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Ultra wideband preliminaries

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1. Introduction

"*Ultra-wideband technology holds great promise for a vast array of new applications that have the potential to provide significant benefits for public safety, businesses and consumers in a variety of applications such as radar imaging of objects buried under the ground or behind walls and short-range, high-speed data transmission*"[FCC,2002]

This quote focuses the level of importance of UWB technology as its applications are various. The FCC outlined possible applications of this technology such as imaging systems, ground penetrating radar (GPR) systems, wall-imaging systems, through-wall imaging systems, medical systems, surveillance systems, vehicular radar systems and communications and measurements systems. The spectrum allocation for UWB is in the range from 1.99 GHz- 10.6 GHz, 3.1 GHz- 10.6 GHz, or below 960 MHz depending on the particular application [FCC,2002]. The global interest in this technology is huge especially in communications environment due to the potential delivery of ultra high speed data transmission, coexistence with existing electrical systems (due to the extremely low power spectrum density) with low power consumption using a low cost one-chip implementation. There are many advantages and benefits of UWB systems as shown in Table 1 over narrowband technologies. Therefore, with the approval of FCC regulations for UWB, several universities and companies have jumped into the realm of UWB research [Nokia, 2006].

Advantage	Benefit
Coexistence with current narrowband and wideband radio services	Avoids expensive licensing fees
Huge data rate	High bandwidth can support real-time high definition video streaming
Low transmit power	Provides low probability of detection and intercept.
Resistance to jamming	Reliable to hostile environments
High performance in multipath channel	Delivers higher signal strengths in adverse conditions
Simple transceiver architecture	Enables ultra-low power, smaller form factor at a reduced cost

Table 1. Advantages and benefits of UWB communication

UWB offers many advantages over narrowband technology where certain applications are involved. Improved channel capacity is one of the major advantages of UWB. The channel is the RF spectrum within which information is transferred. Shannon's capacity limit equation shows capacity increasing as a function of BW (bandwidth) faster than as a function of SNR (signal to noise ratio).

$$C = BW * \log_2(1 + SNR) \tag{1}$$

C = Channel Capacity (bits/sec)

BW = Channel Bandwidth (Hz)

SNR = Signal to noise ratio.

SNR = P/ (BW*N_0)

P = Received Signal Power (watts)

N_0 = Noise Power Spectral Density (watts/Hz)

The above Shannon's equation shows that increasing channel capacity requires a linear increase in bandwidth while similar channel capacity increases would require exponential increases in power. This is why, UWB technology is capable of transmitting very high data rates using very low power. It is important to notice that UWB can provide dramatic channel capacity only at limited range which is shown in Fig. 1. This is due mainly to the low power levels mandated by the FCC for legal UWB operation. UWB technology is most useful in short-range (less than 10 meters) high speed applications. Longer-range flexibility is better served by WLAN applications such as 802.11a, whose narrowband radio might occupy a BW of 20 MHz with a transmit power level of 100 mW. The power mask, as defined for UWB by the FCC, allows up to –41.3 dBm/MHz (75 nW). From Fig. 2, it is observed that the emitted signal power can't interfere with current signals even at short propagation distances since it appears as noise.
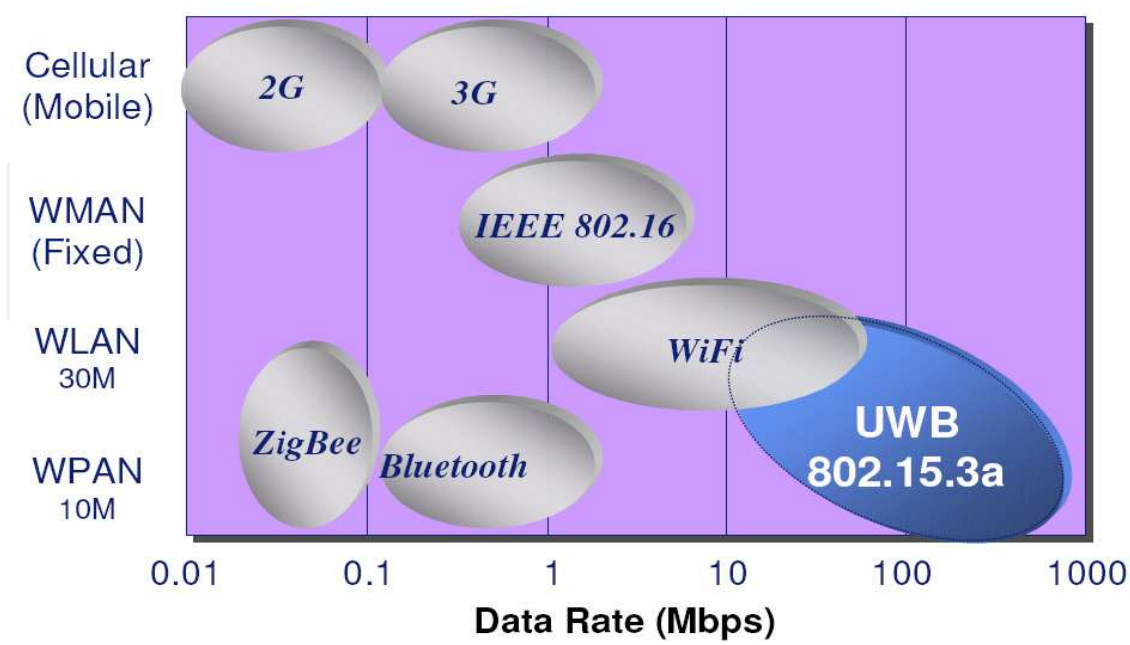

