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An introduction to UWB communication systems

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Ultra-wideband (UWB) wireless communication is a revolutionary technology for transmitting large amounts of digital data over a wide frequency spectrum using short-pulse, low-powered radio signals. UWB commonly refers to a signal or system that either has a large relative bandwidth (BW) that exceeds 20% or a large absolute bandwidth of more than 500 MHz. A 14 February 2002 Report and Order by the Federal Communications Commission (FCC) authorizes the unlicensed use of UWB in 3.1–10.6 GHz. This is intended to provide an efficient use of scarce radio bandwidth while enabling both high data rate personal area network (PAN) wireless connectivity and longer-range, low data rate applications as well as radar and imaging systems.

Historical perspective

UWB communications is not a new technology. It was first employed by G. Marconi in 1901 to transmit Morse code sequences across the Atlantic Ocean using spark gap radio transmitters. However, the benefit of a large bandwidth and the capability of implementing multi-user systems provided by electromagnetic pulses were never considered at that time. Approximately 50 years after G. Marconi, modern pulse-based transmission gained momentum in military applications in the form of impulse radars. The genesis of UWB technology is a result of the research works in time-domain electromagnetics that began in 1962. The concept was to characterize linear, time-invariant (LTI) systems by their output response to an impulse excitation, instead of the more conventional means of swept frequency response (i.e., amplitude and phase measurements versus frequency). This output response is known as impulse response $h(t)$ of the LTI system. Output response $y(t)$ of an LTI system to any input response $x(t)$ is determined by the convolution theorem:

$$y(t) = \int_{-\infty}^{+\infty} h(\tau)x(t-\tau)d\tau.$$

It was not possible to measure the impulse response directly until the development of impulse excitation and measurement techniques. Once these techniques were in place, it became obvious that these could be used for short pulse radar and communication systems. Many of the communication technologies were first experimented and used in military applications for some decades, only to be used for commercial applications at a much later time. UWB is no exception to this trend. From the 1960s to the 1990s, this technology was restricted to military and Department of Defense (DoD) applications under classified programs such as highly secure communications. In 1978, G.F. Ross and C.L. Bennett applied these techniques for radar and communication applications. This technology was referred to as base band, carrier-free, or impulse until the late 1980s and was termed UWB by the U.S. DoD around 1989. By that time, UWB theory had experienced 30 years of development. Although UWB technology is old, its application for communication is relatively new. The recent advancements

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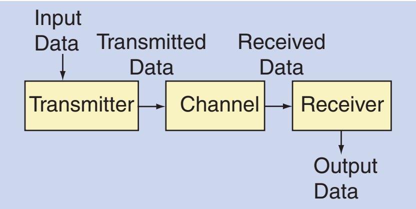

Fig. 1 Block diagram of a communication system.

in microprocessor and fast switching in semiconductor technology has made UWB ready for commercial applications. Therefore, it is more appropriate to consider UWB as a new name for a long-existing technology.

As interest in the commercialization of UWB has increased over the past several years, developers of UWB systems began pressuring the FCC to approve UWB for commercial use. In February 2002, the FCC approved the first Report and Order for commercial use of UWB technology under strict power emission limits. Typical values of transmitted power by a radio, television, IEEE 802.11a wireless local area network (WLAN), and 2 G cellular devices are 50 kW, 100 kW, 1 W, and 500 mW respectively. For UWB systems, the transmitted power is much less and is of the order 0.5 mW.

Another useful parameter is power spectral density (PSD), which is defined as the ratio of power transmitted in watts and bandwidth of the signal in hertz. Due to the huge bandwidth of UWB systems (3.1–10.6 GHz allotted by FCC), the PSD is even less than other wireless communication systems or devices. For instance, for IEEE 802.11a WLAN systems with a bandwidth of 20 MHz, the PSD for the above mentioned transmitted power is 0.05 W/MHz whereas for UWB systems it is just 6.670×10^{-8} W/MHz. The huge bandwidth coupled with a very low power level makes UWB signals more or less like a background noise to other wireless communication systems. This allows UWB systems to coexist with other radio communication devices as well and make them immune to detection and interception by other narrowband wireless communication receivers. We will not go into too much detail of UWB power levels and PSD and interference with other existing systems like personal communication service (PCS), digital communication systems (DCS), and code division multiple access (CDMA). You may refer to any one of the books mentioned in the references for more information.

