Principle and Motivations of UWB Technology for High Data Rate WPAN Applications

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Abstract

A new data transmission technique is about to create a revolution in the field of wireless personal area networks. This new method, called Ultra Wideband, is based on the transmission of data through the communication channel below the noise floor. The objective of this article is to present this new data transmission method, outline the main advantages and introduce the future applications.

1. Introduction

Today, the home entertainment networking market is expanding fast. Interoperability of consumer applications like digital video disk (DVD) players, digital cable, satellite TV, broadband internet access, etc., have created a need for reliable short-range, (several centimetres to about ten meters) high-throughput (more than 100Mbits/s) data links. In addition, portability is one of the key features of a lot of new consumer applications. This means that power saving has become an essential requirement. The cost is an increasingly important consideration for those potentially high volume consumer applications too. The Ultra Wideband radio link offers potential for addressing all of these issues. This makes this “new” transmission technique a likely candidate for network applications like WLAN (Wireless Local Area Network), WPAN (Wireless Personal Area Network) or WBAN (Wireless Body Area Network). Ultra Wideband is not, in fact, a new concept. It was introduced in the sixties and first used to study the transient effects of microwave networks. Today, research aims to extend its use to wireless data transmission for consumer applications.

2. Definition and Principle

UWB signals are usually defined as signals having an instantaneous bandwidth of, at least, 20% of the centre frequency or at least 500 MHz (where the bandwidth is generally defined by the difference of the 10 dB lower points of the signal spectrum). To generate such signals, data symbols are carried by a set of very short pulses. UWB uses similar spread spectrum technique concepts to those found in Code Division Multiple Access. Hence, some UWB implementations are actually more or less ultra-fast DS-SS transceivers.

A more general modulation scheme consists in transmitting spaced pulses trains. An illustration of a uniformly spaced Gaussian monocycle (0.5ns pulse width) pulse train and the corresponding spectrum is shown in Figure 1. A pseudo central frequency of 2 GHz can be identified.

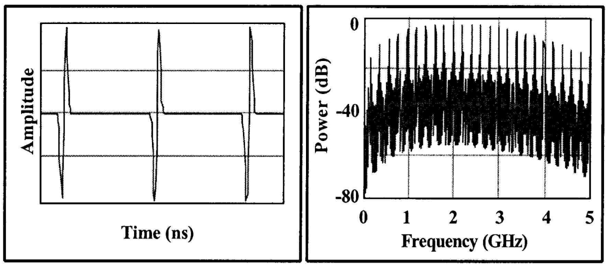


Figure 1: Gaussian Monocycle and associated spectrum

2.1. Data transmission principle

In order to transmit information, it is necessary to modulate the pulse train. One classical modulation used in UWB is Pulse Position Modulation (PPM): the temporal positions of the pulses are varied according to the information data. For example a digital zero can be coded by transmitting the pulse about 100ps earlier than a reference position and a digital one by transmitting the monocycle 100ps later, as shown in Figure *2*. More generally, many positions can be used to increase the number of symbols. If there are n positions, the modulation is called n-PPM.

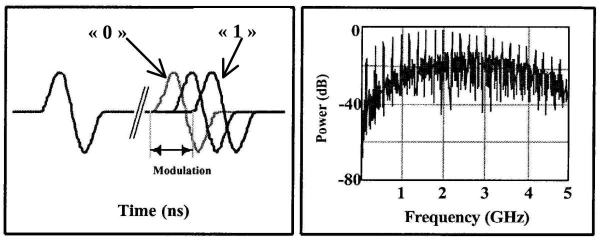


Figure 2: Pulse position modulation

The periodicity of the pulse repetition, called the Pulse Repetition Period (PRP) makes appear energy spikes in the spectrum. These spikes might interfere with conventional radio systems at short ranges. It should be underlined that this position modulation could enable the RF energy to be more uniformly distributed across the band. In other words, for a sufficient modulation order, the modulation may slightly "smooth" the spectrum of the signal. However, in many cases

this is not sufficient and it is necessary to add a pseudo random sequence of delays to the pulse train to achieve a reliable level of spectrum smoothing. This technique, called Time Hopping (TH), is illustrated in Figure 3.
In addition, it should be noted that random codes can also be used for channel multiple access, in a similar way to that of CDMA systems.