Fig. 1. Range Vs Data rate [Source WiMedia]

Fig. 3 and Fig. 4 show the typical "narrowband" and "UWB" transceiver. UWB radios can provide lower cost architectures than narrow band radios. Narrow band architectures use high quality oscillators and tuned circuits to modulate and de-modulate information. UWB transmitters, however, can directly modulate a base-band signal eliminating components and reducing requirements on tuned circuitry. On the other hand, UWB receivers may require more complex architectures and may take advantage of digital signal processing techniques. Reducing the need for high quality passively based circuits and implementing sophisticated digital signal processing techniques through integration with the low cost CMOS processes will enable radio solutions that scale in cost/performance with digital technology [Intel,2002].
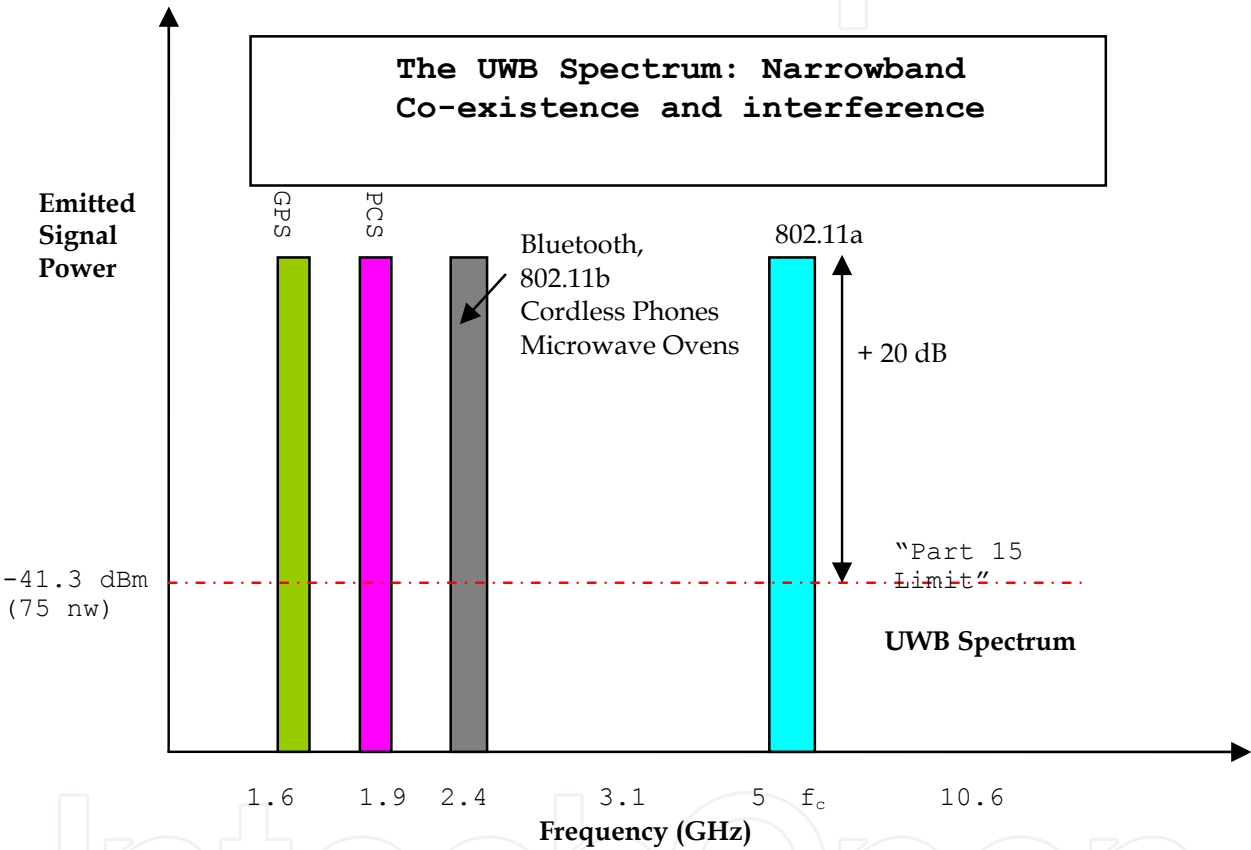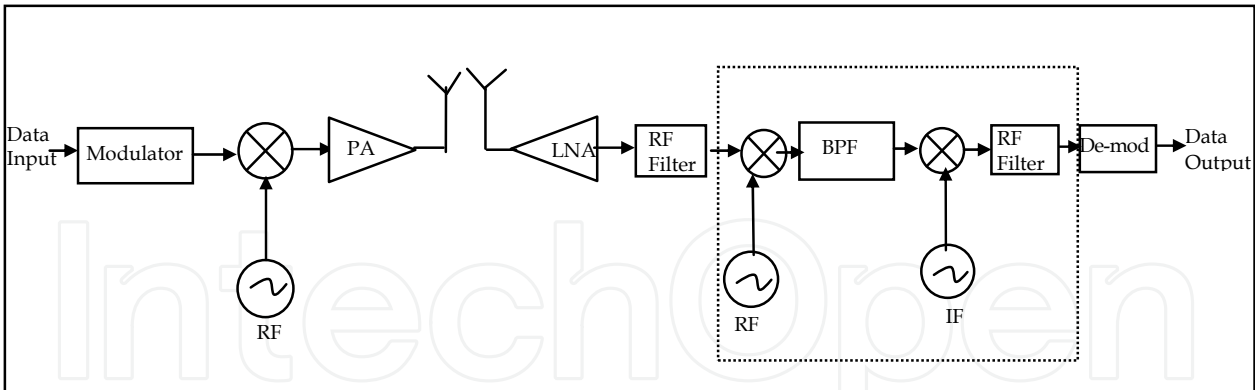
Fig. 2. Emitted signal power vs. Frequency