High data rates, low power

Shannon's formula expresses the channel capacity of a band-limited information transmission channel with additive white, Gaussian noise: $C = BW \log_2(1 + S/N)$ bits/second. Shannon's formula gives how many bits of information per second can be transmitted without error over a channel with a bandwidth of BW Hz when the average signal power is limited to S watt and the signal is exposed to an additive, white (uncorrelated) noise of power N with Gaussian probability distribution. The essential elements of "Shannon's formula" are:

1) The channel bandwidth sets a limit to how fast symbols can be transmitted over the channel.

2) The signal-to-noise ratio (S/N) determines how much information each symbol can represent. The signal and noise power levels are measured at the receiver end of the channel. Thus, the power level is a function of both transmitted power and the attenuation of the signal over the transmission medium (channel).

Shannon's capacity limit equation shows capacity increasing as a function of BW faster than as a function of signal to noise ratio (SNR). Shannon's equation shows that increasing channel capacity requires linear increases in bandwidth while similar capacity increases would require exponential increases in power. Therefore, UWB technology is capable of transmitting high data rates using very low power.

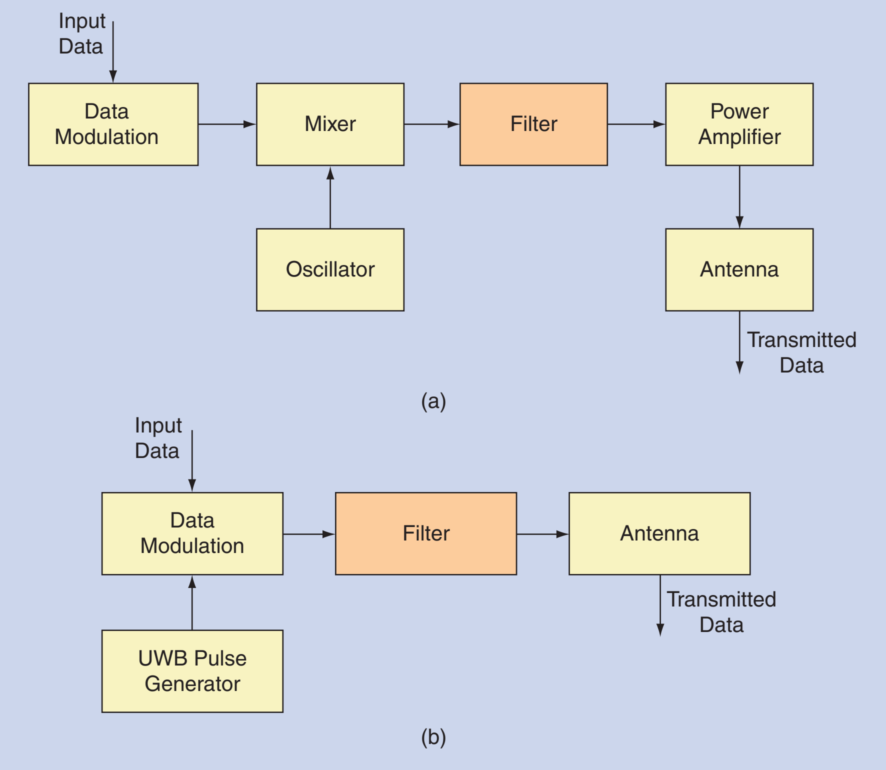

Fig. 2 Block diagram of a typical (a) narrowband and (b) UWB transmitter.

UWB communications systems

Fig. 1 shows a general model of a single-link communication system. It includes three major blocks of communication, viz., a transmitter, the channel, and a receiver.

The input data to the transmitter is the message to be sent from the source to the destination. The main function of the transmitter is to send out the message to the channel, which is done with the help of an antenna. An antenna is a means for radiating (transmitting antenna) or receiving (receiving antenna) radio waves. Data modulation is the systematic variation of some properties of the carrier signal such as amplitude, phase, or frequency according to the message signal. There are several reasons for modulating a message using a carrier: a) ease of radiation, b) to reduce noise and interference, and c) for transmission of several messages over a single channel. Besides these, other functions of a transmitter are mixing, filtering and amplification [refer to Fig. 2(a)].

An ideal mixer produces an output consisting of the sum and difference frequencies of its two input signals (one signal from the modulated signal and the other from the local oscillator). In the transmitter, filter after the mixer filter out (will not allow) the lower frequency components of the two frequencies signals also known as frequency up-conversion. As we know, the higher the power of the signal, farther destinations it can reach. The signal is amplified using a power amplifier before sending it out to the channel from the transmitting antenna. The channel is the medium through which the transmitted data reaches the destination or receiver.

