Research Center of Ultra-Wideband Technologies of the Moscow Aviation Institute*

There have been extensive research and development of UWB systems and subsystems in the former Soviet Union and present Russian Federation. Most of the initial work was aimed to improve power systems (1950s) and to study the difference between conventional continuous waves description and ultra short pulse methods. At the end of the 1990s, the interest on UWB systems accelerated in Russia and since 1998 Russian UWB Group has been involved in the design of medium-range UWB radars and UWB communication and data transmission systems. Some of the most significant recent research and development projects include (from [19]):

i. Development of UWB radar for a system of remote non-contact and identification patient's psychological condition.
ii. Refinement of requirements to the library of basic functional blocks for transmitter-receiver devices operating in cm-range. " (Code "Millimetr-VT-MAI").
iii. Ultra-wide band meter of the level of liquid in a reservoir.
iv. Since 2007, under the contract with Rostov-na-Donu Scientific Institute for Radio Communication, the Center is performing the design work "Researches of possibilities for designing efficient systems for reception and radiation of ultra wide band signal " (code "Kafel'-I").Ultra wideband antenna prototypes are being developed and manufactured.
v. In 2006, the Group performed the development of "Ultra wide band medical radar for detection and monitoring of patient's breath beats".
vi. In 2005, the Group designed the project "Ultra wide band radar for detecting people hidden behind nontransparent obstacles in natural disasters and other emergency situations".
vii. In 2005, the Group performed R&D project "Investigation of possibilities for development of a transmitter-receiver system operating with UWB probing signals"
viii. In 2005, the Group completed the first stage of works on designing "Radar measurer of pulse wave velocity and variability of cardiac rhythm"

Papers published by the Russian UWB Group (RUG) suggest that great effort is given to the understanding of short pulse duration signals as opposed to the long duration narrowband signals [79],[80] (chapter 1). One particular work at the RUG focuses in the theoretical aspect of UWB radars for calculating the antenna design and predicting its performance [82]. It is clear that recent studies and publications do not present a comprehensive theory for calculating parameters such as precision range and direction measuring systems. The work at RUG led by Igor Immoreev[13] looks at this issue; his team is currently analyzing the radiation process occurring in linear UWB antennas and its physical interpretation. They are trying to explain how UWB signal will produce effects not encountered in conventional low-resolution radar [80], [81] (chapter 2). The study of these differences will help them to understand when the traditional theory of radar-tracking detection can and cannot be used for designing UWB radar.

c) Asia - Pacific

- *China – Research*

UWB research and development in China have been mainly carried out at the most important universities and government controlled institutions as those mentioned in Section II.C. We will look at some of the areas currently being researched and also provide an overview of the work in the area of UWB radar in China. At Southeast University (SEU), researchers are focusing particularly in short pulse and modulation schemes for UWB [23]. One typical signal, a monocycle pulse, such as the Gaussian or Raised Cosine pulse, has large frequency components at the lower end of the spectrum. One benefits of this property is its penetration ability. However, additional work, such as notching or pulse redesign, is usually required, especially to meet FCC's UWB mask requirements. Researchers at SEU are addressing these issues. Another area being explored is in high-speed data rate, particularly baseband pulse UWB schemes. Baseband pulse UWB methods find difficulties when applied to high speed data transmission. One of the most difficult problems is the uncertainty of the received pulse shape. One current existent scheme, the Transmitted Reference (TR) method [25], addresses this problem. The idea of this method is to generate pulses in pair with each pair made of two identical pulses. These pulses carry information in a "differential" way. However, the minimal interval between the two pulses (each pulse pair), which accumulates major path delays, also limits the highest information rate of the system. This is also being investigated at SEU.

It is well understood that UWB can be implemented in the more traditional way with carrier modulation. In carrier modulation, an UWB baseband signal modulates a carrier before transmission. Bandwidth of the baseband signal must meet the definition of an UWB signal. The idea is to utilize spectrum resources in a more flexible and efficient way. Some of the mature technologies in this area include Orthogonal Frequency Division Multiplexing (OFDM) and Direct Sequence Spread Spectrum (DSSS). Unfortunately none of these schemes was accepted to make itself a UWB standard. Although the above schemes achieve certain success in their development, SEU researchers are looking at ways to obtaining more efficient and optimal performance. The claim is that these current schemes are based on traditional "narrowband" analysis and do not exploit UWB properties. For example, the baseband signal is still treated as the complex envelope of the pass-band signal, and analyzed through the I and Q components separately. The high relative bandwidth of the UWB may lead to sub-optimal performance. SEU has been experimenting on a Dual Carrier-OFDM (DC_OFDM) scheme. In this method, DC-OFDM uses a narrower band, e.g. 264 MHZ or smaller, to enable more flexible use of the spectrum. A narrower band is a more viable way to achieve cognitive[14] UWB at the next phase of UWB development. Cognitive UWB has the ability to find and utilize free spectrum adaptively.

Since the 1980s, a large number of Chinese researchers and scientists have been involved in UWB radar technology. Before the middle 1990s, UWB radar research was concentrated on time-domain or impulse UWB radar with special emphasis on Impulse Ground Penetrating Radar (IGPR) [28]. Since then, and with exception on

[13] Igor Ya. Immoreev was born in 1930. Graduated from the Leningrad Higher Naval College in 1954. Doctor of Science, a professor, a head of «Analog and digital radioelectronic systems» chamber of the Moscow aviation institute and The Scientific-and-Research Center of Ultra-Wideband technologies of the Moscow aviation institute (SRC UWB MAI). Honoured worker of sciences of Russian Federation. Laureate of The State Prize of USSR, full member of International Academy of informatization and of Academy Engineering sciences of Russian Federation. Senior member of IEEE. The author of more than 100 science works in the field of radiolocation, applied points of electrodynamics and informatics (from http://uwbgroup.ru/eng/contacts/members.html).

[14] The term Cognitive Radio was first coined by Mitola [26] in 1999 and it is a great topic of current research interests. Cognitive Radio is described as a transceiver capable of sensing and learning the characteristics of an existing wireless channel, evolving its operation to accommodate the perceived wireless channel, and evaluating what happens to be appropriate [27].

the impulse GPR technique, UWB research has focused on linearly-chirped pulse Synthetic Aperture Radar (SAR) methods. UWB radar research in China can be classified in six areas [28]:

i. Model and Numerical Simulation.
ii. UWB antenna and impulse generation techniques.
iii. GPR system development.
iv. Signal processing for GPR system.
v. Airborne UWB-SAR technique.
vi. GPR applications.

The two-dimensional GPR model was first studied by the end of 1980s using Finite-Difference Time-Domain (FDTD) methods. Inverse techniques for GPR were also studied. For subsurface detection, target discrimination is the main goal. Unfortunately, GPR techniques only provide answer as to whether a target exists or not. More sophisticated methods to discriminate targets have been the most recent focus for GPR applications. Researchers at the China Research Institute have been carrying out research on target discrimination using FDTD methods. For GPR signal processing techniques, extensive methods and algorithms have been studied by both electrical and geophysical engineers. Since the 1990s, Chinese publications in GPR signal processing and applications have grown substantially with many proposed methods in the area of filters and wavelet transforms, different migration methods, instantaneous methods, and so on [28] - [31]. Since 2003, through-wall imaging UWB radar techniques have also been studied at the China Research Institute and the University of Electronic Science and Technology of China. One particular technique being explored is Time Reversal Mirror (TRM) imaging with UWB technology [84]. Time Reversal Mirror has been widely used in the area of acoustics and electromagnetics and first developed by Mathias Fink [85]-[88]. In TRM, radiation produced by an emitter (the source) propagates through a complex media (for example a reciprocal media) and then collected (time domain fields) by an array of receivers. The received signal is then time-reversed and re-transmitted through the same media. Based on the principle of reciprocity[15], it is assumed that all the energy arrives at the original source in unison allowing the recreation of the original excitation. As the process is repeated, the expectation is that the waves become more and more focused in the target. As a result, better resolution is achieved. Preliminary results based on numerical simulations suggest that higher image quality is obtained (i.e. better than back projection methods), reduction of the resolution and SNR [84]. Time Reverse Imaging in the content of UWB technology constitutes an attractive technique for further research, work that is actually being undertaken at the University of Electronic Science and Technology of China. Other areas of applications include wireless communication (for example indoor communication), medicine and geophysics [89],[90].

❖ *Japan – Research*

One leading institution in the research, development, standardization and regulation activities in telecommunication in Japan is the National Institute of Information and Communications Technology (NICT). NICT was established to carry out research and development in the field of information and communications technology, which supports the upcoming “ubiquitous network society in an integrated manner from basis to application and also provides comprehensive assistance to the public and private organizations working in this field” [32]. NICT started a project on UWB technologies (Consortium on UWB) beginning in 2002, organized a UWB consortium in cooperation with more than 20 companies and 7 universities in Japan [L72]. NICST promotes R&D of UWB commercial systems and technology and transfers the technology to industry by cooperation with both industry and academia. Since then, extensive research has been conducted, including the following:

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[15] The Free Online Encyclopedia [L70] refers to the principle of reciprocity as “In the scientific sense, a theory that expresses various reciprocal relations for the behavior of some physical systems. Reciprocity applies to a physical system whose input and output can be interchanged without altering the response of the system to a given excitation. Optical, acoustical, electrical, and mechanical devices that operate equally well in either direction are reciprocal systems, whereas unidirectional devices violate reciprocity. The theory of reciprocity facilitates the evaluation of the performance of a physical system.” In terms of the wave equation, reciprocity infers that if a solution of the wave equation is known, then the time reversal of that solution is also a solution of the wave equation.

i. Key technology development such as MMIC (Monolithic Integrated Circuit) chips, antennas and other devices.
ii. Measurement and channel modeling for UWB signal propagation.
iii. Standardization in international activities of IEEE 802.15, ITU-R TG1/8 as well as in a national regulatory committee of Ministry of Internal Affair and Communications (MIC).

Frequency bands in the range from microwave band (3–5 GHz) to quasi-millimeter wave band (24–29 GHz) are being studied. Various prototype UWB systems including multi-functional terminals have been developed. One particular applications of UWB is in Wireless Personal Area Network (WPAN) with main focus in high-speed communication in short ranges and low-speed communications and high precision ranging. The main goal is to define common specifications for devices designed for the same purpose and to guarantee interconnectivity between devices. NICT has also developed a UWB Sensor Network Test Bed for the design, transmission and reception of arbitrary UWB signals. The UWB Test system is designed to measure the propagation characteristics, and to assess the interference performance of UWB wireless systems in practical use environments, such as office and homes.

Problems associated with UWB (especially for commercial application) which are being analyzed at NICT are [L72] :

i. Design and Mass-Production of pulse generators, RF devices and antennas.
ii. Detection of accurate pulse waveform in receiver inter-symbol interference in the presence of multipath.
iii. Multi-user interference or intra-system interference.
iv. Inter-symbol interference with co-existing overlaid systems.
v. Spectral allocation for UWB system to avoid collision or interference with conventional systems.

In dealing with cases (4) and (5) above, a new method has been developed, called Soft-Spectrum UWB. Soft-Spectrum aims to design proper pulse waveform to avoid interference to coexisting radio systems in the same band and to match its spectra with required spectral mask, even if regional spectral mask is different and changed [34].

The Japanese UWB Consortium, from which NICT has a lead role, is divided in five Working Groups [33], [L72]:

i. Working Group on UWB System Design and directed by Dr. Ryuji Kohno who is also the director of NICT [L32], [L71] .
ii. Working Group on UWB System Implementation: directed by Dr. Toshiaki Matsui.
iii. Working Group on UWB on Channel Propagation: directed by Dr. Takehiko Kobayashi.
iv. Working Group on UWB on System Measurement: directed by Dr. Jun-ichi Takada.
v. Working Group on UWB on International Collaboration: directed by Dr. Tetsuya Yasui.

The Consortium is formed by 83 researchers from 22 different organizations. Some of the companies include CASIO Computer Co., Fujitsu Limited, Furukawa Electric Co., Hitachi Communications Technologies, NEC Corporation, Samsung Electronics and NTT Advanced Technology Corporation [33]. Specific areas currently being researched (in addition to those mentioned above) include:

i. Ultra high speed transmission technologies, over 100 Mbps. Key issues in this area include pulse shaping, modulation and multiple access schemes as well as protocols.
ii. Ultra high accuracy ranging and positioning technologies.
iii. Implementation of low-cost chipsets and SoC (System-on- a- chip) with low power consumption for portable UWB systems. This is one of the most important developments currently being investigated.