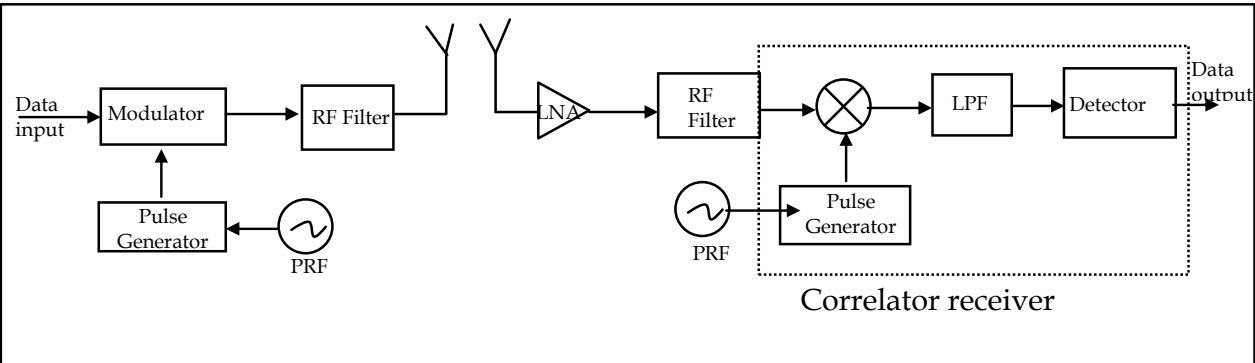Fig. 3. Typical "narrowband" Transceiver Architecture

Fig. 4. Typical "UWB "Transceiver Architecture

Another key advantage of UWB is its robustness to fading and interference. Fading can be caused when random multipath reflections are received out of phase causing a reduction in the amplitude of the original signal. The wideband nature of UWB reduces the effect of random time varying amplitude fluctuations. Short pulses prevent destructive interference from multipath that can cause fade margin in link budgets. However, another important advantage with UWB technology is that multipath components can be resolved and used to actually improve signal reception. UWB also promises more robust rejection to co-channel interference and narrowband jammers showing a greater ability to overlay spectrum presently used by narrowband solutions.

2. Background of UWB

The history of interest in UWB dates back to the 1960´s. Terms used for the concept were "nonsinusoidal," "baseband," "impulse radio," and "carrier free signals." The origin of this technology stems from work in time-domain-electromagnetics in the early 1960s which describes the transient behaviour of certain classes of microwave networks by examining their characteristic, i.e. their impulse response [Multispectral solution Inc.,2001].

Time-domain electromagnetics would have probably remained a mathematical and laboratory curiosity, however, had it not occurred that these techniques could also be applied to the measurement of wide-band radiating antenna [Ross,1968]. However, unlike a microwave circuit such as microstrip filter, in which the response to an impulsive voltage excitation could be measured in circuit, the impulse excitation of an antenna results in the

