Ultra Wideband vs. Narrowband Communications

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1 Introduction

Ultra wideband (UWB) wireless communication has been the subject of extensive research in recent years due to its potential applications and unique capabilities. However, many important aspects of UWB-based communication systems have not yet been thoroughly examined. The area of narrow band communication is well developed. The objective of this paper is to present Ultra Wideband (UWB) communication in a comparative context.

Ultra wideband (UWB) systems use precisely timed, extremely short coded pulses transmitted over a wide range of frequencies. Although UWB technology had some old roots, UWB communication is a relatively new technology.

Ultra wideband technology originated from work in time-domain electromagnetics begun in 1962. The concept started with the objective of characterizing linear time invariant systems. It became clear that short pulse radar and communication systems can be developed in the same way. In 1978 efforts turned toward the communication using UWB signals. An experiment was successfully presented where intelligible voice signals could be communicated over hundreds of feet without the need for synchronization. Six years later, greater ranges were possible. The term “ultra wideband” was not used until around 1989. By that time, the theory of UWB has experienced thirty years of developments.

In rest of this paper, UWB communication is compared with narrowband communications. The comparison includes: definition and frequency band allocation, communication signal (shape and spectrum), coding and modulation, interference, security, hardware, and applications.

2 Definition and Band Allocation

In principle UWB technology is the use of short pulses instead of continuous waves to transmit information. The pulse directly generates a very wide instantaneous bandwidth signal according to the time-scaling properties of the Fourier transform relationship between time, t, and frequency, f.

Before presenting a formal definition for ultra wideband signals and systems, it should be noted that different terms are used in the literature which essentially refer to the same thing such as impulse radio, orthogonal functions, Walsh waves, nonsinusoidal, sequency theory, carrier-free, video-pulse transmission, large relative bandwidth, time-domain techniques, baseband, large-relative bandwidth and ultra wideband .

Researches from Russia and China have been actively developing and testing UWB impulse generators [Kis92]. The Soviets developed the “superwideband” signal definition. All RF signals with a low frequency bound, f_l, and high frequency bound, f_h, have a corresponding index of breadth of band, μ_b, or relative bandwidth [Ast97],

$$\mu_b = \frac{f_h - f_l}{0.5(f_h + f_l)} \qquad (1)$$

Researchers from Russia and China term an impulse-like signals “superwideband” or UWB when $\mu_b \geq 1.0$. Although, spread spectrum communications can be designed with $\mu_b \geq 1.0$, they are not called UWB because they do not possess the transient behavior.

There is no general definition of UWB in the IEEE dictionary. However some researcchers defined UWB for EM waves with instantaneous bandwidth greater than 25% of center frequency [Pan99].

It is important to note that some technical terms can have different meaning based on the subject where they are used. Narrowband (NB), wideband (WB) or broadband (BB) and ultra wideband (UWB) can have different definitions based on the application, i.e. communication, radar, electromagnetic interference (EMI) / electromagnetic cancellation (EMC), etc. In mobile communication it is common to refer to the system's bandwidth as being narrow or wide relative to the coherence bandwidth. However, the terminology used here is the one used by RF engineers based on the ratio of the bandwidth relative to the carrier frequency.

3 Communication Signal (Shape and Spectrum)

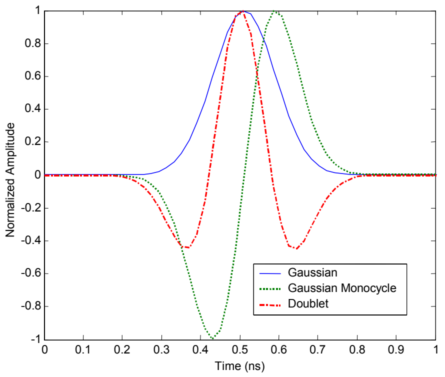
Narrowband communication is usually achieved by modulating a sinusoidal carrier with the information to be transmitted. The resultant signal possesses the sinusoidal nature and occupies a narrow band in the frequency domain. On the other hand, for UWB applications, any waveform that satisfies the definition of UWB signal can be used. The choice of a specific waveform is driven by system design and application requirements. The signal waveform may be designed to be suitable for UWB applications and yet has minimal interference with proximity systems.