2) Industry Research Centers

In this section, we discuss some of the most relevant work currently being developed at companies and research centers in the United States and other countries. We concentrate on those that have a more established history on UWB technology.

a) USA

❖ *Multispectral Solutions, Inc.*[16]*, Germantown, MD USA*

Under the leadership of Robert J. Fontana, Multispectral Solutions (MSSI) has long been involved in UWB technology with application in both military and commercial applications. Most of UWB technology at MSSI has been in the application of short-pulse UWB systems. These systems span UWB technology in communications, radar sensing, precision localization and RFID. MSSI has developed solutions in each of these areas.

i. Communication Systems: MSSI has developed three recent UWB transceivers (DRACO, ORION and AWICS) capable of accommodating multiple simultaneous users with each design having its own unique application and configured as a network radio. DRACO, is a mobile and hoc radio that utilizes a combination of frequency-division multiplex (FDM) and time-division multiple access (TDMA). ORION, on the other hand, has a fixed TDMA architecture and is configured to operate as a master/slave to coordinate transmission among multiple units. It was designed for squad-level-type communications, where all the transceivers are in constant communication with a centralized unit, the master unit. AWICS is designed to address the problem associated with multipath environments such as those found inside helicopters and aircraft. Packet and data rate take into account problems associated with confined environment, i.e. spread spectrum and multipath degradation of the signal [17].

ii. HFUWB is another transceiver developed by MSSI and is a predecessor of ORION. HFUWB operates in the VHF tactical vehicular broadband (used by the military). HFUWB is a high-power UWB transceiver operating in the 30-50 MHz portion (50% fractional bandwidth) designed for extended-range operation (a long range UWB system for over-the-water and non line-of-sight) with a range of 60 nautical miles over water. HFUWB is capable of supporting both encrypted voice/data and video transmission with a throughput of 850 kbps with an average power of 6 Watts and a peak power of 120 Watts [83].

iii. Short-pulse Radar System: certified by the FCC for commercial use under the new Part 15 Subpart F (UWB) rules and originally designed for the U.S. Navy, MSSI designed short-pulse radar for unmanned aerial vehicles (UAV) and applied to collision and obstacle avoidance, radar altimetry, through-wall sensing and others [17].

iv. Short-pulse Positioning and RFID Applications: MSSI has fielded several UWB precision localization systems which include a soldier tracking system designed to track personnel and vehicles without the use of GPS over a few square kilometers area. First tested in 1997, modified as a smaller version in 1998 and further improved in 2002, the system is a high precision asset location system (PALS). This system designed more strictly for military purposes, has immediate commercial application since it is more a wireless system solution than a defensive or offensive device. The PAL system has the promise of UWB communications and ranging applications because short pulses can give more accurate results even in an extreme multipath environment.

More recently, Multispectral Solutions has been engaged in systems that can provide RFID tagging, and precise localizations, particularly for applications to homeland security, i.e. personnel ID, container manifest and tracking, intrusion detection, etc. Another area that MSSI has been researching, and has published important information is in low-data-rate applications, especially for commercial use. MSSI is exploring certain properties of pulse power measurements using narrowband equipment, which could have unique characteristics for certain sensor applications. One of the observation is that UWB waveforms have very different properties than high data rate signals when measured using modern spectral analysis equipment. MSSI is investigating how measurement disparity affects the achievable performance of a compliant UWB system [18].

b) Europe

❖ *Philips Research*

Philips Research [L54] is supporting the development of a range of products offering very high data transmission rates to address the needs of wireless personal-area networks (WPANs) and the creation of a Media Access Control protocol. With a range of around 3 meters for higher data rates and longer distances for lower rates, researchers at

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[16] Zebra Technologies acquires Multispectral Solutions, Inc. – April 2008.

Philips expect to develop and stimulate a host of applications in the PC and consumer electronics industries. Some of the applications envisioned are to enable ultra-high-speed wireless connectivity between a DVD player and a flat-panel display, a laptop and an LCD projector, or an MP3 music source and a player. Improvements in speed and performance of in-home radio links are also expected to come from Philips Research's development of MIMO (Multiple Input Multiple Output) technology, which focuses on the development of multi-antenna systems both from advanced signal coding and radio front-end perspectives.

Philips Research is also actively developing technologies for flexible and robust A/V streaming in wireless. The idea is to deliver superior video quality and simultaneous multimedia streams over a wireless channel. These technologies would operate on top of the physical and MAC (Medium Access Control) layers of say an ultra-wideband card or IEEE 802.11 card. The goal is to maintain a robust wireless A/V streaming even under conditions of varying channel characteristics to ensure optimum reception of audio and video at all times.

❖ *Nokia Research Center (NRC)*

Following the FCC regulatory decision on UWB in 2002, Nokia Research Center [L55] began research in UWB. In the fall of 2003, Nokia joined the Multiband OFDM alliance to support Multiband OFDM UWB technology. In March 2005, Nokia became member of the WiMedia Alliance, with very strong active participation. Research at NRC has been focused on the development of the WiMedia based High Rate Wireless Personal Area Network with emphasis on the following:

- Pursuit of an UWB standard, spectrum regulation, transceiver architecture design.
- Demonstrate capabilities of UWB Radio targeting future applications.
- Enable UWB technology for short range application networks.
- Build and generate its own intellectual property portfolio.

The UWB research effort at NRC currently has the following ongoing projects:

- Medium Access Control (MAC): efforts have been centered in low power consumption modes, i.e. adaptive beaconing periods and hibernation for MAC development in WiMedia. They are currently working on IP and BT (Bluetooth Protocol) protocols over WiMedia UWB development and association model selection. Additional work concentrates on developing simulation models to be able to do performance evaluations and to study potential enhancements in UWB systems.
- Physical Layer and Regulatory issues (PHY): NRC is concerned with UWB transmitter interference to other systems located either in-band or out-of-band on UWB operating frequencies. To study these negative effects, NRC has conducted victim receiver measurements for WCDMA and EDGE systems; NRC has been heavily involved in European regulatory process especially focusing on the impact analysis to the victim systems above 6 GHz. NRC has also carried out advanced coding and high data rate (up to 1 Gbps) research for WiMedia UWB [21].
- Wireless Remote Display over Ultra Wideband: In collaboration with Wiquest, Inc, NRC has been able to transfer the display information signal of a multimedia terminal over UWB radio to a large external display, e.g. TV or projector.
- Dual band group RFIC for global spectrum regulations: This project focuses in the design and implementation of a Dual band group WiMedia UWB radio on full CMOS RFIC. Dual band group means that Band Groups 1 and 3 (3168-4752 MHz, 6336-7920 MHz) are both possible using the same hardware.
- Fast Data Download: NRC has demonstrated file transfer capabilities using UWB technology between mobile terminals using Multi-Media Card (MMC) standard interface and Bluetooth protocol [24].

c) Asia - Pacific

D. Industry and Public Organizations

There are numerous public forums and industry organizations dedicated to the advancement of UWB technology. In here, we concentrate on those that have shown significant work and continue to foster the development of the technology.

1) Wireless World Research Forum (WWRF)

The Wireless World Research Forum is a global organization founded in August 2001 whose main objective is to formulate strategies and visions in the field of wireless technology. It also generates, identifies and promotes research and technical trends in wireless system technologies among industry and academia. The Forum is divided into eight different groups exploring areas from Human Perspective concepts to Spectrum Issues. Working Group 5 addresses technology related to Short Range Radio Communication Systems and is more closely looking at trends and future applications based on UWB.

2) Ultra Wideband Forum (UWF)

3) WiMedia

WiMedia promotes and enables the rapid adoption and standardization of UWB technology worldwide. It also provides open forum for multiple industry segments to set requirements, specifications and interoperability. WiMedia concentrates efforts in providing commercial and market directions to its members and the wireless community by producing detailed reports on the technology and promoting presentations and seminars and publications of papers. Reports include regulatory changes, certifications, worldwide market position of UWB and any decision vital to the technology.

4) Wireless Alliance for Testing and Experiments and Research (WALTER)

The formation of this organ, the project WALTER (Wireless Alliance for Testing Experiment and Research) was most recently formed. WALTER started in 2008 and is funded through December 2009 with over 3 millions of euro in support. WALTER was implemented under the European Union 7th Framework Programme [L61], [L62] and includes eight partners from Europe, Israel and China (see Table 3 for a list of participant companies). WALTER has been framed to investigate some of the issues with UWB technology with regard to efficient spectrum management and interoperability of technologies. This project is aimed to develop the technology needed for measurement, calibrations and testing of radio UWB signals. According to the European Union 7th Framework Programme website [L62]

> The European Telecommunications Standards Institute (ETSI) is producing harmonised standards to foster UWB adoption in Europe but Europe is still late compared to USA and others. If not corrected, such a situation could hinder the European innovation potential to develop new applications and services based on this extremely high capacity networks. To pursue the needed European standardisation and regulation efforts, while reinforcing the European leadership in the field of wireless networks, a new range of UWB testbed has to be developed.
>
> The WALTER project will address this need and overcoming the associated technological issues of measuring ultra-high frequency signals; will develop a pan-European interconnected testbed. This testbed will make use of the strong European expertise in conformance and interoperability testing. Based on a deep needs analysis and specifications definition, it will be flexible enough to address both from short-term needs (industry and regulators) to long-term needs (research communities), while allowing testing of mitigation techniques.

Key objectives also include [11]:

- Identify the main regulatory and standardization for the adoption of UWB in Europe and the world.
- Identify the main challenges in the UWB testing and measurements.
- Discuss the future developments like UWB at 60 GHz and innovative interference and mitigation techniques including Detect and Avoid (DAA).

Table 3. Wireless Alliance for Testing Experiment and Research (WALTER) – Consortium.

Organization Name		Country	Reference Link
INNO AG (coordinator)	Inno	Germany	[L63]
COPSEY TELECOMMUNICATIONS LIMITED	CTL	UK	[L64]
INSTITUT EUROPEEN DES NORMES DE TELECOMMUNICATION	ETSI	France	[L25]
STMICROELECTRONICS N.V., AMSTERDAM	STM	China	[L65]
WISAIR LTD	Wisair	Israel	[L66]
CENTRO DE TECNOLOGIA DE LAS COMUNICACIONES, S.A. (AT4 Wireless)	CTCSA	Spain	[L67]
JOINT RESEARCH CENTER - EUROPEAN COMMISSION	JRC	Belgium	[L68]
TELECOMMUNICATION METROLOGY CENTER OF MII	TMC	China	[L37] [L69]

III. TECHNICAL STANDARDS AND OPERATING RESTRICTIONS FOR UWB DEVICES

One common concern about UWB technology and its applications expressed by regulatory bodies around the world has been the possibility of interference with existing radio services. However, analysis of various technical studies submitted by multiple organizations and government agencies indicate that UWB devices can be permitted to operate on an unlicensed basis without causing harmful interference. At least this is the position of the FCC in his last two rulings as discussed in Section II.A.1) above and in [1], [15]. Other regulatory bodies in Europe and Asia have used the FCC's ruling as break ground model to authorize the deployment of UWB devices. The FCC has published regulatory and operational requirements to ensure that UWB devices do not cause harmful interference and to logically address the technical characteristics of the different UWB applications. In the following sections we discuss (A) the regulatory classification, (B) operational requirements and frequency bands and (C) issues on co-existence and interferences as given in [1] and [15]. We will also present an overview of similar restrictions and technical characteristics as regulated in other regions of the world.

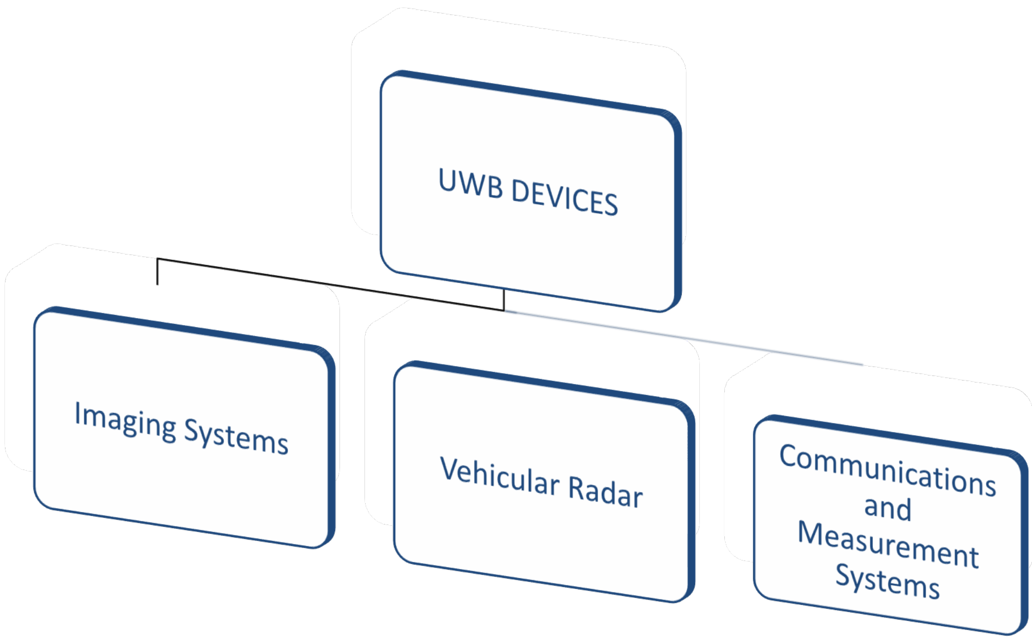


Figure 22. Regulatory classification of UWB devices as determined by the FCC.

A. *Regulatory Classification*

For regulatory purposes, the FCC has categorized three types of UWB devices based on their potential to cause interference. Furthermore, the FCC believes that this is the logical way to address the technical characteristics of the different UWB applications. These three types of UWB devices as shown Figure 22 are:

1) Imaging Systems.
2) Vehicular Radar Systems.
3) Communications and Measurements Systems.

1) Imaging Systems

Based on the FCC classification for UWB devices, we can define Imaging Systems for UWB as those systems capable of generating energy which is largely absorbed by the material against which they are placed. For example, a ground penetrating radar (GPR) system operates when is in close contact with the ground for the purpose of detecting buried images. Imaging systems can also be used to detect objects within or on the other side of walls. Therefore, the UWB signal can penetrate the ground or a wall to sense what is inside or behind it. It is also capable of measuring distance very precisely. These characteristics allow the detection of objects within a concrete structure, side of bridges, or the features of a mine. The same ideas apply to the human body.

