Ultrawideband Communications - An Overview

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Abstract

This paper presents an overview of ultrawideband (UWB) communications systems, i.e., systems with very large relative and/or absolute bandwidth. The large bandwidth and low power spectral density mandated for UWB systems allows to use them as overlay over existing (legacy) systems, i.e., they can be used in the same frequency range as existing systems without causing undue interference. We also describe the most common types of UWB systems, including time-hopping impulse radio, frequency hopping, and multiband-OFDM. We furthermore discuss interference aspects and the peculiarities of UWB propagation channels.

I. Introduction - large absolute and relative bandwidth

Ultrawideband (UWB) communications systems are commonly defined as systems with large absolute and/or large relative bandwidth. Such a large bandwidth offers specific advantages with respect to signal robustness, information transfer speed, and/or implementation simplicity, but leads also to fundamental differences from conventional, narrowband, systems. Though the history of UWB reaches back to the 19th century (e.g., Hertz's experiments using spark-gap transmitters), it was only in the last decade that a confluence of technological and political/economic circumstances enabled widespread commercial use of UWB systems. Consequently, research in UWB has grown dramatically recently. The current paper gives a very brief synopsis of the state of the art; more details and additional references can be found in [1], [2], [3], [4].

The interest in UWB systems stems mainly from the fact that they can be used as an overlay to existing systems. In other words, they do not require new spectrum, but can be operated in parallel to existing legacy systems. This can be understood from the following simple picture (Fig. 1): the transmit power of any system can be (approximately) expressed as the product of power spectral density (PSD) and bandwidth. A large (absolute) bandwidth thus enables a system with reasonable transmit power (say, on the order of 1 mW or less) to exhibit an extremely low power spectral density. A victim legacy (narrowband) receiver will only see the noise power within its own system bandwidth, i.e., a small part of the total transmit power. This implies that the interference to legacy (narrowband) systems is very small.

The large absolute bandwidth allows a transmission of extremely high data rates (>100 Mbit/s), though the transmission can be achieved only over relatively short distances (< 10 m) because only very low power is available for each bit. Alternatively, low-data-rate communication (e.g., <1 Mbit/s) is possible over much larger distances by exploiting the large spreading factor (ratio between used bandwidth and data rate). Besides enabling large data rates or spreading factors, a large absolute bandwidth has also a number of other important benefits:

- it enables very fine range resolution in radar and geolocation.[5]
- it creates a high resilience to fading, by introducing a high degree of frequency diversity [6], and a decrease in the fading depth of resolvable multipath components [7], yielding a significant advantages over conventional narrowband systems.

A large *relative* bandwidth also offers advantages to UWB systems, in particular a greater robustness of the signals. Intuitively, the different frequency components of the signal "see" different propagation conditions. Thus, there is a high probability that at least some of them can penetrate obstacles or otherwise make their way from transmitter to receiver. Consequently, the signal is more robust to shadowing effects.

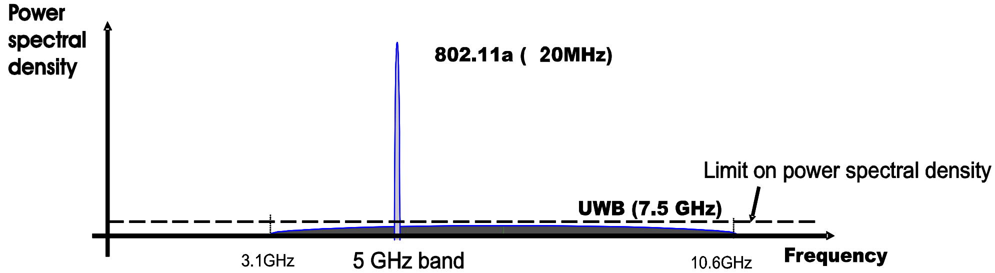

Fig. 1. Interference between a UWB system and a narrowband (IEEE 802.11a) local area network.

II. Frequency regulations and interference aspects

In order to ensure that UWB systems do not interfere significantly with legacy systems, the frequency regulators have defined spectral masks that have to be fulfilled by all UWB transmitters. In the US, the frequency masks depend on the environment in which the devices are operated. For indoor communications, a power spectral density of -41.3 dBm/MHz is allowed in the frequency band between 3.1 and 10.6 GHz. Outside of that band, no intentional emissions are allowed, and the admissible power spectral density for spurious emissions provides special protection for GPS and cellular services. Lower frequencies are admissible for wall imaging systems and ground-penetrating radar. Other countries have similar regulations, though they might foresee additional protection for frequency bands below 6 GHz, either by completely prohibiting transmission, or requiring "detect and avoid" (i.e., a UWB transmitter must detect whether a possible victim receiver is in the vicinity; in this case, the UWB transmitter must cease transmission)

There has been considerable concern whether the protection of legacy systems by the frequency masks is sufficient. The FCC established the mask by making the limits on $deliberate$ UWB emissions identical to limits on $involuntary$ (spurious) emissions from any electric device. Still, there is a concern that widespread use of UWB devices might lead to high aggregate interference that could negatively impact operation of legacy systems. Recent work indicates that the interferer closest to the victim device dominates the overall performance [8].