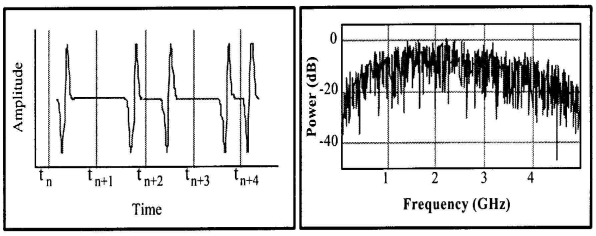


Figure 3: Monocycle dithering and associated spectrum

2.2. Demodulation principle

Having presented the properties of the UWB signal, we shall next turn our attention to the optimal receiving system.
As seen previously, data are transmitted by modulating the pulse waveform. The first operation to be carried out is matched filtering of the waveform in order to introduce a first level of discrimination. To do this, the incoming signal is multiplied with a waveform template and the result is then integrated, as seen in Figure 4.This correlation operation between the received signal and a local pattern (usually a local image of the received pulse waveform) has to be performed for each possible pulse position. Then, the correlation results are sent to the baseband for further processing.
It is interesting to note in this figure that a small offset in the timing base of the template can lead to very different correlation results and, consequently, a degradation in the demodulator performance. The very nature of UWB signals and the way they are processed makes them highly sensitive to clock imperfections.

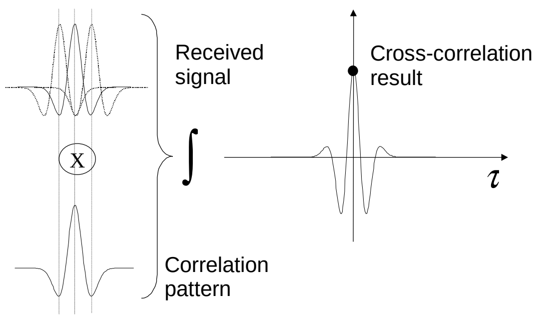


Figure 4 : Correlation with a template

Given the shape of this cross-correlation function (and in particular the two negative secondary lobes), R. Scholtz [1] proposed a binary pulse position modulation scheme based on a symmetric correlation pattern (see Figure 5). The objective is to use the same correlation pattern to deal with two consecutive pulse positions. In this scheme, advantage is taken of the sharp edges of the cross-correlation function to reduce the time between two PPM positions. Still, this method also depends on the quality of the receiver clock, which has to be good.

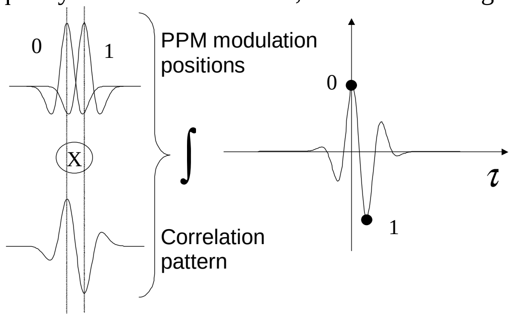


Figure5: Correlation pattern proposed by R. Scholtz

As UWB emissions are generally low power, the received signal can be buried in the ambient noise (intentional as well as unintentional electromagnetic radiation). To overcome this problem, the receiver has to sum numerous correlator samples from subsequent pulses so that the noise, which has a nil average, will be considerably reduced. This process, called "coherent integration", allows the transmitted signals to be retrieved.

3. Motivations

Commonly used modulation schemes for data transmissions via radio link (Hiperlan, 802.11) still rely on a traditional phase and/or amplitude modulated carrier based signal. For these techniques, the bandwidth is limited and the signal to noise ratio is quite good. If we want to increase the data rate, given the Shannon formula:

$$(1) \quad C = W \log_2(1 + SNR)$$

there are two possibilities: we can increase either the signal to noise ratio or the bandwidth. As the channel capacity increases linearly with the bandwidth and only logarithmically with the signal to noise ratio. For low power high data rate applications, it is preferable to increase the bandwidth rather than the signal to noise ratio. The main idea of UWB is to transmit data symbols below the allowed unintentional emission "noise" level, but on a bandwidth which extends over several gigahertz. This concept is based on the radiation of very short pulses and consequently the associated spectrum extends over a very wide frequency range.
An illustration of formula1 is given in figure 6 where UWB is compared to IEEE 802.11, one can see that UWB is very well suited for very high throughput communications (hundreds of Mbps), while the range has rather to be kept below about 10 meters. Moreover, for communication issues, the UWB concept has several advantages:

- Companies do not want to pay for new spectrum licenses. And there is no such large frequency available, anyway. This is why UWB transmissions focus on respecting the FCC spectrum mask, normally used to regulate unintentional radiation from consumer every-day-life devices such as TV's, hair dryers, etc. In addition, this allows to reuse allocated spectrum resources by hiding the average signal under the noise floor.