Imaging Systems include: (a) GRPs; (b) wall imaging systems; (c) through-wall imaging systems; (d) surveillance systems; (e) medical systems.

a) Ground Penetrating Radar (GPR) Imaging Systems

Ground Penetrating Radar Imaging systems are those that operate in close proximity or in contact to the ground for the purpose of detecting or obtaining images of buried objects. These devices must be operated with their -10 dB bandwidth below the 960 MHz or in the frequency 3.1 – 10.6 GHz. GPRs energy emission is intentionally directed down into the ground and is not intended to be transmitted in air. GPRs operations are restricted to law enforcement, fire and emergency rescue units, scientific research and to mining and construction companies [1].

b) Wall Imaging Systems

Wall imaging systems are those units designed to detect the locations of objects within a wall structure. These wall structures can be concrete walls, side of bridges or the wall of mine. These devices must be operated with their -10 dB bandwidth below the 960 MHz or in the frequency 3.1 – 10.6 GHz. Emission is directed towards the wall. Wall imaging system operations are restricted to law enforcement, fire and emergency rescue units, scientific research and to mining and construction companies [1].

c) Through-wall Imaging Systems

Through-wall imaging systems are those that detect the location and movement of objects or persons that are located on the other side of structures such as walls or ceilings. These devices must be operated with their -10 dB bandwidth below the 960 MHz or in the frequency 1.99 – 10.6 GHz. Emission is directed towards the wall. Through-wall imaging system operations are restricted to law enforcement, fire and emergency rescue units [1].

d) Surveillance Systems

Surveillance systems are stationary radar systems designed to provide security by delimiting RF boundaries and detecting the movement and location of persons or objects within those boundaries. These devices must be operated with their -10 dB bandwidth in the frequency 1.99 – 10.6 GHz. Emission is directed towards a body. Surveillance system operations are restricted to law enforcement, fire and emergency rescue units, public utilities and to industrial entities [1].

e) Medical Imaging Systems

Medical Imaging Systems are those units that detect the location or movement of object within the human or animal body. These devices must be operated with their -10 dB bandwidth in the frequency 3.1 – 10.6 GHz [1].

A pictorial representation of all imaging systems and their frequency bands of operations is shown in Figure 23.

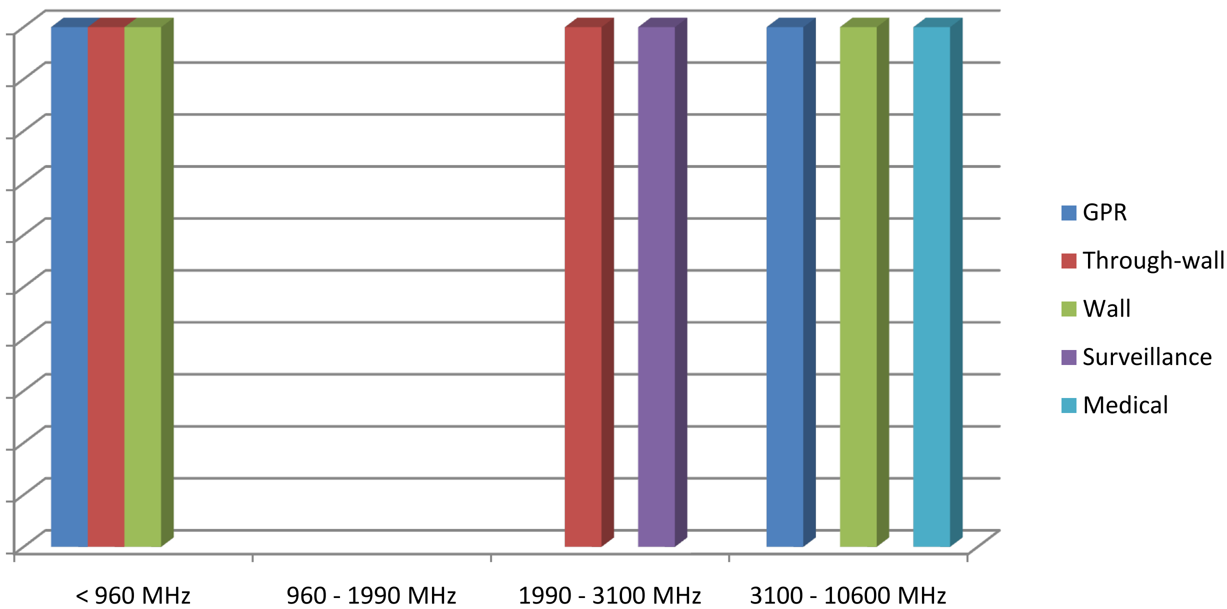


Figure 23. Frequency bands of operations for all imaging systems.

2) Vehicular Radar

Vehicular radar systems are mostly mobile outdoor units use on terrestrial transportation. Vehicular radar systems are able to detect the location and movement of objects near a vehicle providing near collision avoidance capabilities, improving airbag activation and suspension control systems which react better to road condition. Devices in this category are equipped with a directional antenna provided that the center frequency of the emission and the frequency at which the highest radiated energy occurs are greater than 24.075 GHz. These devices must be operated with their -10 dB bandwidth in the frequency 22 – 29 GHz. Additionally, attenuation of the emission below 24 GHz is required above the horizontal plane to protect sensors operating in the frequency range 23.6 – 24.0 GHz [1].

3) Communications and Measurements Systems

Communications and measurement systems include those indoor and hand held[17] devices that can encompass a wide range of applications designed for home and business networking devices. These devices must be operated with their -10 dB bandwidth in the frequency 3.1 – 10.6 GHz. Equipments under this category must be designed to ensure that operation is strictly indoor or when designed as hand held devices their operation is restricted to peer-to-peer mode.

B. Operational Requirements – Frequency Bands

The FCC believes that sufficient protection from harmful interference can be achieved by setting a combination of technical requirement and operational restrictions on imaging systems, vehicular radar and communications systems. In the following sections we discuss their technical characteristics and emission limits as regulated by the FCC. We will present emission masks for every class as set by the FCC. We will also present an overview of similar restrictions and technical characteristics as regulated in other regions of the world. The FCC has designated three classes of imaging systems which are discussed below. We will also present emission masks for every class as set by the FCC.

[17] The term hand held devices in [1] refers to portable devices, such as a lap top computer or a PDA that are hand held during operations and are not part of a fixed infrastructure when operated outdoor.

1) *Imaging Systems*

Similar to the classification presented in Section A above, the FCC has established three classes of imaging systems, each one subjects to technical standards and operational limits. These three classes are: (a) Low-frequency imaging systems; (b) Mid-frequency imaging systems and (3) High-frequency imaging systems.

a) *Low-frequency Imaging Systems*

Low-frequency imaging systems include all systems operating with a -10 dB bandwidth that is contained below 960 MHz. These systems are permitted to operate at the emission limits contained in FCC Part 15 Section 209(a) ([1], [15]). Refer to Appendix B or select document 209 in [L17] for further details. In general, operators in this class of devices must be eligible for licensing under Part 90 of FCC rules. Operators in this class are also required to complete a coordination procedure with the Government. Devices in this class include GPRs and wall imaging systems operated by law enforcement, fire and emergency rescue organizations, by scientific research institutes, by construction, or by mining companies. Through-wall imaging systems operated by law enforcement, fire and emergency rescue organizations are also devices included in this class of imaging systems. More technical and operational requirements are contained in ([1], [L1]) in Appendix D.

b) *Mid-frequency Imaging Systems*

Mid-frequency imaging systems are those that operate with their -10 dB bandwidth between 1.99 – 10.6 GHz. Mid-frequency imaging systems include through-wall and surveillance systems. These systems are permitted to operate at the emission limits contained in FCC Part 15 Section 209(a) ([1], [15]). Refer to Appendix B or select document 15.209 in [L17] for further details. In general, operators in this class of devices must be eligible for licensing under Part 90 of FCC rules. Operators in this class are also required to complete a coordination procedure with the Government. The coordination information shall describe the geographic area in which the device is to be operated. Surveillance systems can operate only at fixed locations. More technical and operational requirements are contained in ([1], [L1]) in section 15.511 in Appendix D.

c) *High-frequency Imaging Systems*

High-frequency imaging systems are those that operate with their -10 dB bandwidth between 3.10 – 10.6 GHz. High-frequency imaging systems include GPRs, wall and medical systems. These systems are permitted to operate at the emission limits contained in FCC Part 15 Section 209(a) ([1], [15]). Refer to Appendix B or select document 209 in [L17] for further details. Similar to low-frequency systems, operators in this class are also required to complete a coordination procedure with the Government. More technical and operational requirements are contained in ([1], [L1]) in section 15.513 in Appendix D.

Figure 24 shows the FCC Part 15 classification of UWB systems based on both regulatory and operational requirements.

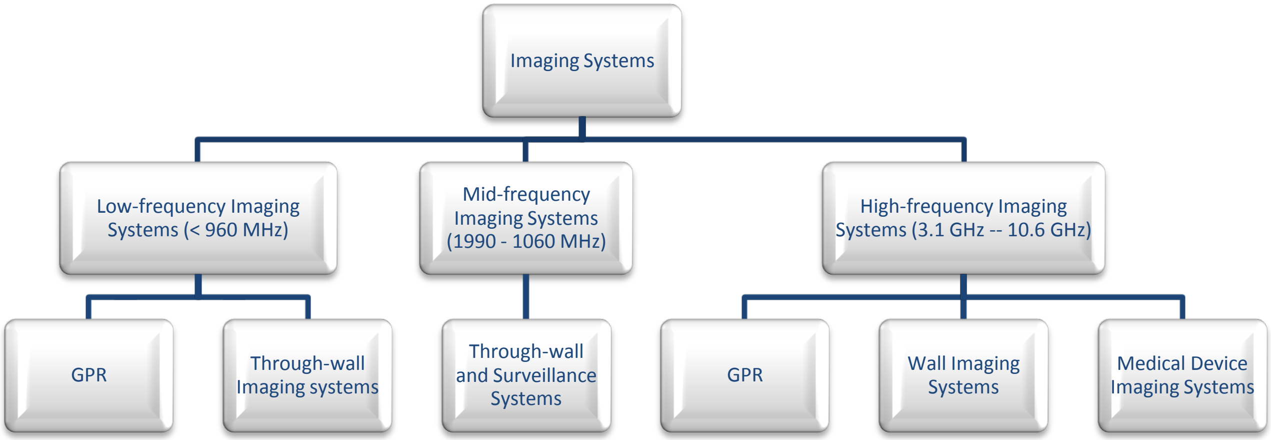


Figure 24. UWB systems based on the FCC Part 15 regulatory classification and operational requirements.

In addition to the emission limits described in 1) above, imaging systems are also required to meet the following out-of-band emission limits:

Table 4. FCC Emission limits (dBm) for UWB Imaging Systems.

UWB Systems	**GPR, Wall and Through-wall Imaging**	**Through-wall Imaging, and Surveillance**	**GPR, Wall Imaging, and Medical Imaging**
Frequency Band	Low-frequency UWB BW below 960 MHz	Mid-frequency UWB BW in 1990 – 10600 MHz	High-frequency UWB BW in 3100 – 10600 MHz
≤ 960 MHz	Radiated emission limits contained in FCC Part 15Section 209: Radiated emission limits; general requirements.		
960 -1610 MHz	-65.3	-53.3	-65.3
1610 – 1990 MHz	-53.3	-51.3	-53.3
1990 – 3100 MHz	-51.3	-41.3	-51.3
3100 – 10600 MHz	-51.3	-41.3	-41.3
Above 10600 MHz	-51.3	-51.3	-51.3

Figure 25 shows the frequency masks and emission limits of UWB imaging systems and their applications.