III. Propagation channels

Ultrawideband propagation channels differ from narrowband propagation channels in several key respects (see [9], [10], [11] for more discussion and extensive references. Again, it is useful to distinguish between channels with large relative, and those with large absolute bandwidth. In channels with large relative BW, we find that

- each multipath component (MPC) suffers from distortion, so that the channel impulse response cannot be written as a sum of weighted and delayed delta pulses
- the WSSUS (wide-sense stationary uncorrelated scattering) assumption is not valid anymore
- the pathloss and shadowing becomes a function of the frequency at which it is considered
- similarly, angular spreading can become frequency dependent

Related to those properties are also challenges for the design of antennas: building antennas with bandwidth larger than 10 % is challenging [12]; furthermore, the shape of the antenna pattern changes with frequency, which increases the peak EIRP and makes compensation of antenna gains in beamforming designs more difficult.

Channels with large absolute bandwidth show the following key characteristics

- the amplitude fading statistics of resolvable delay bins are not necessarily Rayleigh
- impulse responses can become "sparse", i.e., resolvable MPCs are separated (in the delay domain) by delay regions that do not contain any significant energy contribution.
- impulse responses show a "soft onset", i.e., the main energy is not arriving (even on average) at the smallest delay.

Most of these effects are reflected in the IEEE 802.15.4a standardized channel model [13], which is the currently most detailed and accurate channel model. The earlier IEEE 802.15.3a model [14] is also still in widespread use.

IV. Modulation and multiple access

Signals with extremely large bandwidth can be created by a variety of methods. Most prominent among them is time-hopping impulse radio (TH-IR), a technique that was invented in the pioneering work of Win and Scholtz [15], [16], [17]; by operating with short pulses, it enables very simple and cost-effective transmitter structures. Other notable techniques include frequency-hopping, OFDM, direct-sequence CDMA, and combinations of the above techniques.

A. Impulse radio

Communication by transmitting short pulses has many attractive properties, like enabling extremely simple transmitters. However, an important problem that plagued such impulse radios for a long time was the spectral efficiency: it seemed that only a small number of users could be "on air" simultaneously. Consider the case where one pulse per symbol is transmitted. Since the UWB transceivers are unsynchronized, so-called “catastrophic collisions” can occur, where pulses from several transmitters arrive at the receiver simultaneously. The signal-to-interference ratio then becomes very bad, leading to a high bit error probability (BER). Time-hopping impulse radio (TH-IR) [17] avoids this problem by representing each data bit by $several$ short pulses. The transmitted pulse sequence is different for each user, according to a so-called time-hopping (TH) code. Thus, even if one pulse within a symbol collides with a signal component from another user, other pulses in the sequence will not, see Figure 2. In other words, collisions can still occur, but they are not catastrophic anymore. TH-IR achieves a multiple-access interference suppression that is equal to the number of pulses in the system. The possible positions of the pulses within a symbol follow certain rules: the symbol duration is subdivided into N_f “frames” of equal length. Within each frame the pulse can occupy an almost arbitrary position (determined by the time-hopping code). Typically, the frame is subdivided into “chips”, whose length is equal

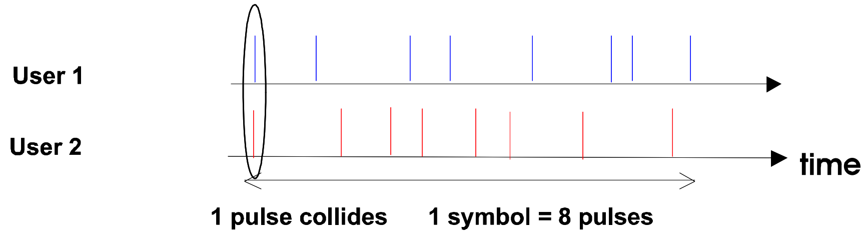

Fig. 2. Principle of time-hopping impulse radio for the suppression of catastrophic collisions.

to a pulse duration. The (digital) time-hopping code now determines which of the possible positions the pulse actually occupies. More detailed aspects of multiple access and narrowband interference can be found in [18], [19], [20], [21].