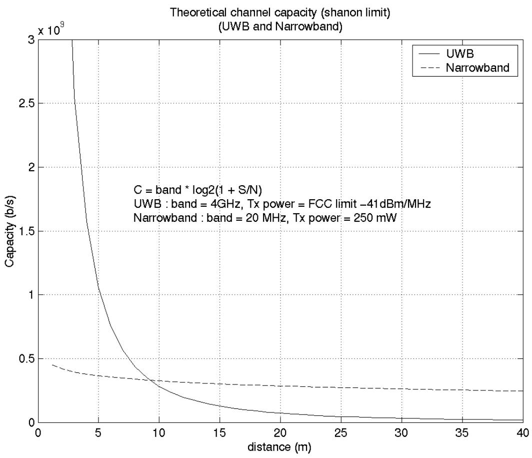


Figure 6: Theoretical channel capacity(Shannon limit) for UWB and narrowband

- Short pulses suffer less from "self interference" (fading and inter-pulse interference) than continuous transmission of a modulated sine wave do thanks to their short temporal spreading, leading to good -auto-correlation properties. This is why the UWB based system is an excellent candidate for high density of multipath channels such as indoor environments. The receiver can resolve all echoes and exploit the whole multipath energy spreading.
- Short pulses naturally spread energy among a large frequency range.
- The transmitted energy is fully contained in the data symbol (no carrier), which optimises the power consumption and makes it a good candidate for portable applications.
- The temporal discontinuity which can be introduced between two consecutive pulses allows an extra level of modulation: pulse position modulation.
- Low probability of detection and interception due to the spread of energy over a wide frequency range with a very low spectral power density.

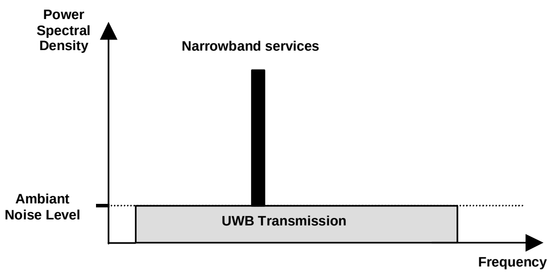


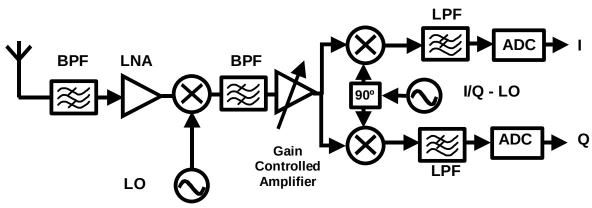
Figure 7: comparison of UWB transmission with a classical system

- High processing gain: like in most spread spectrum systems, processing gain is an important characteristic in a UWB system. The processing gain is split in two parts and can be expressed as:

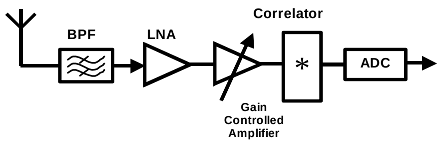
$$(2) \quad PG = 10.\log\left(\frac{1}{duty\ cycle}\right) + 10.\log(N_{ci})$$

where N_{ci} is the number of coherent integrations, which corresponds to the number of pulses repeatedly transmitted for one data symbol. For example, for a duty cycle of 1% and ten coherent integrations the total PG is about 30 dB. This represents a considerable gain compared with many other communication systems. For the UMTS cellular system the maximum processing gain is 25 dB and the associated data rate is 12.2 kbps.

- Low complexity: in its simplest form, RF and analogue circuitry is reduced to a wideband low noise amplifier, a correlator and an analog to digital converter. There is no need for heterodyne architecture, which will result in a substantial reduction of the transceiver area as well as the power, and could ultimately be integrated with low cost CMOS technology. A comparison of digital heterodyne receiver and UWB receiver architectures is shown in Figure 8. It illustrates that UWB technology may be implemented as a simple integrated circuit with very few off-chip components.



a) Complex narrowband receiver



b) UWB receiver

Figure 8: Comparison between a complex narrowband receiver and a UWB receiver

4. Challenges

This technology seems to be very promising, but what is the truth behind such promises? Many aspects are still under investigation:

- How can the different characteristics (modulation schemes, pulse repetition period, pulse shape, pulse dithering, channel code, channel access, etc.) of the UWB signal be precisely defined in order to optimise its capacity ?

- Which process technology should be used ? Owing to the UWB frequency band, SiGe and AsGa seem to be likely candidates today, but CMOS is ideal for mass market applications.
- Synchronization plays a crucial role in the reception and decoding of information. What is the extra complexity introduced by this function compared to other systems ?
- What is the impact of narrowband users on the UWB system ?
- How can multi-user detection be managed efficiently ?