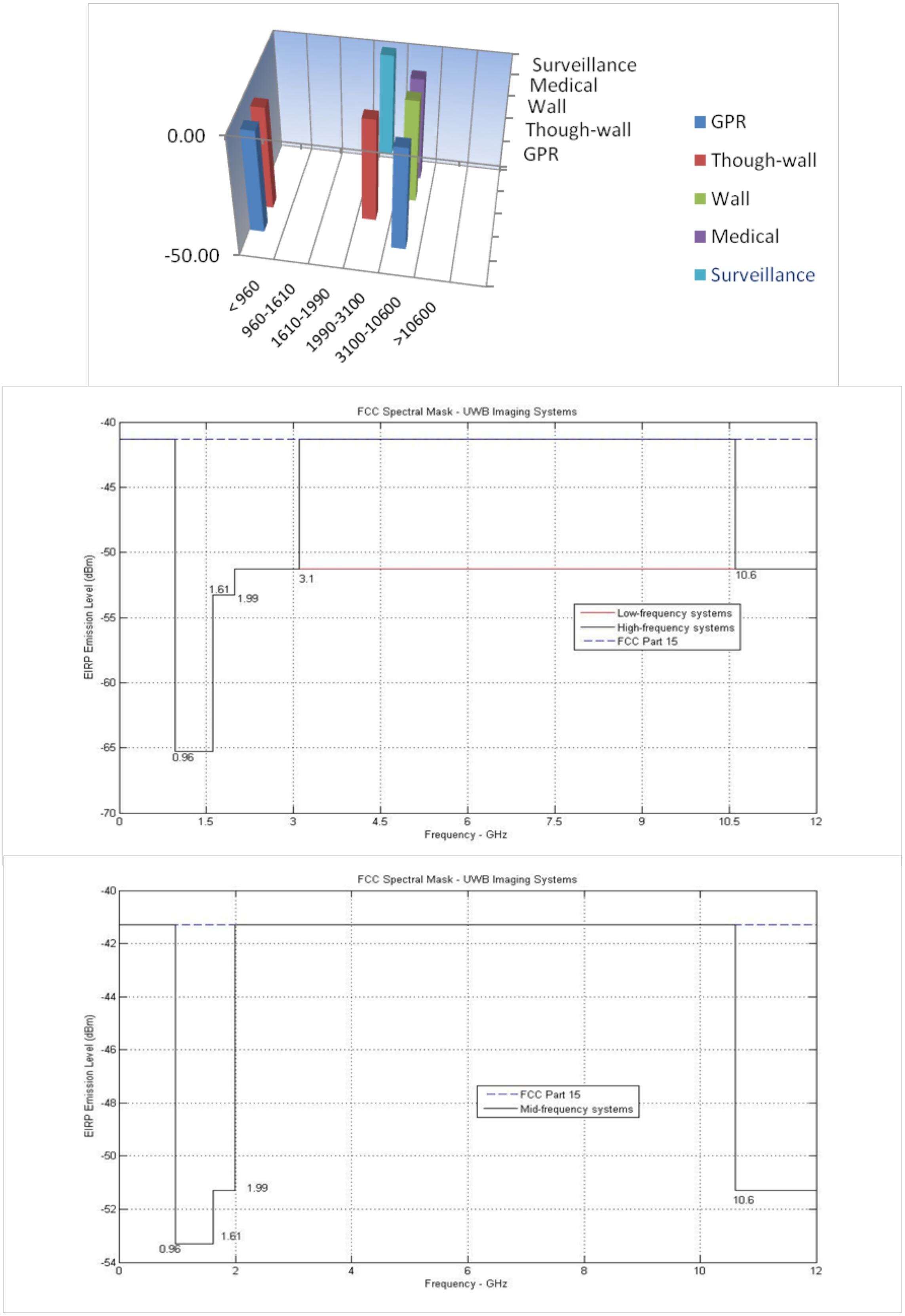


Figure 25. FCC emission level masks for high, mid and low frequency imaging systems and their applications.

2) Vehicular Radar Systems

Vehicular radar systems are mostly mobile outdoor units use on terrestrial transportation. Vehicular radar systems are able to detect the location and movement of objects near a vehicle providing near collision avoidance capabilities, improving airbag activation and suspension control systems which react better to road condition. Devices in this category are equipped with a directional antenna provided that the center frequency of the emission and the frequency at which the highest radiated energy occurs are greater than 24.075 GHz. These devices must be operated with their -10 dB bandwidth in the frequency 22 – 29 GHz. Additionally, attenuation of the emission below 24 GHz is 38 degrees or greater above the horizontal plane to protect sensors operating in the frequency range 23.6 – 24.0 GHz [1]. The amount of attenuation is equal to 25 dB below the limit specified in Table 5. The UWB devices in this class shall operate when the engine of the vehicle is running. Emission below 960 MHz must be at or below at the emission limits contained in FCC Part 15 Section 209(a) ([1], [15]). Emissions above 960 MHz must comply with the following emissions mask:

Table 5. FCC Emission limits (in dBm) for UWB vehicular systems.

Frequency	**EIRP (dBm)**
960 – 1610 MHz	-75.3
1610 – 22000 MHz	-61.3
22000 – 29000 MHz	-41.3
29000 – 31000 MHz	-51.3
Above 31000 MHz	-61.3

More technical and operational requirements are contained in ([1], [L1]) in section 15.515 in Appendix D.

3) Communications and Measurements Systems

a) Indoor UWB Systems

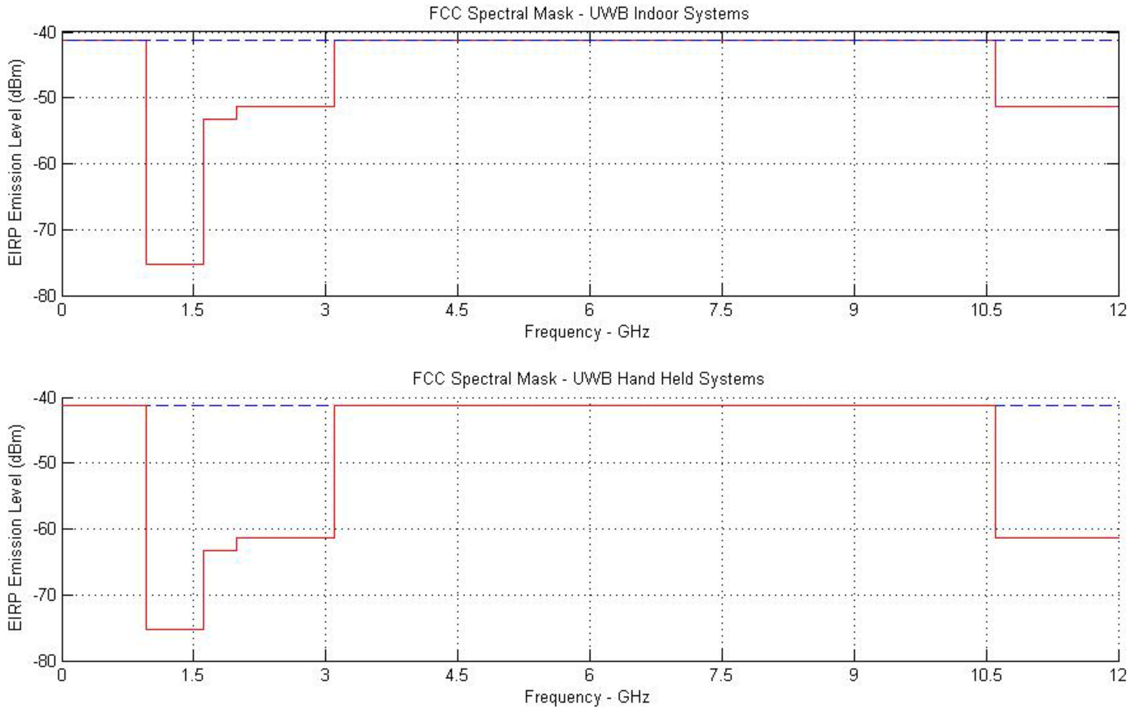
These devices must be operated with their -10 dB bandwidth in the frequency 3.1 – 10.6 GHz. Equipments under this category must be designed to ensure that operation is strictly indoor; therefore, these devices must be capable to fail operation if the transmitter is removed from an indoor location. Emission below 960 MHz must be at or below at the emission limits contained in FCC Part 15 Section 209(a) ([1], [15]). More technical and operational requirements are contained in ([1], [L1]) in section 15.517 in Appendix D.

b) Hand Held UWB Systems

UWB Hand held devices are primarily intended to operate in a peer-to-peer mode without restriction on location. These devices must be operated with their -10 dB bandwidth in the frequency 3.1 – 10.6 GHz. Emission below 960 MHz must be at or below at the emission limits contained in FCC Part 15 Section 209(a) ([1], [15]). More technical and operational requirements are contained in ([1], [L1]) in section 15.519 in Appendix D.

For emission above 960 MHz, both Indoor and Hand held UWB systems are also required to meet emission levels shown in Table 6 and Figure 26 below.

Table 6. FCC Emission limits (in dBm) for UWB indoor and hand held systems.



Frequency	Indoor UWB Systems EIRP (dBm)	Hand Held UWB Systems EIRP (dBm)
960 – 1610 MHz	-75.3	-75.3
1610 – 1990 MHz	-53.3	-63.3
1990 – 3100 MHZ	-51.3	-61.3
3100 - 10600 MHz	-41.3	-41.3
Above 10600 MHz	-51.3	-61.3

Figure 26. FCC masks for UWB indoor and hand held systems.

C. Operational Requirements in Europe and Asia-Pacific

1) Europe

a) Communication Systems

In March of 2006, the ECC approved the use of UWB for Europe in the 6 to 8.5 GHz band ([12], [L39], [52], [L40]). In February 2007, the ECC issued its final Decision report allowing the use of the radio spectrum by equipment using ultra-wideband technology ([13], [L38]). In this report, the FCC stated “The Member States shall, as early as possible and no later than six months following the entry into force of this Decision, allow the use of the radio spectrum on a non-interference and non-protected basis by equipment using ultra-wideband technology provided that such equipment meets the conditions set out in the Annex to this Decision and it is either used indoors or, if it is used outdoors, it is not attached to a fixed installation, a fixed infrastructure, a fixed outdoor antenna, or an automotive or railway vehicle.” For all practical purposes, under the ECC’s Decision, any equipment using ultra wideband technology means “equipment incorporating, as an integral part or as an accessory, technology for short-range radiocommunication, involving the intentional generation and transmission of radio-frequency energy that spreads over a frequency range wider than 50 MHz, which may overlap several frequency bands allocated to radiocommunication services”.

The issue with interference at specific bands is also addressed in [13]. Limited conditions for mitigation techniques were stated with regard to the 3.4 to 4.8 GHz band. One particular mitigating technique is the so-called detect and avoid (DAA) mechanism. The use of DAA allows UWB systems to detect if there is other signal energy on the vicinity at the same time and on the same frequency. When another signal is detected, then the UWB system should decrease its own power level. A maximum mean EIRP of -41.3 dBm/MHz is allowed in the 3.4 – 4.8 GHz band provided that interference detection and avoidance (DAA) techniques are provided and a low duty cycle interference mitigation method is applied. However, in the band 4.2 – 4.8 GHz the maximum mean EIRP of -41.3 dBm/MHz is allowed without any mitigation technique until December 31, 2010. Table 7 shows the maximum EIRP densities in the absence of appropriate mitigation techniques. Figure 27 shows the corresponding emission limits as set by the ECC.

Table 7. ECC radiation mask for UWB devices.

Frequency	**Maximum Mean EIRP[18] (dBm/MHz)**	**Maximum Peak EIRP[19] (dBm/50MHz)**
Below 1600 MHz	-90.0	-50.0
1600 – 3400 MHz	-85.0	-45.0
3400 – 3800 MHz	-85.0	-45.0
3800 – 4200 MHz	-70.0	-30.0
4200 – 4800 MHz	-41.3 (*)	0.0 (*)
	-70.0 (**)	-30.0 (**)
4800 – 6000 MHz	-70.0	-30.0
6000 – 8500 MHz	-41.3	0.0
8500 – 10600 MHz	-65.0	-25.0
Above 10600 MHz	-85.0	-45.0
(*) until 31 December 2010 (**) beyond 31 December 2010		

[18] For the purpose of the ECC's Decision, *mean EIRP density* means "the mean power measured with a 1 MHz resolution bandwidth, a root-mean-square (RMS) detector and an average time of 1 ms or less" [13].

[19] For the purpose of the ECC's Decision, *peak EIRP density* means "the peak level of transmission contained within a 50 MHz bandwidth centered on the frequency at which the highest mean radiated power occurs. If measured in a bandwidth of x MHz, this level is to be scaled down by a factor of 20log(50/x)dB" [13].

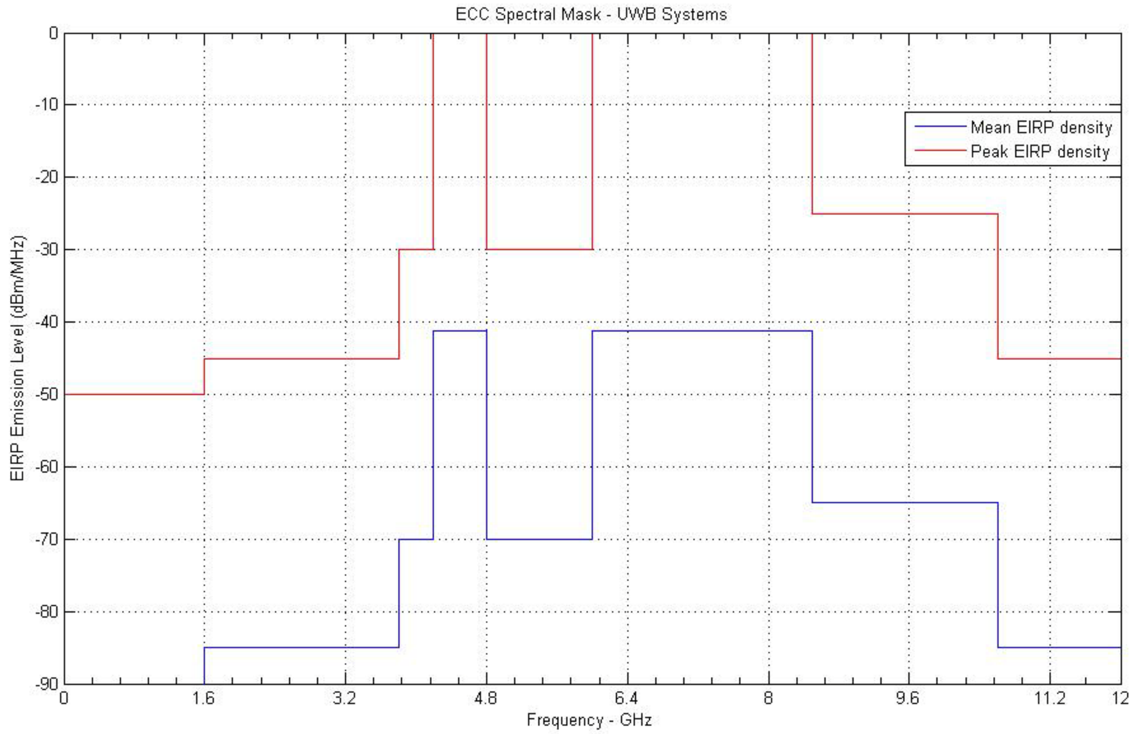


Figure 27. Maximum EIRP density emission levels for UWB devices granted by the ECC.