generation of an electromagnetic field that must be detected and measured remotely. The time-domain sampling oscilloscope, with an external wide-band antenna and amplifier, was used to perform this remote measurement. It became immediately obvious that one can now have the rudiments for the construction of an impulse radar or communications system [Bennet et al., 1978].

The term "UWB" was not adopted until approximately 1989. Prior to this Harmuth conducted revolutionary work in the late 1960´s [Harmuth,1968; 1984; 1979; 1977 ;1972, 1977; 1981; Harmuth et al., 1983]. In the early 1970s, hardware likes the avalanche transistor and tunnel diode detectors were constructed in attempts to detect these very short duration signals, which enabled real system development. The arrival of the sampling oscilloscope further aided in system development. During the 1970´s, evolution and research into UWB often focused towards radar systems, which needed to be enhanced with better resolution [Black,1992; Hussain, 1996; 1998; Immoreev et al.,1995]. This demand required wider bandwidth. At this time extensive research was conducted in the former Soviet Union by researchers like Astanin, and in China as well [Astanin et al., 1992]. Taylor has published some material based on research in the United States from this period [Taylor, 1995]. In 1978, Bennett and Ross wrote a summary of time-domain electromagnetics [Bennett et al., 1978]. At about this time, efforts using carrier-free radio for communication purposes were started. During the last decade, the military has begun to support initiatives for developing commercial applications. These commercial applications, and the evolution of increasingly faster digital circuits, have led to the development of inexpensive hardware. The possibility of producing low cost units, and unlicensed use, has recently boosted the interest in UWB.
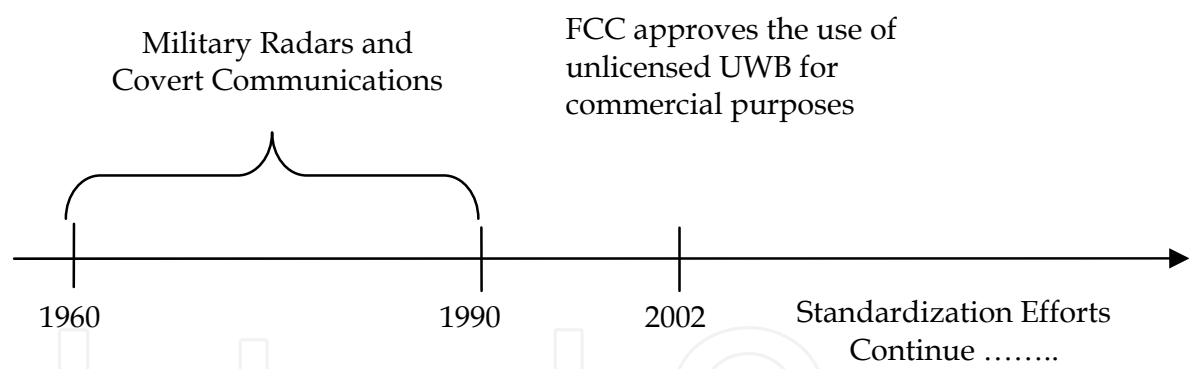