The basic theoretical model for impulse radio uses a class of waveforms known as "Gaussian waveforms". They are called Gaussian waveforms because they are very similar to the Gaussian function. In the time domain a Gaussian waveform, $v_g(t)$, is given by

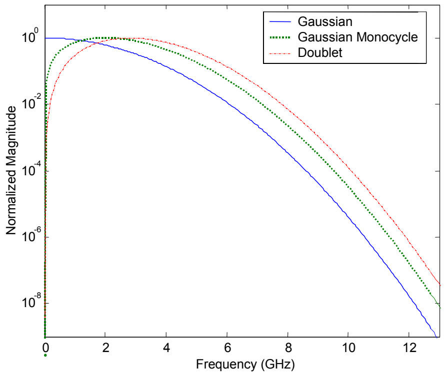
$$v_g(t) = e^{-(\frac{t}{\tau})^2} . \qquad (2)$$

where t is the time and τ is a parameter which represents the temporal width of the pulse. Another waveform can be created by filtering or differentiating the Gaussian pulse to get the Gaussian Monocycle. For the Gaussian monocycle, τ is the time between minimum and maximum amplitudes and it defines the time decay constant that determines the monocycle's duration. The Gaussian monocycle has a single zero crossing. By increasing the order of differentiation, the number of zero-crossings increases, the bandwidth decreases and the center frequency increases.

Gaussian excitation pulse provides excellent radiation properties. Other possible waveforms include pulse like triangular, trapezium and other shaped pulses.



a) Gaussian, Gaussian monocycle, and doublet waveforms



b) Normalized spectrum for Gaussian, Gaussian monocycle, and doublet waveforms

Figure 1. Gaussian, Gaussian monocycle, and doublet waveforms and their corresponding normalized frequency spectrum

Figure 1 illustrates the basic Gaussian, and its first and second derivatives, which are the Gaussian monocycle and the doublet waveforms. The corresponding normalized frequency spectrum is shown in the same figure. Practical implementation of such Gaussian monocycle remains an important issue.

Multiple access techniques for narrowband systems include: time, frequency, and code division techniques. The multiple access UWB system model proposed by Scholtz [Sch93] is based on time hopping codes. In a typical hopping format for impulse radio with pulse position modulation, the time access is divided into frames, T_f, and every frame is subdivided into time slots, T_c. Every transmitter send a pulse per frame at different time slots from frame to another. See Figure 2.

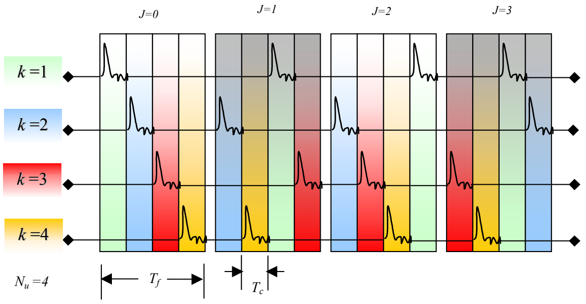


Figure 2. Illustration of four users time hoping multiple access format (impulse radio)

The assumed channel model is that N_u users are active during transmission. The received waveform is generally different from the transmitted one. Signal undergoes constant amplitude attenuations and waveform deformation because of the antennas and the propagation channel. Because of the antenna, the received signal is related to the derivative of the transmitted signal. For example, for TEM horn antennas in boresight configuration, if a Gaussian pulse is transmitted then a Gaussian monocycle is received. On the other hand, if a monocycle is transmitted, the expected received waveform will have a doublet shape. This is because the response of the radiating system will act as a differentiator.