When the transmitted data passes through the channel, other unwanted effects also come into picture. For instance, it picks up noise from the surrounding area and due to refelection and refraction of the signal from vaious obstacles on the way of the signal, the transmitted signal from the transmitter will be received at different times in different versions at the receiver, which is also known as multipath. Sometimes the signal from the transmitter could be completely blocked by the obstacles or black out. The duty of the receiver is to extract the desired message from the received signal from the receiving antenna. The receiver signal may be extremely weak, so it needs to be amplified first with the help of a low-noise noise amplifier (LNA) as illustrated in Fig. 3(a).

The use of employing LNA is to amplify the desired signal and not amplify the noise component of the signal. If we use a power amplifier in the receiver, both the noise and signal will be amplified equally. We don't want this to happen, since noise is an unwanted component of the signal. The filter next to LNA also filters out the noisy components of the received signal. Then the signal is passed through the mixer, which will give us two frequencies of the signal as described before in the transmitter. But the filter after the mixer will filter out (will block) the higher frequency component and this process is known as down-conversion. The main function of the receiver is to demodulate the signal to get the message sent by the transmitter. After data demodulation, we can get the message sent from the source.

UWB communications are fundamentally different from all other communication techniques because it employs extremely narrow radio frequency (RF) pulses, which are generated from the UWB pulse generator, to communicate between transmitters and receivers. Utilizing short-duration pulses as the building blocks for communications directly generates a very wide bandwidth, as we know that a very short signal in time domain produces a very wide spectrum signal in frequency domain from Fourier analysis. A significant difference between traditional radio transmissions and UWB radio transmissions is that traditional transmissions transmit information by varying the power/frequency/ and/or phase of a sinusoidal wave also known as modulation.

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UWB transmissions can transmit information by generating radio energy at specific time instants and occupying large bandwidth thus enabling a pulse-position or time-modulation. Information can also be imparted (modulated) on UWB signals (pulses) by encoding the polarity of the pulse, the amplitude of the pulse, and/or also by using orthogonal pulses. UWB pulses can be sent sporadically at relatively low pulse rates to support time/position modulation, but can also be sent at rates up to the inverse of the UWB pulse bandwidth.

Pulse-UWB systems have been demonstrated at channel pulse rates in excess of 1.3 giga-pulses per second, supporting forward error correction encoded data rates in excess of 675 Mbit/s. Such a pulse-based UWB method using bursts of pulses is the basis of the IEEE 802.15.4a draft standard and working group, which has proposed UWB as an alternative physical layer. UWB transmission is carrier-less, meaning that data is not modulated on a continuous waveform with a specific carrier frequency, as in narrowband and wideband technologies. Carrier-less transmission requires fewer RF components than carrier based transmission as shown in Fig. 2(b). For this reason UWB transceiver architecture is significantly simpler and thus cheaper to build. Fig. 2 and Fig. 3 compare the

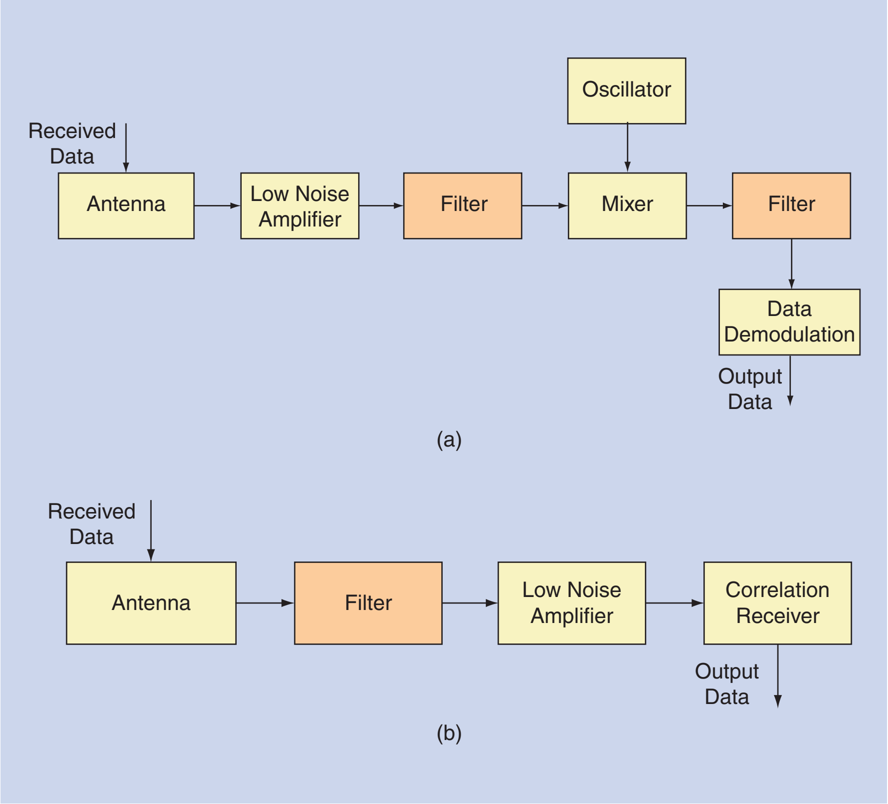

Fig. 3 Block diagram of a typical (a) narrowband and (b) UWB receiver.