Fig. 5. UWB trend

3. UWB Characteristics

3.1 Introduction

UWB technology has been mainly used for radar-based applications [Taylor, 1995] due to wideband nature of the signal resulting in very accurate timing information. Additionally, due to recent developments, UWB technology has also been of considerable interest in communication demanding low probability of intercept (LPI) and detection (LPD), multipath immunity, high data throughput, precision ranging and localization.

Multipath propagation is one of the most significant obstacles when radio frequency (RF) techniques are used indoors. Since UWB waveforms are of such short time duration, they

are relatively immune to multipath degradation effects as observed in mobile and in-building environments. Thus, UWB has gained recent attention and has been identified as a possible solution to a wide range of RF problems. For example, in communication systems, UWB pulses can be used to provide extremely high data rate performance in multi-user network applications. Additionally, UWB applications can co-exist with narrowband services over the same [[Multispectral solution Inc.,2001]

3.2 Definition of UWB Technology

UWB signals can be defined as signals having a fractional bandwidth of at least 25% of the center frequency or those occupying 1.5 GHz or more of the spectrum. Fractional bandwidth B_f is defined as:-

$$B_f = 2\frac{f_h - f_l}{f_h + f_l} \tag{2}$$

Where, B_f = Fractional bandwidth (Hertz)

f_h = The highest -10 dB frequency point of the signal spectrum

f_l = The lowest -10 dB frequency point of the signal spectrum

UWB is a wireless technology for transmitting digital data over a wide spectrum with very low power and has the ability to carry huge amounts of data over short distances at very low power. In addition, UWB has the ability to carry signals through doors and other obstacles. Instead of traditional carrier wave modulation, UWB transmitters broadcast digital pulses that are precisely timed on a signal spread across a wide spectrum. The transmitter and receiver must be synchronized to send and receive pulses with accuracies approaching picoseconds. The basic concept is to develop, transmit and receive an extremely short duration burst of RF energy, typically a few tens of picoseconds to a few nanoseconds in duration. The UWB advantage rests in its ability to spread the signal energy across a wide bandwidth.

4. UWB spectrum issues

There are many organizations and government entities around the world that set rules and recommendations for UWB usage. The structure of international radio-communication regulatory bodies can be grouped into international, regional, and national levels. At the regional level, the Asia-Pacific Telecommunity (APT) is an international body that sets recommendations and guidelines of telecommunications in the Asia-Pacific region. The European Conference of Postal & Telecommunications Administrations (CEPT) has created a task group under the Electronic Communications Committee (ECC) to draft a proposal regarding the use of UWB for Europe. At the national level, the USA was the first country to legalize UWB for commercial use. In the UK, the regulatory body, called the Office of Communications (Ofcom), opened a consultation on UWB matters in January 2005. All the regulatory bodies set rules for protection of existing radio devices and keep UWB out of their frequency range.