5. Standardization aspects

In February 2002, the FCC approved the use of UWB technology by amending part 15 of the communication rules. This section outlines recommendations for unintentional emissions of consumer devices (like TV, computers, hair dryers, etc.). The amendment extended rules to intentional emissions such as UWB data transmission.
Still, the spectrum masks (see Figure 9) imposed by this rule had to take into account stricter considerations in order to prevent sensitive frequency bands such as navigation systems like GPS from possible interference with UWB devices. It can be noted that the maximum authorised level is -41.3 dBm/MHz or 75nW/MHz, so for an allocated bandwidth of 7.5 GHz the maximum transmitted power is –2.5dBm. This level is quite low compared to the transmitted power of other WLAN systems which is between 10 to 23dBm for indoor applications.

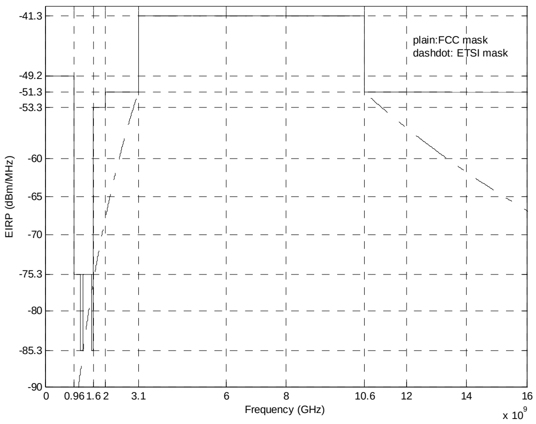


Figure 9: Spectrum mask for UWB emissions

In Europe, the ETSI ERM-TG31A (indoor UWB data transmission) and TG31B (UWB radar) task groups are working to define European rules for UWB emissions.
In the USA, the IEEE 802.15 body, acting for WPANs, has formed a study group (SG3a), which is at work to start defining a WPAN standard dedicated to UWB high data rate transmission. The group has just started in 2002, but, while defining the physical layer (PHY), has also the mission to adopt the existing draft standard for MAC. This draft MAC standard was primarily intended for 2.4GHz WPANs (IEEE 802.15.3) and did not take into account the specificities of UWB. The SG802.15.3a functional requirement defines a number of applications which are aimed by the future standard:

- Video and audio distribution: high speed Digital Video transfer (e.g camcoder to TV), cable replacement, HD MPEG2, MPEG4 between DVD/gateways and multiple HD TV, home theatre, PC to LCD projectors, Interactive video games.
- High speed data transfer: multimedia digital content wireless collector (e.g. kiosk for still images), MP3 players, personal home storage, printer/scanner connection.

The anticipated data rate is ranging from 110 Mbps (10m range), to 200 Mbps (4m range), to up to 400Mbps at degraded conditions (range, BER).

6. Discussion

It should be underlined that the introduction of UWB technology is a major subject of controversy. The fact that UWB radio spectrum can extend over licensed frequency bands frightens companies that have paid for licenses. They do not want their communication systems to be disturbed by such emissions. In Europe, cellular telephony lobbying has a strong effect on regulation issues. In the United States, the GPS frequency band, in particular, has been strongly protected against UWB signals. Other important frequency bands, like HIPERLAN and 802.11a, are also very concerned since they are located in the [3GHz-10GHz] band where UWB allowed transmission power is the highest. In addition, UWB is a potential competitor for high speed WLAN applications.

7. Conclusions

To begin with, UWB was seen as a likely candidate for low cost, low power consumer devices owing to the apparent simplicity of the transceiver architecture. In fact, this simplicity hides a considerable number of problems due to the wide bandwidth, the very low emitting power and the high speed of the signals to be processed. Moreover, UWB raises a lot of technical challenges in many domains, like RF design (analog design, antennas, etc.), high speed digital or demodulation and synchronisation algorithms. Channel behaviour study is also very important for modelling the UWB radio link [2].
The themes of research currently raised by UWB are so numerous that it will probably be a great source of work and innovation in R&D laboratories over the next 5 or 10 years. Whatever the future holds in store, the first solutions are about to appear on the market and tend to prove that UWB will probably reach its initial ambitious targets.

8. References

[1] S WIN (M.), SCHOLTZ (R.), Impulse Radio: How it works, IEEE COMMUNICATIONS LETTERS, VOL. 2, NO. 1, pp10-12, (January 1998).

[2] KEIGNART (J.), DANIELE (N.), Subnanosecond UWB Channel Sounding in Frequency and Temporal Domain, 2002 IEEE Conference on Ultra Wideband Systems and Technologies, proceedings, pp.25-30, (2002).