It is evident from the emission limits shown in Figure 27 that the ECC has established more restricted conditions on UWB systems than the FCC. There is a significant difference of at least 30 dBm/MHz in the frequency band below 3.4 GHz and of 25 dBm/MHz above the 8.5 MHz frequency. This power emission requirement imposes an extra design constraint for all those UWB devices that fall within these frequency bands. Figure 28 shows the emission limit masks as set by both the FCC (low, mid and high frequency) and the ECC.

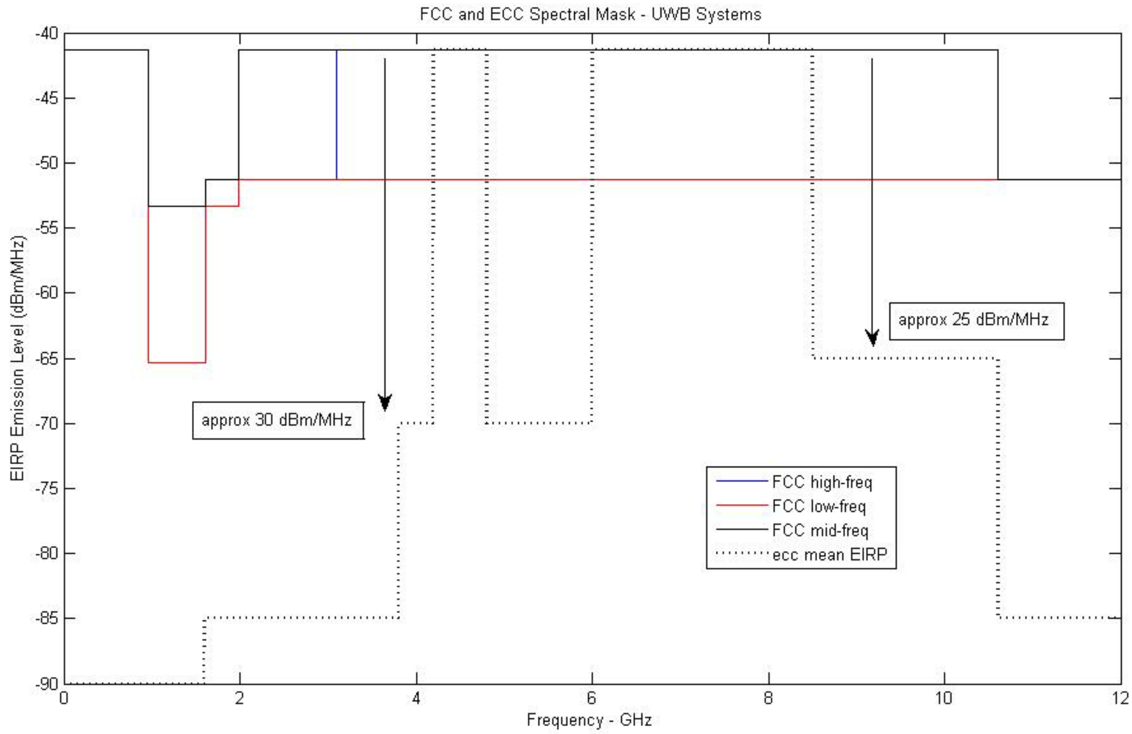


Figure 28. ECC and FCC radiation limits for UWB systems.

b) Radar and Imaging Systems

In December 2006, the ECC released its decision "on the conditions for use of the radio spectrum by Ground- and Wall- Probing Radar (GPR/WPR) imaging systems" in which emission limits and technical specification of UWB imaging systems are addressed ([54],[L42]) . The ECC has classified UWB imaging systems into two classes: (1) Ground probing radar (GPR) and (2) Wall probing radar (WPR) imaging systems. These classifications and their technical and emission limits were based on a series considerations related to UWB imaging systems. Among the most important considerations, the ECC noted:

- That UWB technology has clear benefits for imaging applications.
- That both GPR and WPR imaging systems has been operating in Europe for many years without reported interference to other radio services.
- There exists a need for a harmonized regulatory framework for their operations in Europe.
- That their operations have been limited to a very small number of professionals and therefore their use can be subject to individual licensing requirements.
- That their applications shall be understood as applications for the "purpose of detecting or obtaining the images of objects buried into the ground or contained within a 'wall', or of determining the physical properties within the ground or a 'wall' ."

The ECC then decided and defined:

- Ground probing radar (GPR) imaging system is a field disturbance sensor designed to operate only when in contact with the ground or within one meter of the ground. The main purpose of operation is to detect or obtain images of buried objects or to determine the physical properties within the ground. Energy from the GPR is intentionally directed into the ground. Any energy emitted into the air from the operation of GPRs is referred to as "undesired emission".
- Wall probing radar imaging system is a filed disturbance sensor designed to detect the location of objects contained within a "wall" or to detect the physical properties of objects within the "wall". Identify the main challenges in the UWB testing and measurements.

- That GPR/WPR systems operate on a non-interference, non-protected basis.
- That their use shall be subject to an appropriate licensing procedure.
- That GPR/WPR systems shall be equipped with a deactivation mechanism when normal use is interrupted.

Table 8 shows the maximum emission limits for GPR/WPR imaging systems which are also illustrated in Figure 29.

Table 8. Maximum mean EIRP density for GPR/WPR imaging systems granted by the ECC.

Frequency range	**Maximum Mean EIRP Density (dBm/MHz)**
< 230 MHz	-65
230 – 1000 MHz	-60
1000 – 1600 MHz	-65(*)
1600 – 3400 MHz	-51.3
3400 – 5000 MHz	-41.3
5000 – 6000 MHz	-51.3
>6000 MHz	-65
(*) Additionally, a maximum EIRP density of -75 dBm/MHz applies in the bands 1164-125 MHz and 1559-1610 MHz in case of spectral lines in these bands.	

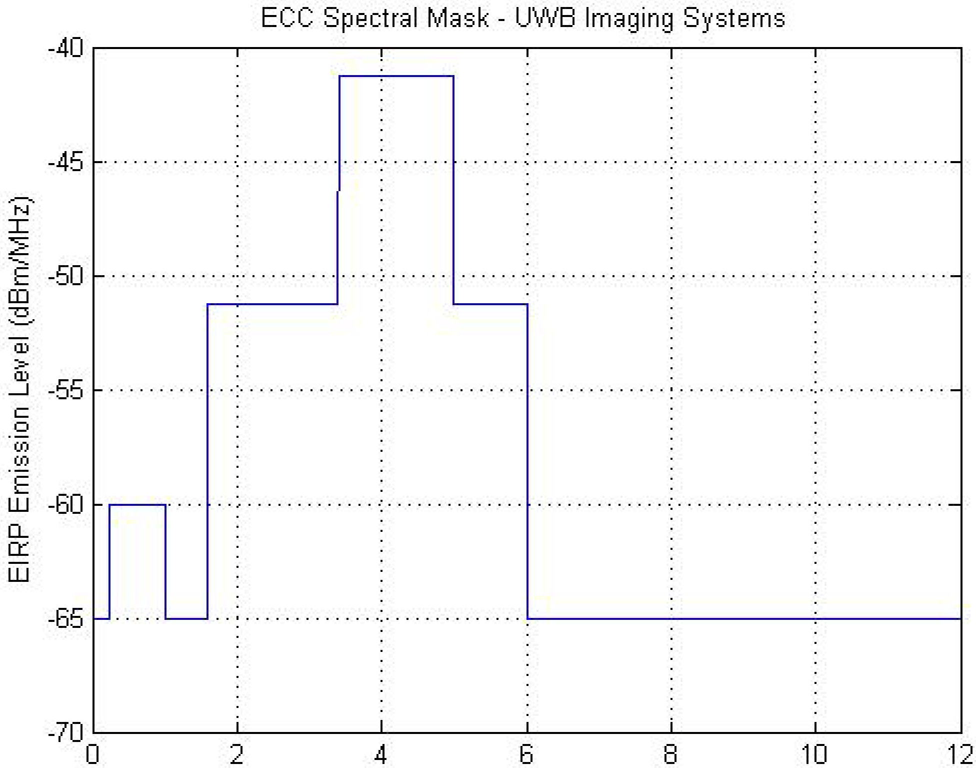


Figure 29. Maximum EIRP density emission levels for UWB imaging systems granted by the ECC.

Again, relevant differences are observed between the FCC's emission limits and the ECC's EIRP limits especially for frequencies in the bands above the 6 GHz and below the 1.6 GHz. These differences vary from about 15 dBm/MHz when compared against the ECC high-frequency imaging systems to about 25 dBm/MHz when compared against the FCC mid and low frequency systems. Figure 30 shows emission mask granted by both the ECC and FCC.

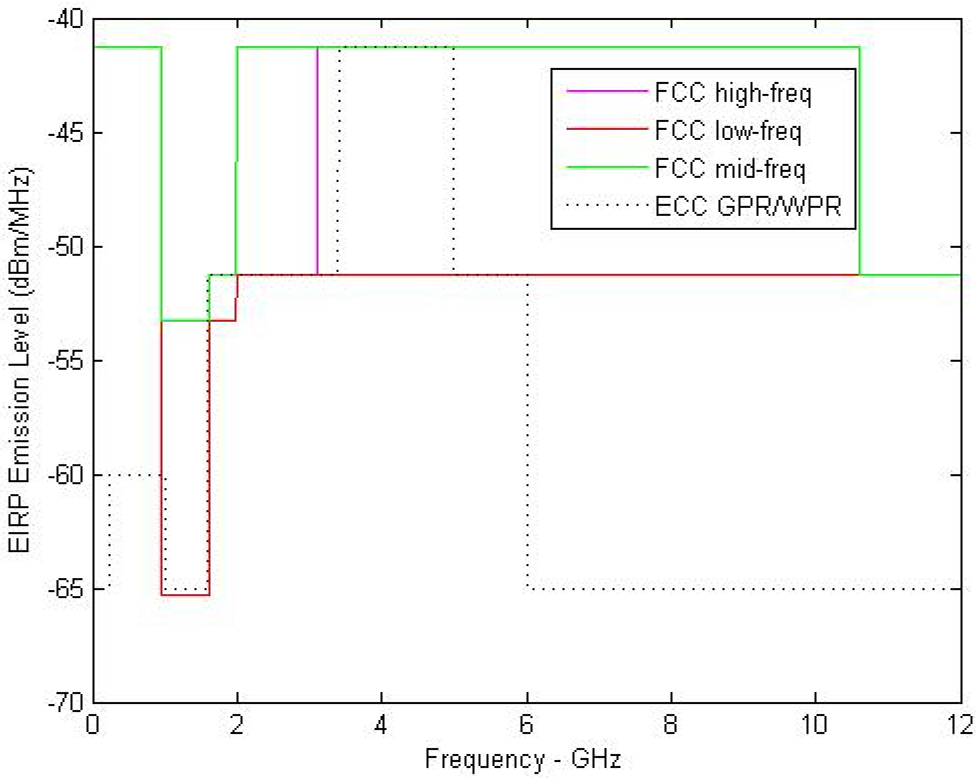


Figure 30. ECC and FCC emission masks for UWB imaging systems.

The ECC has also adopted emission limits for probing radar frequencies with applications to building material analysis. Building material analysis (BMA) devices, as ruled in ([53], [L41]), are defined as “field perturbation sensors that are designed to detect the location of objects within a building structure or to determine the physical properties of a building material.” These devices are exempt from individual licensing and shall operate on a non-interference, non-protected basis. Table 9 depicts the maximum mean and peak EIRP limits for BMA devices [53].

Table 9. ECC radiation mask for BMA devices using UWB technology.

Frequency	Maximum Mean EIRP (dBm/MHz)	Maximum Peak EIRP (dBm/50 MHz)
Below 1730 MHz	-85[1]	-45
1730 – 2200 MHz	-65	-25
2200 – 2500 MHz	-50	-10
2500 – 2690 MHz	-65[2]	-25
2690 – 2700 MHz	-55[3]	-15
2700 – 3400 MHz	-82[2]	-42
3400 – 4800 MHz	-50	-10
4800 – 5000 MHz	-55[3]	-15
5000 – 8000 MHz	-50	-10
8000 – 8500 MHz	-70	-30
Above 8500 MHz	-85	-45

(1) Listen Before Talk (LBT)[20] devices are permitted to operate in this band with a maximum mean limit of -70 dBm/MHz and a maximum peak limit of -30 dBm/50MHz.
(2) LBT devices are permitted to operate in this band with a maximum mean limit of -50 dBm/MHz and a maximum peak limit of -10 dBm/50MHz.
(3) Total Radiated Power spectral density[21] must not exceed -65 dBm/MHz.