A single bit of information is generally spread over multiple monocycles to form a train of pulses. The frame time, T_f, may be 100 to 1000 times the monocycle width, resulting in a signal with very low duty cycle.

Multiple access signals composed of uniformly spaced pulses are vulnerable to occasional catastrophic collisions. To eliminate catastrophic collisions, each link (*k*) uses a distinct pulse shift pattern.

To give the reader a practical view of the signal characteristics, an example of a typical signal have the following characteristics:

- Bandwidth of 2 GHz (>1 GHz).
- f_C typically in the range 650 MHz – 5GHz.
- Tightly controlled pulse-to-pulse interval.
- Pulse width 0.2 –1.5 ns.
- Pulse-to-Pulse interval 100-1000 ns.

4 Coding and Modulation

4.1 Coding

All source and channel coding applicable for narrowband systems are also applicable for UWB systems. The advantage for UWB communication is the fact that UWB signals seem to be easier to deal with because the signal is readily presented in a digital form. UWB technology can be considered as the modulation layer of the communication system. Thus, the remaining coding principles for the higher-level communication layers, which are used in narrowband communications, are also valid for UWB communication.

Pulse position coding or “dithering” is a basic building block of the proposed multiple access UWB system. Pseudo-random noise coding (PN Code) is used for channelization. The code is used to apply a relatively large time offset at every frame. Each user has a different code. Only the receiver with the same code can decode the transmission. In the frequency domain the PN code makes the signal like noise. The code is essential to suppress multiple access interference. PN codes must be orthogonal to one another. They must effectively smooth the energy distribution and allow fast signal locking [Ful00].

In addition to channelization and energy spectrum smoothing, the PN code makes the UWB signal highly resistant to jamming.

4.2 Modulation

Narrowband modulation includes amplitude modulation (AM), frequency modulation (FM), phase modulation (PM) and many other variations. UWB impulse radio can be modulated in analog form or digital form. [Win97] presented a comparison between analog and digital impulse radio for wireless multiple-access communications.

UWB signals are usually time domain modulated using pulse position modulation. This modulation allows for the use of an optimal receiving matched filter technique. Pulse position modulation is accomplished by varying the pulse position about a nominal position. For example in a 10 Mpps (Mega pulse per second) system, pulses would be transmitted nominally every 100 ns. If the information bit is “0”, the pulse would be transmitted 100 ps early. For a digital bit of “1”, the pulse would be transmitted 100 ps late.

[Ram99] discussed higher order time domain *M*-ary pulse position modulation. It was shown that by increasing *M* to a value more than 2, it is possible to reduce the **b**it **e**rror **r**ate, BER, or to increase the number of users at the same bit error rate.

A single bit of information is generally spread over multiple monocycles. Thus, to demodulate the received signal, the receiver sums the proper number of pulses to recover the transmitted information. The receiver is based on decorrelating the received impulse with a template signal. The template signal is the difference between the pulse that represent an information bit=1 and the pulse used for an information bit=0.

5 Interference

Interference on UWB systems can result from other UWB users - multiple access-, multipath, other narrowband systems, etc. Similarly, interference to narrowband system could be multiple access, co-channel, multipath, leakage from other narrowband systems, or UWB interferences. First, the interference from other radiators to UWB systems is reviewed. Second, the interference on other narrowband systems as a result of UWB system will be discussed.

5.1 Interference from Other Radiators to UWB Systems

UWB receiver has to deal with many narrowband radiators. The external interference to the UWB receiver strongly depends on the antenna. Measurements of the received power across the spectrum using UWB antenna give an illustrative image of the interfering signals. A significant amount of lower frequency interference power (TV, FM, and land mobile radiators) can get through the antenna's frequency side lobs below the main pass band of the UWB antenna system.