4.1 FCC Regulation

The Federal Communications Commission (FCC) has the power to regulate the emission limit of Ultra-Wideband (UWB) transmissions. Due to the wideband nature of UWB emissions, it could potentially interfere with other licensed bands in the frequency domain if left unregulated. It's a fine line that the FCC must walk in order to satisfy the need for more efficient methods of utilizing the available spectrum, as represented by UWB, while not causing undue interference to those currently occupying the spectrum, as represented by those users owning licenses to certain frequency bands. In general, the FCC is interested in making the most of the available spectrum as well as trying to foster competition among different technologies. The first FCC report has come on 14th Feb., 2002. They placed restriction on the allowed UWB emission spectrums. For ground penetrating radar (GPR) they required that emissions be below 960 MHz and for UWB vehicular radar, the FCC restricted the -10dB bandwidth to 22-29 GHz. There are a number of key points to the related emission regulations (US 47 CFR Part 15(f)). To avoid inadvertent jamming of existing systems such as GPS satellite signals, the lowest band edge for UWB for communication is set at 3.1 GHz, with the highest at 10.6 GHz. Within this operational band, emission must be below –43 dBm/MHz EIRP- a limit the FCC has stated to be conservative, which is shown in Fig. 6.
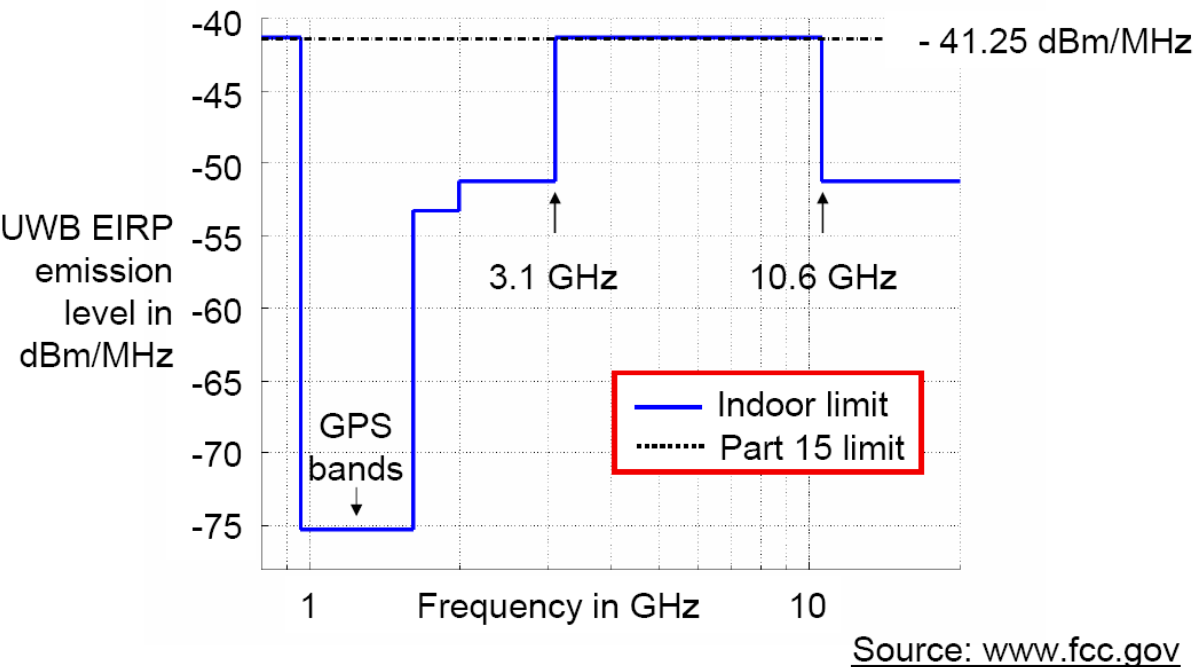