2) Japan

The regulatory body in Japan that sets policy on UWB is called the Ministry of International Affairs and Communications (MIAC)[L34]. On limit of emission, it set the limits of UWB systems to be the same as that set by the FCC. In August 2005, the Ministry of International Affairs and Communications adopted the use of UWB communications with unlicensed spectrum with initial allocation between 3.4-4.8 GHz and between 7.25-10.25 GHz for indoor devices. "The allocation requires the implementation of Detection and Avoidance (DAA) for the 3.4-4.8GHz band to ensure co-existence with existent systems and new services such as 4G and no DAA for the higher band (7.25-10.25GHz). The emission limits from 3.4-4.75GHz and from 7.25-10.25GHz is -41.3dBm/MHz, and is the same as what the U.S. Federal Communications Commission (FCC) ruled" [14]. The most significant emission requirements include [22]:

- The band 3.1 – 3.4 GHz is restricted to protect radio access & spectrum (RAS) services operating in the 3.3 GHz frequency.
- Interference mitigation techniques shall be included in UWB devices operating in the 3.4 – 4.2 GHz band. This band is licensed for satellite (downlink) communication operators and requires DAA. This restriction is to be reviewed as more satellite links are replaced by fibers.
- The band 4.2 – 4.8 is reserved (in Japan) for the next generation mobile communication or 4G use and shall require DAA. Without DAA, emission power is limited to -70 dBm/MHz or less. The DAA mitigation restriction is valid until December 2008.

[20] Listen before Talk refer to the feature in which the transmitter senses the air before transmit in order not to interfere with the on-going transmission [35].

[21] Total Radiated Power spectral density values are measured "over a sphere around the measurement scenario with a resolution of at least 15 degree" in Annex 1 of [53].

- The band 6.0 – 7.25 GHz is licensed to earth exploration satellite service (EESS) and TV news gathering use; therefore, its use is restricted.

Table 10 shows the maximum emission limits for UWB radio systems which are also illustrated in Figure 31.

Table 10. Power density emission limits for UWB devices granted by the MIAC (Japan).

Frequency	**Maximum EIRP (dBm/MHz)**
Below 1600 MHz	-90
1600 – 2700 MHz	-85
2700 – 3400 MHz	-70
3400 – 4200 MHz	-70(*)
4200 – 4800 MHz	-41.3
4800 – 7250 MHz	-70
7250 – 10250 MHz	-41.3
10250 – 10600 MHz	-70
10600 – 10700 MHz	-85
10700 – 11700 MHz	-70
11700 – 12750 MHz	-85
Above 12750 MHz	-70
(*) For devices using DAA the maximum EIRP is -41.3 dBm/MHz and shall operate in the band 3.4 – 4.8 GHz.	

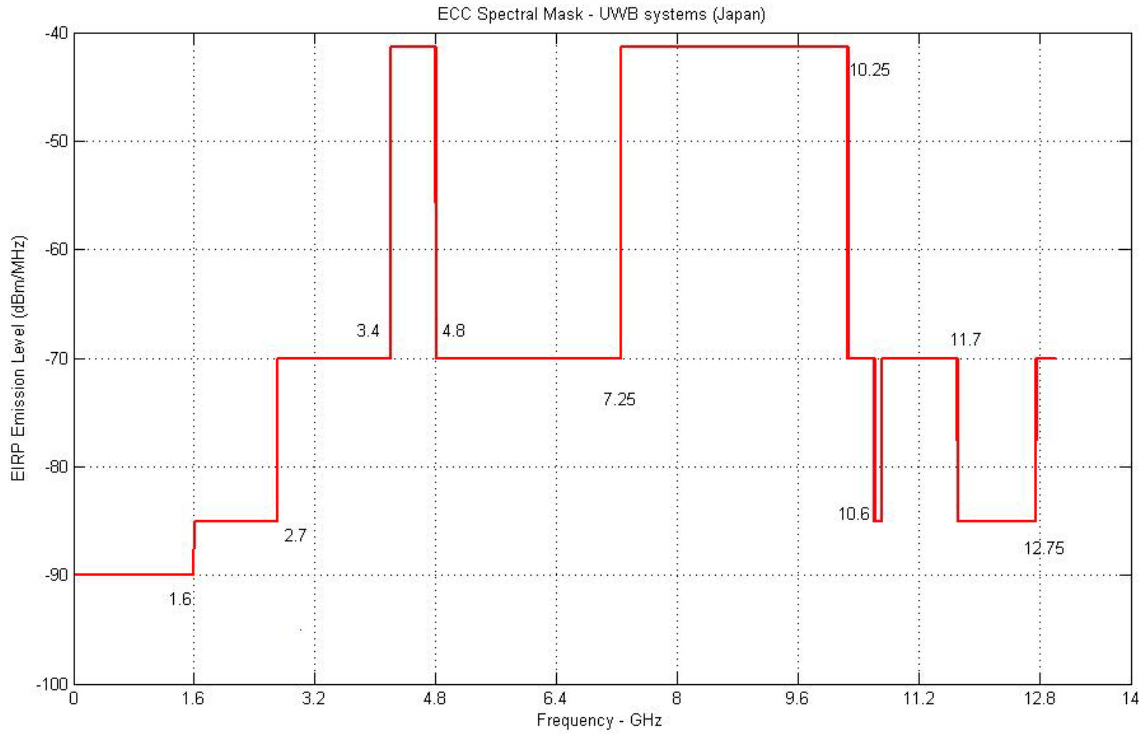


Figure 31. Power density emission limits for UWB systems granted by the MIAC (Japan).

3) Singapore

Singapore is another important country in the Asia region that in February 2003 initiated a UWB program through its regulatory body: the Infocomm Development Authority (IDA) [L35]. In December 2007, the Infocomm Development Authority adopted the use of UWB and issued the Technical Specification document for Ultra Wideband (UWB) Devices ([35], [L36]). This Specification defines the minimum technical requirements for UWB devices. In its definition of UWB systems, the IDA adopted very similar characteristics as those described by the FCC. Basically, the IDA refers to UWB devices as those that have "intentional radiation from the antenna with either a -10 dB bandwidth of at least 500 MHz or a -10 dB fractional bandwidth greater than 0.2" [35].

The IDA has classified UWB technology into three important groups: (a) Consumer and business data communication systems; (b) Vehicular radar systems (c) Ground or wall probing radar imaging systems.

a) Consumer and Business Data Communication Systems

Typical applications include standalone or plug-in radio devices for host systems. This type of devices typically operates in all or any part of the frequency bands between 3.4 – 8.5 GHz.

Table 11. Power spectral density radiation limit mask for UWB devices granted by the IDA (Singapore).

Frequency	**Maximum Mean EIRP (dBm/MHz)**	**Maximum Peak EIRP (dBm/50MHz)**
Below 1600 MHz	-90.0	-50.0
1600 – 2700 MHz	-85.0	-45.0
2700 – 3400 MHz	-70.0	-36.0
3400 – 4200 MHz	-70.0 (3)	-30.0
4200 – 4800 MHz	-41.3 (1)	0.0
	(2)	-30.0
4800 – 6000 MHz	-70.0	-30.0
6000 – 8500 MHz	-41.3	0.0
8500 – 10600 MHz	-65.0	-25.0
Above 10600 MHz	-85.0	-45.0

(1) until 31 December 2010.

(2) to be replaced by a more restrictive one beyond 31 December 2010

(3) UWB devices with mitigation techniques are allowed to operate at the -41.3 dBm/MHz

Limit in this band with peal level in 50 MHz not exceeding 0 dB.

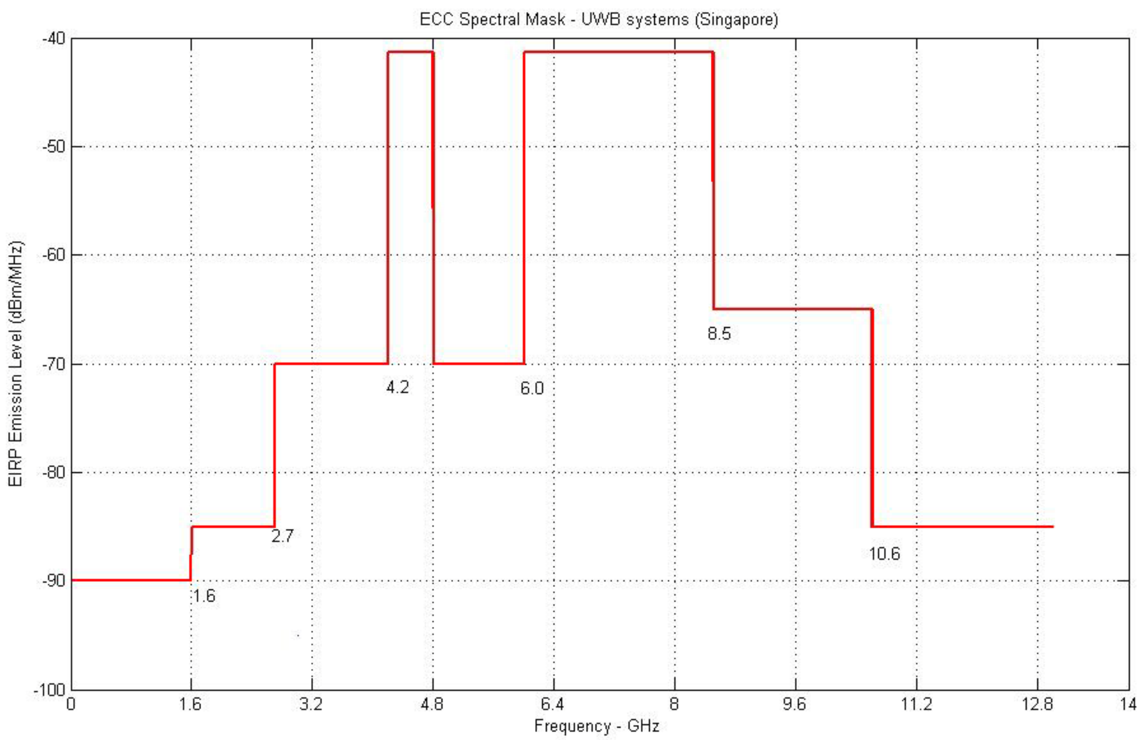


Figure 32. Power density emission limits for UWB consumer and business data communication systems granted by the IDA (Singapore).

b) Vehicular Radar Systems

Vehicular radar systems are automotive short-range systems intended for collision avoidance and traffic safety applications. This type of devices operates in the 24 GHz and/or 79 GHz bands.

Table 12. Power density emission limits for UWB vehicular systems granted by the IDA (Singapore).

Frequency	**Maximum Mean EIRP (dBm/MHz)**	**Maximum Peak EIRP (dBm/50MHz)**
21650 - 26650 MHz (1)	-41.3	0
77000 - 81000 MHz	-3	55
(1) Extension of this band from 21650 to 29500 MHz is acceptable. Emissions within the 23.6 to 24 GHz band that appear 30° or greater above the horizon plane shall be attenuated by at least 25 dB up to year 2010 and 30 dB up to July 2013. In the 24050-24250 MHz band, narrowband emission mode component with a maximum peak EIRP power of 20 dBm and a duty cycle limited to 10% for peak emission higher than -10 dBm is allowed [35].		

c) Ground and Wall Probing Radar Systems

Ground and wall probing radar (GPR/WPR) systems are those used in survey and detection applications. GPR and WPR imaging systems shall be designed to operate while in contact or close proximity to the ground or wall with their emission directed into the ground. This type of devices typically operates in all or any part of the frequency band from 30 MHz to 12.4 GHz. Emission limit mask for GPR and WPR were adopted as those set by the ECC and discussed in Section III.C.1)b) above. Table 8 shows the maximum emission limits for GPR/WPR imaging systems which are also illustrated in Figure 29.

4) China

Another important country in the region, China, has been rather slower in setting regulatory rules on UWB technology. In China, the Ministry of Information and Industry (MII) [L37] is the government body responsible in setting rules and regulation related to the radio frequency spectrum, and to understand the regulatory changes needed to support wireless technologies including UWB. MII is a regulatory body in charge of the “manufacture of electronic and information products, the communications and software industry, as well as the promotion of informatization of the national economy and social services” [L37] . MII issued a public call for comments on their first draft UWB regulation effective thru September 30, 2008. It has proposed uses of UWB transmission in the frequency range band 4.224 – 4.752 and 6.336 – 8.976 GHz. Devices using UWB technology which have UWB transmission in the band 4.224 – 4.752 GHz are restricted for indoor applications only and are required to implement DAA. Devices using UWB technology which has UWB transmission in the band 6.336 – 8.976 GHz can be used indoor and outdoor. In the 4.2 – 4.8 GHz band, the maximum EIRP is restricted to -41.3 dBm/MHz until December 31st, 2010. After that, UWB devices shall adopt the use of mitigating techniques such as DAA.

Table 13 and Figure 33 show the power density emission limit mask for UWB systems [22].

Table 13. Power density emission limits for UWB devices granted by the MII (China).