A specific UWB antenna tested by [Sch00] resulted in an interference power of about -33.5 dBm when the entire system spectrum was utilized. The level of the interfering power was reduced greatly by using a bandpass filter at the front end of the receiver. With 97% bandwidth usage (780 MHz, 2.05 GHz) the interference power level reduced to -40 dBm. A further reduction to 86% bandwidth usage (960 MHz, 1.93 GHz) removed the strong interference at the edges (900 MHz). The captured signal approached the noise floor of the spectrum analyzer which is nearly -60dBm.

The previous analysis suggests the possibility of incorporating a notch filter to remove the strongest interferer. It is important to note that since the noise is highly dominated by specific interferers, the level of the interferer power would be sensitive to the location of the measurements. This is because the interferer signal may suffer from multipath enhancement or fading [Sch00].

UWB Multipath interference is not a problem due to the high time resolution. Signals reflected from different objects can be easily resolved from the line of site signal. Practical multiuser interference rejection performance is not guaranteed. The processing gain is used as a theoretical measure to the system ability to reject interference. The inherent pseudo-random code that is usually associated with UWB communication system makes the system highly resistant to interference. All other signals act as jammers to the UWB communication system. UWB signals are designed to share the same band as other existing systems.

5.2 UWB Interference to Other Systems (Narrowband)

Communication applications require signals free from interception and interferences. The electromagnetic (EM) environment due to the UWB systems can occupy the entire used EM spectrum band of 100 kHz to 10 Ghz. A careful study needs to be carried out to mitigate the intra system and inter system electromagnetic aspects of the UWB technology.

The instantaneous power from an UWB source could be very high even with a very low average power due to the low duty cycle. It is the question of which one is more dominant to interference: average or instantaneous power? According to [Ful00], the driver for local interference is the average power rather than the peak power in most scenarios. However, other researchers are opposing this conclusion [Bar01].

There are already thousands of devices that operate across the spectrum like hair dryers and computers. Some researchers claim that UWB transmitters could be designed to radiate no more than a hair dryer! [Ful00] claims that tested UWB prototypes cause only one-quarter of interference of laptop computers or other comparable electronic devices. Another important issue is the noise generated as an aggregate level that would cause interference when multi UWB users are in operation.

In addition to the level of interference, the possibility of narrowband front-end electronic upset should be studied. Those front ends were not designed with UWB transient signals in mind.

Interference to GPS receivers is a cause for concern and the results of interference analyses will strongly influence regulatory decisions. Significant amount of work is being carried out on measuring and analysing the interference to GPS receivers [Sch00]. Other important existing systems to be protected from UWB interference are also initiating measurements and analysis projects.

6 Security

UWB technology has great value in the development of low probability of intercept and detection communication systems. UWB employs baseband pulses of very short duration, typically about a nanosecond, and spread the signal energy through the entire used spectrum. Due to the low energy spectrum, probabilities of intercept and detection are both low.

Time hopping codes is a communication security feature integrated in the UWB multiple access system. Encryption will add to the security of the system. A new development in the area of secure UWB communications utilizes fractal mathematical characteristics. The advantage of the low average power UWB system over narrowband systems is the communication security rather than just the information security.

7 Hardware

The hardware requirements for UWB communications is based on sophisticated digital electronics. The basic components for UWB communications have so far been used are the following: pulse train generator, pulse train modulator, switch pulse train generators, detection receivers, leading edge detector, ring demodulators, monostable multivibrator detectors, correlation detectors, signal integrators, synchronous detectors and wideband antenna.

Figure 3 presents a higher-level block diagram for a UWB transmitter and receiver. Amplifiers are not shown explicitly. The power level of the pulse generator is assumed to be sufficient. The receiver is similar to the transmitter except that the generated pulses are fed to the correlator. Signal processing is required to extract the modulated information and control signal acquisition and tracking .

Conventional narrowband transmitter/receiver block diagram includes intermediate frequency (IF) stages. Considering the number of building blocks, UWB radios are simpler to build than equivalently sophisticated conventional narrowband radios. The key elements include the pulse generator, the antenna and the receiver front end.