block diagrams of typical narrowband and UWB transmitter and receiver, respectively. As shown, the UWB transceiver architecture is considerably less complicated than that of the narrowband transceiver. The transmission of low-powered pulses eliminates the need for a power amplifier (PA) in UWB transmitters. Also, because UWB transmission is carrier less, there is no need for mixers and local oscillators to translate the carrier frequency to the required frequency band; consequently there is no need for a carrier recovery stage at the receiver end.

In general, the analog front end of a UWB transceiver is noticeably less complicated than that of a narrowband transceiver. This simplicity makes an all-CMOS (short for complementary metal-oxide semiconductors) implementation of UWB transceivers possible, which translates to smaller form factors and lower production costs. The UWB communication systems could be pulse- or multicarrier-based communications.

In multicarrier-based UWB systems, usually orthogonal frequency-division multiplexing (OFDM) is employed. In multiband UWB systems, instead of using the whole UWB spectrum of 7.5 GHz as a single band, it can be divided into 15 subbands of 500 MHz or more. Then, we can use OFDM techniques to transmit the information using orthogonal carriers in each subband. One obvious advantage of a multiband scheme is avoid sending signals in those frequency regions where a radio communication device is present. Disadvantages of a multiband scheme is that it requires sophisticated signal processing techniques and transreceiver architecture will not be as simple as the one we have shown in Fig. 2(b) and 3(b). We will concentrate on the single band or carrier less UWB systems for easier understanding.

Advantages and disadvantages

Advantages

Future generations of communication systems will require high mobility, flexibility, and very high data-rate. In this context, broadband wireless digital communications is inevitable. As the capacity of the channel is directly related to its bandwidth, UWB technologies are advantageous for use in a number of wireless communication applications, especially in short range high data rate networking. Impulse radio, a form of UWB spread-spectrum signaling, has properties that make it a viable candidate for short-range communications in dense multipath environments. There are many advantages of UWB communication systems over conventional communication systems including

- High data rate and very low power: Due to the huge bandwidth mentioned above, the UWB systems can achieve high data rate even for low SNR in noisy environments. The battery life of UWB devices will also be more because of the very low transmitted power as well as very low power consumption due to the more simple transreceiver architecture of UWB devices.
- Very low power secure communications: The FCC has specified an Effective Isotropic Radiated Power (EIRP), which is defined as the highest signal strength measured in any direction and at any frequency from the UWB device, limit lower than noise floor level of –41.3 dBm/MHz, which is equal to 75 nW/MHz, so that UWB devices could coexist with other electronic users working within the same frequency region. The low emission and impulsive nature of UWB radio leads to enhanced security in communications. UWB provides low probability of detection and low probability of jamming since it uses very low energy per frequency band and precisely timed patterns. UWB technology is very suitable for high security applications such as military communications.

> **There are two common multiple access techniques for impulse radio UWB systems. Time hopping is one, and direct sequence is another that is popular in the UWB community.**

- Very low power operation, low-cost, and minimal hardware: Another reason that UWB devices consume less power is that UWB transmits short impulses constantly instead of transmitting modulated waves continuously, as do most narrowband systems. UWB chipsets do not require radio frequency (RF) to intermediate frequency (IF) conversion, local oscillators, mixers, and other filters, so transmitter power requirements are low.
- Multiple access communications: Due to large bandwidth, UWB-based radio multiple access communication system can accommodate many users. There are two common multiple access techniques for impulse radio UWB systems. Time hopping is one such technique. Direct sequence (DS) is another multiple access technique that is popular in the UWB community. The transmitter information symbol to be transmitted is first spread with a pseudo random (PN) sequence and then amplitude modulated with a train of short pulses. At the receiver, the received information is initially despread using the same PN sequence used for spreading.

Some researchers did an extensive study of the bit error rate (BER) performance of UWB systems in comparison with CDMA systems. CDMA is a widely accepted multiple access communication system and the two most popular methods of CDMA are: direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS). It has been observed that UWB systems have a similar performance with both DSSS and FHSS systems. UWB systems have a much cheaper implementation possibility than DSSS and FHSS systems.