Frequency	**Maximum EIRP (dBm/MHz)**
Below 1600 MHz	-90
1600 – 3600 MHz	-85
3600 – 6000 MHz	-70
6000 – 9000 MHz	-41.3
9000 – 10600 MHz	-70
Above 10600 MHz	-85

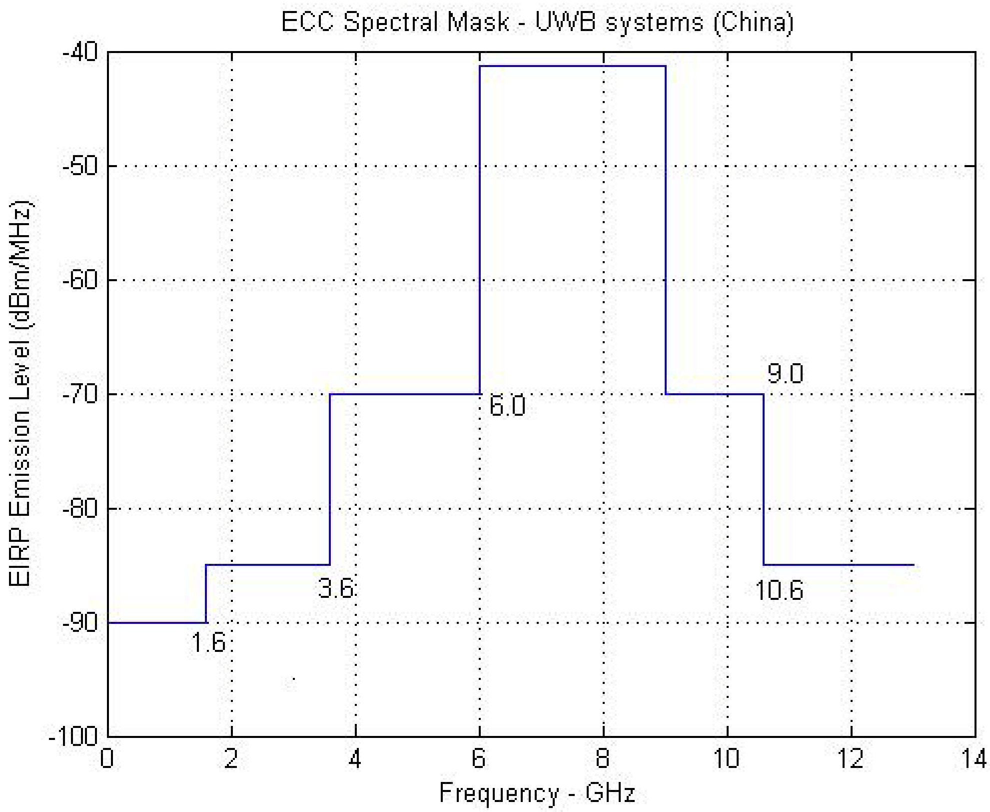


Figure 33. Power density emission limits for UWB systems granted by the MII (China).

D. Issues On Co-existence and Interference

On February 14, 2002, the Federal Communications Commission ruled to permit the marketing and operation of certain types of products incorporating UWB technology. UWB devices operate by employing very narrow or short duration pulses that result in very large transmission bandwidth. Given this “ultra” wideband, the FCC was very cautious in authorizing UWB technology. However, after a lengthy consultation with industry and primarily The National Telecommunications and Information Administration (NTIA) at the US Department of Commerce [L5], the FEC released Revision of Part 15 of the Commission’s Rules Regarding Ultra-Wideband Transmission Systems ([L1]) designed “to ensure that there is a low probability that these devices will cause harmful interference to other users of the radio spectrum.” One very strict limitation states that “operator must accept whatever interference is received and correct whatever interference is caused.” The FEC took into considerations, to a large degree, standards that the NTIA found to be necessary to protect vital federal government telecommunication devices and operations. For this purpose, the NTIA conducted measurements and analysis of potential interference to a variety of federal systems ([42],[L2]). Some of these systems include the Global Positioning System, which we discuss in the following section.

1) UWB and GPS System

The objective of compatibility study between UWB and GPS system receivers [42] was to determine the maximum allowable UWB equivalent isotropically radiated power (EIRP) levels that can be tolerated by GPS receivers without degrading their operations. Computations were based on EIRP average power. NTIA rather than concentrating on GPS applications, it concentrated on GPS architectures. Three receivers, one from each of three basic GPS architectures, were selected. These architectures include: C/A-code tracking receivers, semi-codeless receivers and C/A-code tracking receivers. These three GPS architectures encompass most of all GPS applications and offer a good benchmark for the desired objective. GPS satellites transmit a SS-CDMA (Spread Spectrum Code Division Multiple Access) signal using two microwave frequencies: Link 1 uses 1575.42 MHz and Link 2 on 1227.60 MHz. A third link to provide improvement in the use of satellite navigation with civilian applications is being added and will operate at 1176.45 MHz; it is referred as Link 5. Link 5 is part of the recently allocated Radio navigation-Satellite Service frequency band of 1164-1188 MHz.

In order to evaluate performance and better assess interference to GPS receiver operations, the following performance criteria were set ([42]):

- Break-lock (BL): a condition that causes a loss of signal between the satellite and the receiver.
- Re-acquisition time (RQT): the time it takes a receiver tracking a satellite signal to re-acquire the signal after it has been momentarily removed.
- Impulse waveform Parameters: to properly characterize UWB emission environments, a set of impulse waveform parameters were included (32 permutations):
    - Four pulse repetition frequencies (PRF) of 0.1, 1, 5, 20 MHz.
    - Four modulation types: constant PRF, On-Off keying, 2% relative reference dither and 50% absolute dither.
    - Two types of signal gating: 100% and 20%.

NTIA observed that UWB pulse of sufficient amplitude would degrade the performance of the GPS receiver. However, if the pulses are relatively short with relatively low duty cycle, then they will not degrade its performance. Furthermore, the interference is independent of the pulse amplitude as long as the amplitude is below the receiver peak pulse power limit of approximately 20dBm. NTIA concluded and concurred with independent studies from the Department of Transportation that GPS performance is relatively robust to pulse-like UWB emissions. The results indicates that both the C/A code tracking GPS receiver and the semi-codeless GPS shows a tolerance to all of the UWB signal permutations with a PRF of 100 KHz. At 1 MHz, the C/A-code receiver showed continuous wave-like (CW-like) interference[22] to the UWB signal at low power levels. When the PRF was set to 5 MHz and then 20 MHz, interference was more prevalent. The measured performance thresholds for the C/A-code GPS receiver were compared with the interference protection criteria documented within the Radio Technical Commission for Aeronautics (RTCA) and the International Telecommunication Union – Radio Communications Bureau (ITU-R). There exists significant agreement between the performance thresholds measured by the NTIA's study and the protection criteria documented in the national and international standards 0:

- In-band pulse interference: the RTCA limit is a peak power of +20 dBm for pulse within less than 1 millisecond and pulse duty cycle less than 10%.

[22] UWB signal interference effects in the GPS receiver were classified into 3 categories: pulse-like, CW-like, and noise-like. Pulse-like interference was defined by received UWB pulses that were independent, had low-duty cycle (low PRFs) and could not cause a GPS BL condition within the available power limit of the UWB test generator. Pulses are independent when the filter bandwidth is greater than the repetition rate. CW-like pulses were defined by a received UWB environment composed of dominant spectral lines that caused severe disruption in GPS receiver performance when one spectral line aligned with a C/A code line in the received GPS signal. The noise-like category was defined as UWB spectra with no dominant lines and with repeatable measured values for GPS receiver re-acquisition thresholds.

- In-band CW interference: both the RTCA and ITU-R limits are defined as -120.5 dBm for GPS receiver operating in tracking mode.
- In-band noise interference: both the RTCA and ITU-R limits are -110.5 dBm/MHz for GPS receiver operating in tracking mode.
- The RTCA and ITU-R are based on a minimum available GPS C/A code signal level of -130 dBm with an antenna gain assumed to be -4.5 dBi.

Table 14summarizes the types of interference that resulted from all UWB signal characteristics permutation and the C/A code architecture.

Table 14. Summary of Analysis of UWB signal characteristics (all permutations) to assess GPS Interference.

GPS Receiver Architecture	**UWB Signal Characteristics**			**Classification of Interference**	**Max. Interference Threshold**	**Permutation Count**	
	PRF (MHz)	**Modulation**	**Gating (%)**				**Comments**
C/A Code	0.1	various	various	Pulse-like		8 cases	
C/A Code	1	various	various	Pulse-like		7 cases	
C/A Code	1	No specified	No specified	CW-like		1 case	
C/A Code	5	various	various	CW-like		4 cases	
C/A Code	5	2% relative dither	100%	Noise-like	-108 dBm/MHz	1 case	Worst case (for Noise-like)
C/A Code	5	50% absolute dither	100%	Noise-like		1 case	
C/A Code	5	2% relative dither	20%	Pulse-like		1 case	
C/A Code	5	50% absolute dither	20%	Pulse-like		1 case	
C/A Code	20	various	various	CW-like	See Note 1	4 cases	
C/A Code	20	2% relative dither	100%	Noise-like		1 case	
C/A Code	20	50% absolute dither	100%	Noise-like		1 case	
C/A Code	20	2% relative dither	20%	Pulse-like		1 case	

Note 1: Among the 9 CW-like cases, the worst case was -116.5 dBm.

Note 2: Information on one more permutation case for the FRP of 20 MHz was not specified.

The semi-codeless receiver measured in this assessment showed susceptibility similar to what would be expected from noise-like interference for all of the UWB signal permutations employing PRFs of 1, 5, and 20 MHz. The semi-codeless GPS receiver was also observed to be more susceptible than the C/A-code receiver to noise-like interference.

The concluding remarks in the study noted that if the PRF is significantly less than the bandwidth of the victim receiver, UWB interference is impulsive and rarely causes GPS lock loss. UWB signals with high PRF and no dithering have strong spectral line components; therefore, they are more disruptive to GPS receivers. High UWB PRF systems require more dithering to minimize the effect on GPS or any other possible victim in the vicinity. Additional conclusions derived from the NTIA's study are:

- When considering multiple noise-like UWB signals with equivalent power levels at the GPS receiver input, the effective aggregate signal level in the receiver IF bandwidth is determined by adding the average power of each of the UWB signals.
- It was determined that the maximum permissible EIRP levels between -73.2 and -26.5 dBW/MHz are necessary to ensure electromagnetic compatibility for UWB signals with a PRF of 100 KHz. Similarly, for those UWB signals examined with PRF of 1 MHz, the EIRP levels range from -70.2 to -104.3 dBW/MHz (CW-like waveforms) and -57.6 to -91.6 dBW/MHz for the noise-like UWB signals. In the case of PRF of 5 MHz, the permissible EIRP levels range from -70.7 to -106.1 dBW/MHz for CW-like (non-dithered) UWB signals, and from -49.6 to -97.6 dBW/MHz for the noise-like (dithered) UWB waveforms. Finally, in case of PRF of 20 MHz, the permissible EIRP levels range from -71.0 to -106.9 dBW/MHz for CW-like (non-dithered) UWB signals, and from -60.0 to -98.6 dBW/MHz for the noise-like (dithered) UWB waveforms.
- A GPS antenna does not offer any additional attenuation to that portion of a UWB signal within the GPS frequency band.
- Table 15 thru Table 18 (see Appendix A) indicate that the maximum allowable EIRP to prevent interference to GPS receivers is highly dependent on the characteristics of the UWB signal. Appendix A summarizes the results for UWB devices that operate with PRF of 100 KHz, 1 MHz, 5 MHz and 20 MHz.

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Appendix A

The following tables contain the summary of all the UWB measurements and tests as performed by the NTIA in their study on compatibility between UWB systems and Global Positioning System (GPS)(from [42]).

Table 15. Summary: PRF = 100 KHz.

Operational Scenario Description					Signal UWB Characteristics			GPS Receiver Architecture	Classification of Interfering Signal	Maximum Interference Threshold (dBW/MHz)	Maximum Allowable EIRP (dB/MHz) W/M	Comparison with the Curren Part 15 Level (dB)
Application	**UWB Single**	**UWB Multiple**	**UWB Indoor**	**UWB Outdoor**	**PRF (MHz)**	**Gating %**	**Mod.**					
Terrestrial	X			X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-73.2	1.9
Terrestrial		X	X		0.1	100	None	C/A-code	Pulse-Like	-112.6	-57.6	-13.7
Terrestrial		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-62.3	-9
Maritime		X	X		0.1	100	None	C/A-code	Pulse-Like	-112.6	-41.7	-29.6
Maritime		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-48.1	-23.2
Railway		X	X		0.1	100	None	C/A-code	Pulse-Like	-112.6	-56.3	-15
Railway		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-57.8	-13.5
Surveying	X			**X**	0.1	20	2% Rel.	Semi-Codeless	Noise-Like	-138	-81.1	9.8
Surveying		X		X	0.1	20	2% Rel.	Semi-Codeless	Noise-Like	-138	-81.2	9.9
Aviation-NPA		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-52.9	-18.4
Aviation-ER		X	X		Note 1	Note 1	Note 1	C/A-code	Noise-Like	-134.8	-76.62	5.3
Aviation-ER		X		X	Note 1	Note 1	Note 1	C/A-code	Noise-Like	-134.8	-85.62	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)
1. In this operational scenario, it is assumed that there is a large enough number of UWB devices such that independent of the individual UWB signal parameters, the aggregate effect causes noise-like interference.
2. This maximum allowable EIRP is based on a density of 200 UWB devices per square kilometer transmitting simultaneously.

Table 16. Summary: PRF = 1 MHz.