Fig. 6. UWB EIPR Emission level vs. Frequency

Following Part 15 of the FCC rules for radiated emission of unlicensed intentional radiators (such as garage door openers, cordless telephones, wireless microphones, etc., which depend on intended radio signals to perform their jobs) and unlicensed unintentional radiators (devices such as computers and TV receivers, all of which may generate radio signals as part of their operation, but aren't intended to transmit them), is divided into two classes A and B depending on the environment. Class A explains the limits related to digital devices that are marketed for use in commercial and industrial environments. The more

restrictive class B explains the limits related to devices used in residential environments, as well as, commercial and industrial environments. These emissions are defined in terms of microvolts per meter (uV/m), representing the electric field strength of the radiator as

$$P = \frac{E_o^2 \, 4\pi R^2}{\eta} \tag{3}$$

Where, $E_0 =$ Electric field strength (V/m)

$R =$ Radius of the sphere (meters)

$\eta =$ Characteristic impedance of vacuum ($377\,\Omega$)

The FCC Part 15.209 rules limit the emissions for intentional radiators to 500 uV/m measured at a distance of 3 meters in a 1MHz bandwidth for frequencies greater than 960 MHz. This corresponds to an emitted power spectral density of -41.3 dBm/MHz. Levels for class A and B under part 15 are given in Table 2.

Class	Limits (mV/m)
A	300@ 10 m
B	500@ 3 m

Table 2. Electric field strength under part 15

4.2 Interference problem and Ofcom (Office of Communication) regulation

There are many factors which affect how UWB impacts other "narrowband" systems, including spatial separation between devices, channel propagation losses, modulation techniques, the UWB Pulse Repetition Frequency (PRF), and the "narrowband" receiver antenna gain in the direction of the UWB transmitter [Intel,2001]. For example, a UWB system that sends impulses at a constant rate (PRF) with no modulation causes spikes in the frequency domain that are separated by the PRF. Adding either amplitude modulation or time dithering (i.e., slightly changing the time the impulses are transmitted) results in spreading the spectrum of the UWB emission to look more flat. As a result, the interference caused by a UWB transmitter can be viewed as a wideband interferer, and it has the effect of raising the noise floor of a "narrowband" receiver.

There are three main points to consider when looking at wideband interference [Intel, 2001] . First, if UWB complies with the Part 15 power spectral density requirements, its emissions are no worse than other devices regulated by this same standard, including computers and other electronic devices. Second, interference studies need to consider "typical usage scenarios" for the interaction between UWB and other devices. Third, FCC restrictions are only a beginning. Further coordination through standards participation may be necessary to come up with coexistence methods for operational scenarios that are important for the industry. For example, if UWB is to be used as Personal Area Network (PAN) technology in close proximity to an 802.11a Local Area Network (LAN), then the UWB system must be designed in such a manner as to peacefully coexist with the LAN. This can be achieved

through industry involvement and standards participation, as well as, by careful design. As over the designated UWB band, the existing wireless LAN operating (5.15-5.35) GHz and (5.725-5.825) GHz band, causes significant interference with UWB operations. Office of Communication, UK (Ofcom) consultants have considered the impact of regulation of UWB PAN applications under the alternative regulatory scenarios [Ofcom, 2005] – out of the 3 to 10 GHz frequency band, and UWB PAN transmissions is restricted to a lower band (3-5 GHz) and an upper band (6-10 GHz).

5. UWB signal

More popular used UWB signals are the Gaussian pulse, Gaussian doublet, Gaussian monopulse (derivative of Gaussian), Mexican hat (2nd derivative of Gaussian), Morlet (modulated Gaussian), Rayleigh, Laplacian, prolate spherical wave functions and Hermite families of waveforms [Allen et al.,2004]. The design of these signals for emission control is important. The pulse length, rise time of the leading edge of the pulse, and the pass-band of radiating antenna determine signal bandwidth and spectral shape, while the pulse shape determines its centre frequency. Gating, pulse repetition rate, modulation and selection of dithering code are other factors that determine overall waveform shape.

6. Technology basics and how it works?

UWB wireless technologies spread a signal over an incredibly wide bandwidth like spread-spectrum and orthogonal frequency-division multiplexing (OFDM) at very low power. This offers the following four benefits:-

First, due to broadband characteristics, ultra-wideband wireless technologies are better in applications that experience multipath propagation problems because the wider the bandwidth, the better the resistance to reflections and related propagation problems.