When all the transmitted pulses have the same polarity, as shown in Figure 2, the signal spectrum shows a number of lines. This can be eliminated by choosing the polarity of the transmit pulses in a pseudorandom way; a process that is then undone at the receiver [22], [23]) .The modulation of this sequence of pulses can be pulse-position modulation, or pulse amplitude modulation (PAM) such as BPSK (binary phase shift keying) [24].

Due to the multipath propagation, a coherent receiver has to employ a Rake receiver, to collect all available energy. A Rake can separately receive different MPCs (e.g., with one correlator for each MPC) and add them coherently.. Since the number of fingers in practical Rake receivers is limited, only a subset of the available MPCs can be received in most practical situations [25], [26]. If PPM is used as modulation format, noncoherent reception (energy detection) is a possible alternative receiver - it is much simpler, but suffers from a significant performance loss compared to coherent receivers.

An alternative modulation scheme is transmitted-reference (TR), which first transmits a reference pulse of known polarity (or position), followed by a data pulse whose polarity (position) is determined by the information bit [27], [28], [29], [30], [31]. At the receiver, we then only have to multiply the received signal with a delayed version of itself, resulting in an extremely simple receiver structure. For heterogenous networks, a hybrid modulation scheme that enables simultaneous quasi-optimum reception by coherent and transmitted-reference receivers was introduced in [32].

As an alternative to TH-IR, direct-sequence CDMA [33], a technique well-known from cellular radio, can be used. A large bandwidth is obtained by employing a very high chiprate.

B. *OFDM and frequency hopping*

OFDM (orthogonal frequency division multiplexing) transmits information in parallel on a large number of subcarriers [24] The modulation process can be done in analogue (using a number of local oscillators, or - preferably - digitally, by performing an Inverse Fast Fourier Transform (IFFT) on the data. OFDM is a well-established technique in wireless communications; however, its application in UWB is challenging, because it requires operating the FFT at a clock speed of at least 500 MHz. For UWB systems with larger bandwidths, it is thus usually combined with slow frequency hopping.

Fast frequency hopping changes the carrier frequency several times during the transmission of one symbol; in other words, the transmission of each separate symbol is spread over a large bandwidth. *Slow frequency hopping* transmits one or several symbols on each frequency. Frequency hopping has a multiple access capability. Different users are distinguished by different hopping sequences, so that they transmit on different frequencies at any given time.

Frequency hopping can be used either as a multiple access scheme of its own, or it can be combined with other schemes. In the latter case, we divide the available frequency band into subbands, and transmit (e.g., with OFDM) in different subbands at different times [34]. This approach simplifies implementation, as the sampling and A/D conversion now has to be done only with a rate corresponding to the width of the subband instead of the full bandwidth.

V. Applications and system standards

One of the most important application areas of UWB is sensor networks, where data rates are low ($<$ 1 Mbit/s), but restrictions on size and energy consumption are very stringent. Low data rate systems are also envisaged for emergency communications, e.g., between people within a collapsed building and rescue workers. A standard for such systems was established by the IEEE group IEEE 802.15.4a [35]. The standard is based on TH-IR, and enables precise geolocation of the transceivers.

Another important application area is data transmission with a very high rate (more than 100 Mbit/s). As discussed in the introduction, the range of such systems is limited to some 10 m. This set of data rates and ranges is used especially for consumer electronics and personal computing applications like transmission of HDTV (high definition television) streams from a set-top box or a DVD player to the TV requires high data rates and wireless USB (universal serial bus). A standard for such systems was established in [36], based on a combination of OFDM with frequency hopping over three 500-MHz bands. A further increase in data rate for wireless HDMI is currently being aimed at by UWB systems operating in the 60 GHz band, where higher transmit power spectral density is allowed.

Going beyond communications, UWB radars have developed into an important market niche, used mainly for two purposes: (i) high-performance radars that have smaller "dead zones", and (ii) radars for close ranges that can penetrate walls and ground. The second application is useful for surveillance, urban warfare, and landmine detection. Most of the applications in this area are classified, as they serve military or law-enforcement purposes. A commercial application is the vehicular collision avoidance radar. Such a radar typically operates in the microwave range ($24-29$, or around 60 GHz). Another promising application is biological imaging, e.g., for cancer detection.

Like many new technologies, UWB was first overhyped, and then prematurely declared dead when it did not live up to the hype. But by now it has become widely accepted that UWB communications is a very useful technique for a number of applications that are important but limited in scope. Further developments of the underlying science will open up additional future applications.

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