Operational Scenario Description					**UWB Signal Characteristics**			**GPS Receiver Architecture**	**Classification of Interfering Signal**	**Maximum Interference Threshold (see Note 1)**	**Maximum Allowable EIRP (see Note 3)**	**Comparison with the Current Part 15 Level (dB)**
Application	**UWB Single**	**UWB Multiple**	**UWB Indoor**	**UWB Outdoor**	**PRF (MHz)**	**Gating (%)**	**Mod**					
Terrestrial	X			X	1	100	None	C/A-code	CW-Like	-143.7	–104.3	33
Terrestrial	X			X	1	100	2% Rel.	C/A-code	Pulse-Like	-131	-91.6	20.3
Terrestrial		X	X		1	100	None	C/A-code	CW-Like	-143.7	-88.7	17.4
Terrestrial		X	X		1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-85.5	14.2
Terrestrial		X		X	1	100	None	C/A-code	CW-Like	-143.7	-93.4	22.1
Terrestrial		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-90.2	18.9
Maritime		X	X		1	100	None	C/A-code	CW-Like	-143.7	-72.8	1.5
Maritime		X	X		1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-69.6	-1.7
Maritime		X		X	1	100	None	C/A-code	CW-Like	-143.7	-79.2	7.9
Maritime		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-76	4.7
Railway		X	X		1	100	None	C/A-code	CW-Like	-143.7	-87.4	16.1
Railway		X	X		1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-83	11.7
Railway		X		X	1	100	None	C/A-code	CW-Like	-143.7	-88.9	17.6
Railway		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-84.5	13.2
Surveying	X			X	1	100	50%Abs.	Semi-Codeless	Noise-Like	-151	-94.1	22.8
Surveying		X		X	1	100	50%Abs.	Semi-Codeless	Noise-Like	-151	-94.2	22.9
Aviation -		X		X	1	100	None	C/A-code	CW-Like	-143.7	-84	12.7
Aviation -		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-80.8	9.5
Aviation-ER		X	X		Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-76.6	5.3
Aviation-ER		X		X	Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-85.6	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)

1. When the interference effect has been classified as pulse-like or noise-like, the value is expressed in units of dBW/MHz. The value is expressed in units of dBW when the interference effect has been classified as being CW-like.

2. In this operational scenario, it is assumed that there is a large enough number of UWB devices, such that independent of the individual UWB signal parameters the aggregate effect causes noise-like interference.

3. This maximum allowable EIRP is based on a density of 200 UWB devices per square kilometer transmitting simultaneously.

Table 17. Summary: PRF = 5 MHz.

Operational Scenario Description					UWB Signal Characteristics			GPS Receiver Architecture	Classification of Interfering Signal	Maximum Interference Threshold[1]	Maximum Allowable EIRP	Comparison with the Current Part 15 Level (dB)
Application	UWB Single	UWB Multiple	UWB Indoor	UWB Outdoor	PRF (MHz)	Gating %	Mod					
Terrestrial	X			X	5	100	None	C/A-code	CW-Like	-145.5	–106.1	34.8
Terrestrial	X			X	5	20	50% Abs.	C/A-code	Pulse-Like	-105	-65.6	-5.7
Terrestrial	X			X	5	100	50% Abs.	C/A-code	Noise-Like	-137	–97.6	26.3
Terrestrial		X	X		5	100	None	C/A-code	CW-Like	-145.5	-90.5	19.2
Terrestrial		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-137	-88	16.7
Terrestrial		X		X	5	100	None	C/A-code	CW-Like	-145.5	-95.2	23.9
Terrestrial		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-92.7	21.4
Maritime		X	X		5	100	None	C/A-code	CW-Like	-145.5	-74.6	3.3
Maritime		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-137	-72.1	0.8
Maritime		X		X	5	100	None	C/A-code	CW-Like	-145.5	-81	9.7
Maritime		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-78.5	7.2
Railway		X	X		5	100	None	C/A-code	CW-Like	-145.5	-89.2	17.9
Railway		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-137	-85.5	14.2
Railway		X		X	5	100	None	C/A-code	CW-Like	-145.5	-90.7	19.4
Railway		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-87	15.7
Surveying	X			X	5	20 & 100	50% Abs.	Semi-Codeless	Noise-Like	-151	-94.1	22.8
Surveying		X		X	5	20 & 100	50% Abs.	Semi-Codeless	Noise-Like	-151	-94.2	22.9
Aviation-NPA		X		X	5	100	None	C/A-code	CW-Like	-145.5	-85.8	14.5
Aviation-NPA		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-83.3	12
Aviation-ER		X	X		Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-76.6[3]	5.3
Aviation-ER		X		X	Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-85.6[3]	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)

1. When the interference effect has been classified as pulse-like or noise-like, the value is expressed in units of dBW/MHz. The value is expressed in units of dBW when the interference effect has been classified as CW-like.

2. In this operational scenario, it is assumed that there is a large enough number of UWB devices, such that independent of the individual UWB signal parameters the aggregate effect causes noise-like interference.

3. This maximum allowable EIRP is based on a density of 200 UWB devices per square kilometer transmitting simultaneously.

Table 18. Summary: PRF = 20 MHz.

Operational Scenario Description					UWB Signal Characteristics			GPS Receiver Architecture	Classification of Interfering Signal	Maximum Interference Threshold[1]	Maximum Allowable EIRP[1]	Comparison with Current Part 15 Level (dB)
Application	UWB Single	UWB Multiple	UWB Indoor	UWB Outdoor	PRF (MHz)	Gating %	Mod					
Terrestrial	X			X	20	20	OOK	C/A-code	CW-Like	-146.3	–106.9	35.6
Terrestrial	X			X	20	20	50% Abs.	C/A-code	Pulse-Like	-135	-95.6	24.3
Terrestrial	X			X	20	100	50% Abs.	C/A-code	Noise-Like	-138	–98.6	27.3
Terrestrial		X	X		20	20	OOK	C/A-code	CW-Like	-146.3	-91.3	20
Terrestrial		X	X		20	100	50% Abs.	C/A-code	Noise-Like	-138	-89	17.7
Terrestrial		X		X	20	20	OOK	C/A-code	CW-Like	-146.3	-96	24.7
Terrestrial		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-93.7	22.4
Maritime		X	X		20	20	OOK	C/A-code	CW-Like	-145	-75.4	4.1
Maritime		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-138	-73.1	1.8
Maritime		X		X	20	20	OOK	C/A-code	CW-Like	-145	-81.8	10.5
Maritime		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-79.5	8.2
Railway		X	X		20	20	OOK	C/A-code	CW-Like	-145	-90	18.7
Railway		X	X		20	100	50% Abs.	C/A-code	Noise-Like	-138	-86.5	15.2
Railway		X		X	20	20	OOK	C/A-code	CW-Like	-145	-91.5	20.2
Railway		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-88	16.7
Surveying	X			X	20	100	50% Abs. & 2% Rel.	Semi-Codeless	Noise-Like	-149.5	-92.6	21.3
Surveying		X		X	20	100	50% Abs. & 2% Rel.	Semi-Codeless	Noise-Like	-149.5	-92.7	21.4
Aviation-NPA		X		X	20	20	OOK	C/A-code	CW-Like	-145	-86.6	15.3
Aviation-NPA		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-84.3	13
Aviation-ER		X	X		Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-76.6[3]	5.3
Aviation-ER		X		X	Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-85.6[3]	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)

1. When the interference effect has been classified as pulse-like or noise-like, the value is expressed in units of dBW/MHz. The value is expressed in units of dBW when the interference effect has been classified as being CW-like.

2. In this operational scenario, it is assumed that there is a large enough number of UWB devices, such that independent of the individual UWB signal parameters the aggregate effect causes noise-like interference.

3. This maximum allowable EIRP is based on a density of 200 UWB devices per square kilometer transmitting simultaneously.

APPENDIX B

FCC 15 Section 209(a) states: "Except as provided elsewhere in this subpart, the emissions from an intentional radiator shall not exceed the field strength levels specified in the following table:"

Table 19. FCC Part 47 Section 15, subpart 209 radiated emission limits for UWB systems.

Frequency (MHz)	Filed Strength (microvolts/meter)	Measurement Distance (mt)
0.009-0.490	2400/F(KHz)	300
0.490-1.705	24000/F(KHz)	30
1.705-30.0	30	30
30-88	100[23]	3
88-216	150 (see 14)	3
216-960	200 (see 14)	3
Above 960	500	3

From Table 19, for the particular case of systems operating above 960 MHz, we can easily read that an UWB radiator must not exceed an electric field strength that is at most 500 µV/mt at 3 mts from the radiator in every 1 MHz band. In order to express this in terms of radiated power, we derive it as follows:

$$\boldsymbol{P = E_0^2\, 4\pi\, R^2/\eta} \qquad (47)$$

Where E_0 represents the electric field, R is the radius of the sphere at which the field strength is measured and η is the characteristic impedance of a vacuum ($\eta = 120\pi \approx 377\ \Omega$). This corresponds to an emitted power of approximately 75 nW, or an EIRP equals to -41.2 dBm/MHz (equivalent to -71.2 dBW/MHz).

[23] Radiators operating under this section shall not be located in the frequency bands 54-72 MHz, 76-88 MHz, 174-216 MHz or 470-806 MHz. However, operation within these frequency bands is permitted under other sections of this part, e.g., 15.231 and 15.241.

APPENDIX C - MATHEMATICAL FORMULAS

- *Definite Integral relation for some type of exponential functions:*

$$\int_{-\infty}^{+\infty} e^{-at^2}\, dt = \sqrt{\frac{\pi}{a}}\ (a > 0) \qquad (48)$$

- *Transform Relations for Derivatives:*

Given:

$$g(t) \xrightarrow{Fourier} G(w)\ and\ h(t) = \frac{d}{dt}\big(g(t)\big) \xrightarrow{Fourier} H(w) \qquad (49)$$

Using the definition of Fourier Transform, we can write:

$$G(w) = \int_{-\infty}^{+\infty} g(t) e^{-jwt}\, dt \qquad \text{(a)}$$
$$g(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} G(w) e^{jwt}\, dw \quad \text{(b)} \qquad (50)$$

Taking derivate at both side of Equation
(50 **)**(b), we obtain:

$$\frac{d}{dt}\big(g(t)\big) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} G(w)(jw)e^{jwt}\, dw \qquad (51)$$

Since, $h(t) = \frac{d}{dt}\big(g(t)\big) \xrightarrow{Fourier} H(w)$

$$h(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} G(w)(jw)e^{jwt}\, dw = \frac{1}{2\pi}\int_{-\infty}^{+\infty} H(w)e^{jwt}\, dw \qquad (52)$$

Or,

$$H(w) = jw\ G(w) \tag{53}$$

In general, given $g_n(t) = \frac{d^n}{dt^n}\left(g_0(t)\right)$, then

$$G_n(w) = (jw)^n\ G_0(w) \tag{54}$$

Equation (54) is also known as the generalized derivative property of the Fourier Transform.

- *Error and Complementary Error Functions*

$$\begin{aligned} \operatorname{erf}(x) &= \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt. \\ \operatorname{erfc}(x) &= 1 - \operatorname{erf}(x) \\ &= \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2}\, dt. \end{aligned} \tag{55}$$

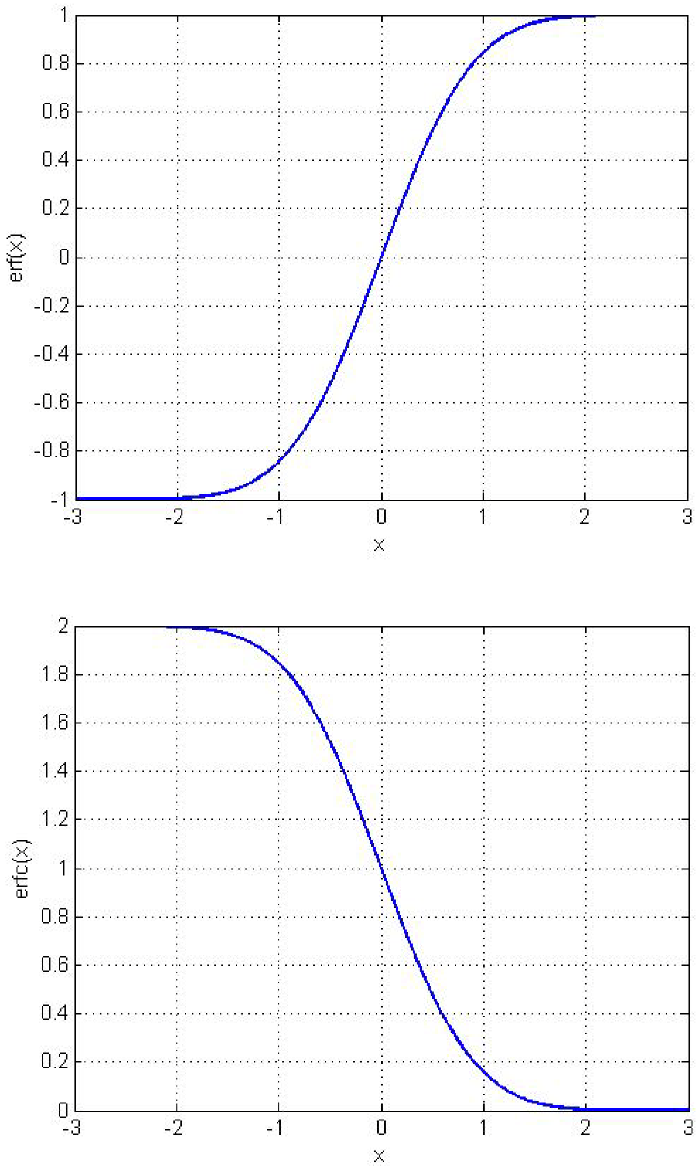

Figure 34. Error and complementary error functions.

❖ *Gaussian Error or Q function*

A Gaussian probability density function (PDF) with variance σ is given by:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-x^2/2\sigma^2} \qquad (56)$$

The probability that a signal with a PDF given by f(x) lies above a given threshold x is given by the Gaussian Error Integral or Q function:

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-u^2/2\sigma^2} du \quad (57)$$

In terms of the erf(.) and erfc(.) functions (with unit variance), Q(x) can be expressed as:

$$Q(x) = \frac{1}{2}\, erfc\left(\frac{x}{\sqrt{2}}\right) = \frac{1}{2}\left(1 - erf\left(\frac{x}{\sqrt{2}}\right)\right) \quad (58)$$