- Resolvable multipath components of UWB signals: Another valuable aspect of pulse-based UWB is that the pulses are very short in space (less than 60 cm for a 500 MHz wide pulse, less than 23 cm for a 1.3 GHz bandwidth pulse), so most signal reflections do not overlap the original pulse, and thus the traditional multipath fading of narrow band signals does not exist.

Since multipath reflections of UWB signals are resolvable, there is a potential for obtaining diversity gain by combining them.

Localization of radio signals indoors is difficult because of the presence of shadowing and multipath reflections from walls and objects. The fine time resolution required by UWB signals makes them ideal for high resolution positioning applications.

Disadvantages

Such systems have some inherent problems due to the huge spectrum (7.5 GHz bandwidth from 3.1–10.6 GHz) allotted by the FCC. Every technology has many challenges and difficulties. The first one is obviously the regulatory issues imposed by the FCC that UWB systems should not interfere with other existing radio systems like IEEE 802.11a devices. Some of the disadvantages of this promising technology includes:

- *Interference:* Interference is one of the major challenges in the design of UWB communication systems. Since UWB communication devices occupy a large frequency spectrum, interference mitigation or avoidance with coexisting users is one of the key issues of UWB technology. Existing electronic devices include current IEEE 802.11a WLAN devices (working at 5.150–5.825 GHz) and 2.4 GHz industrial, scientific, and medical (ISM) band devices, that are used by wireless personal area networks like Bluetooth.
- *Complex signal processing:* For narrowband systems that use carrier frequency, frequency-division multiplexing is very straightforward and the development of a narrowband device needs to consider the frequency bands directly affecting it and minimizing interference to out-of-band systems by emission control techniques like filtering and wave shaping. For carrier-less transmission and reception, every narrowband signal in the vicinity is a potential interferer and also every other carrier-less system. So any carrier-less system has to rely on relatively complex and sophisticated signal processing techniques to recover data from the noisy environment.
- *Bit synchronization time:* Since pulses with picoseconds precision are used in UWB, the time for a transmitter and receiver to achieve bit synchronization can be as high as a few milliseconds. So, the channel acquisition time is very high, which can significantly affect performance, especially for intermittent communications.

Applications

There are myriad of applications for UWB technology. Some, like UWB radars, have been in use for many years while others are new potential applications viz., UWB sensor networks, UWB RFID, and UWB positioning systems. Some of these applications involve:

1) transferring large amounts of data in short-range for home or office networking

2) short range voice, data, and video applications (a television set and computer system without wires and transferring data at a higher rate than wired connections)

3) military communications on board helicopters and aircrafts that would otherwise have too many interfering multipath components

4) anticollision vehicular radars

5) through wall imaging used for rescue, security, and medical applications

6) reducing inventory time and increasing efficiency in several ways (attaching UWB RFID tags to each item inside a box or crate, a scan could count and identify what's in the box without it being opened)

7) accurately locating a person or object within one inch of its location through any structure; Global positioning system (GPS) technology is only accurate up to 1 m and does not work inside buildings; GPS is expensive but UWB will be low cost

8) localization in search and rescue efforts, tracking of livestock and pets

9) detecting land mines

10) assessing enemy locations and tracking troops.

Read more about it

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Rakhesh Singh Kshetrimayum (krs@iitg.ernet.in) received his B. Tech. degree in electrical engineering from the Indian Institute of Technology (IIT) Bombay, India and his Ph.D. degree in electrical and electronic engineering from the Nanyang Technological University, Singapore. Since September 2005, he has been a faculty member at the Department of Electronics and Communication Engineering, IIT Guwahati, India. He is the founder and editor-in-chief of the *International Journal of Ultra Wideband Communications and Systems*. He is serving as a technical program co-chair for the IEEE and IFIP International Conference on Wireless and Optical Communications Networks, 2009.

Errata

In the November/December 2008 issue of *IEEE Potentials* there was an error in an equation contained in the article, "How many neurons must one man have, before you call him a man?" In Fig. 4, the equation:

$$T = P^S - 1$$

where T = total number of states in the population, S = number of states per neuron, and P = total number of neurons in the population.

The equation should be

$$T = S^P - 1.$$

For S = 32 and P = 2, the value for T in Case 1 in Fig. 4 is not 4.2×10^9 but 1,023. For S = 13 and P = 2 in Case 2, T is not 8,191 but 168.

This minor error does not affect the conclusions of the manuscript.