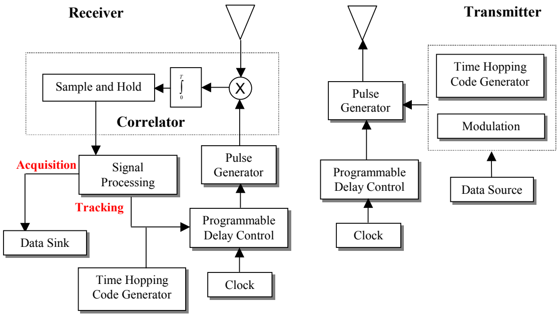


Figure 3. Higher-level block diagram for a UWB transmitter and receiver.

Pulse Generator (Source)

The pulse generator consists of a single transistor that operates in a digital mode and switches between “0” and “1” states. The step waveform at the transition is filtered to produce Gaussian-like pulse shape. Cost and power are reduced by eliminating the need for linear amplifier as in narrowband conventional communications.

Antenna

Antennas should be specifically designed for the UWB task. Ordinary “wideband” antennas do not transmit fast transients because they are not corrected for dispersion [Pra99]. Both frequency and spatial dispersions should be taken into consideration. Frequency dispersion can be overcome by TEM horn or biconical antennas. Both structures are frequency independent. Spatial dispersion can be reduced by using lenses and reflectors [Pra99].

The total frequency domain gain transfer behavior on transmitting and receiving ends must be designed to offset the path loss effects. Knowledge of the transmit antenna characteristics such as gain, impedance matching, and radiation pattern are particularly important for UWB impulse signal collection. When an UWB transient signal is collected, the receiving antenna transfer function should also be documented clearly so that UWB signals can be accurately compared if collected with different antenna. If the receiving antenna transfer function does not match across UWB collection system, the collected signals will have different time and frequency domain characteristics, leading to invalid and/or multiple signal designations to one transmitter type.

More than one antenna could be used to account for different bands [Pra99]. Designing antennas for UWB communications is an important asset to the success of UWB communication technology.

Receiver Front End

An important requirement at the receiver is the ability to sample at very high rate. At the receiver side, no intermediate frequency (IF) stages are required. Synchronization with the transmitter is a key requirement for a successful communication. Timing requirements are more constrained in UWB technology. Very low jitter electronic circuits are required. Proposed applications require no more than 15 ps timing accuracy and stable time bases [Ful00]. Timing requirements make building discrete components very difficult. Application Specific Integrated Circuits (ASIC) implementations are relatively simple and inexpensive. When produced in substantial volume, these chips are expected to cost few dollars.

8 Applications

The original proposal for UWB is based on the assumption that UWB is immune to multipath, can support higher rate communications, the signal has a better wall penetration capabilities, and may consume much less power. These features support many applications including indoor static wireless LANs, home-networking, asynchronous transfer mode (ATM) multimedia, un-centralized multiple access communication and secure military applications.

Besides communication applications, UWB technology has many applications in military, aviation, and space fields. UWB technology applies to both civil and military applications. UWB systems can be used for navigation and communication. It can be used for range measurements [Ada01]. UWB receivers can time the transmitted pulses to within a few thousand billions of seconds.

UWB technology supports integration of services. Some of the services and applications that can be integrated with UWB communications are described briefly below.

- *Precision Geo-location Systems*
- *Imaging*
- *Through –Wall Sensing Radar*
- *Underground Penetrating Radars*

9 Conclusion

The proposed UWB communication holds great promises with radical departure from traditional narrowband systems. Before UWB communication is materialized, propagation characteristics have to be well understood. At a fundamental level we have to understand the basic difference between UWB and narrowband communications. There is a strong relation between the term time domain and the term UWB. On the other hand, narrowband communication lends itself to frequency domain techniques. It is important to understand the differences before extending the theory of narrowband communication to UWB systems.

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