Second, with wideband wireless, many signals can be placed on top of one another, creating a form of multiplexing.

Third, wideband techniques produce signals that seldom interfere with other signals in the same spectrum due to their low power which makes them appear more like noise than as interfering signals.

Fourth, communication is secure because it's so hard to detect (low probability of intercept) and recover.

Some initial concern was raised about potential electromagnetic-interference problems generated by UWB. But most experts now agree it's not a problem. Impulse UWB is generally called time modulated or TM-UWB. This uses extremely short pulses (less than one nanosecond) with a variable pulse-to-pulse interval ie. pulse position modulation (PPM). The interval variation is measured to produce information flow across the link, including the required information plus a channel code. A single bit of information may be spread over multiple pulse pairs and coherently added in the receiver. Since TM-UWB is based on accurate timing, it is well suited to both communications and distance determination.

In direct-sequence (DS) UWB, the data to be transmitted is modulated with a signature waveform. The Gaussian pulse is first modified using unique chips which are defined as signature waveform. Modulation is either phase-shift keying (PSK) or PPM. DS-UWB

transmitters are super simple and use very low power, but the receiver and its complex correlation recovery circuits are somewhat more of a challenge.

The basic transmitted CDMA waveform of user k is given by

$$x_k(t) = \sum_{j=0}^{N-1} C_j^k w(t - jT_c) \qquad (4)$$

Where, $w(t)$ represents the transmitted monocycle and C_j^k denotes jth spreading chip of the pseudo-random noise (PN) Sequence. N is the number of pulses of the PN sequences to be used for each user.

The transmission signal format is shown in Fig. 7. The encoded data of each user are considered as a data symbol, which is multiplied by the transmitted CDMA code.
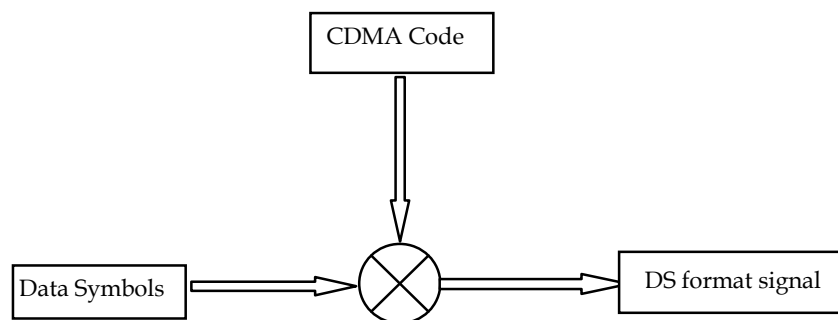
Fig. 7. Transmission signal format

Let, T_f be the symbol period and T_c be the chip period such that $T_f = NT_c$. Hence, a typical DS format of the kth impulse radio transmitter output signal is given by

$$S_k(t) = \sqrt{p_k} \sum_m d_m^k\, x_k(t - mT_f) \qquad \textbf{(5)}$$

Where d_m^k represents the data symbols and p_k is the transmitted power corresponding to the kth user. It is important to note that even an ideal channel and antenna system modify the shape of the transmitted monocycle $w(t)$ to $w_{rec}(t)$ at the output of the receiving antenna, where $w_{rec}(t)$ is the derivatives of a Gaussian function.

MB-OFDM divides the UWB spectrum into multiple 528-MHz wide bands, each 528MHz band comprises 128 carriers modulated using QPSK on OFDM tones [Batra et al., 2004]. The composite signal occupies the 528MHz band for approximately 300ns before switching to another band and is used in group of three. The group in lower band ranging from 3.168 to 4.952 GHz, make up the initial spectrum to be used, mainly because it's relatively easy these days to make all-CMOS radio ICs in this space. The centre frequencies for these three 528-MHz bands are shown in Fig. 8.The main difference between MB-OFDM and a traditional

OFDM system is that the data transmission is not done continually on all sub-bands. Instead, it is time-multiplexed between the different sub-bands.
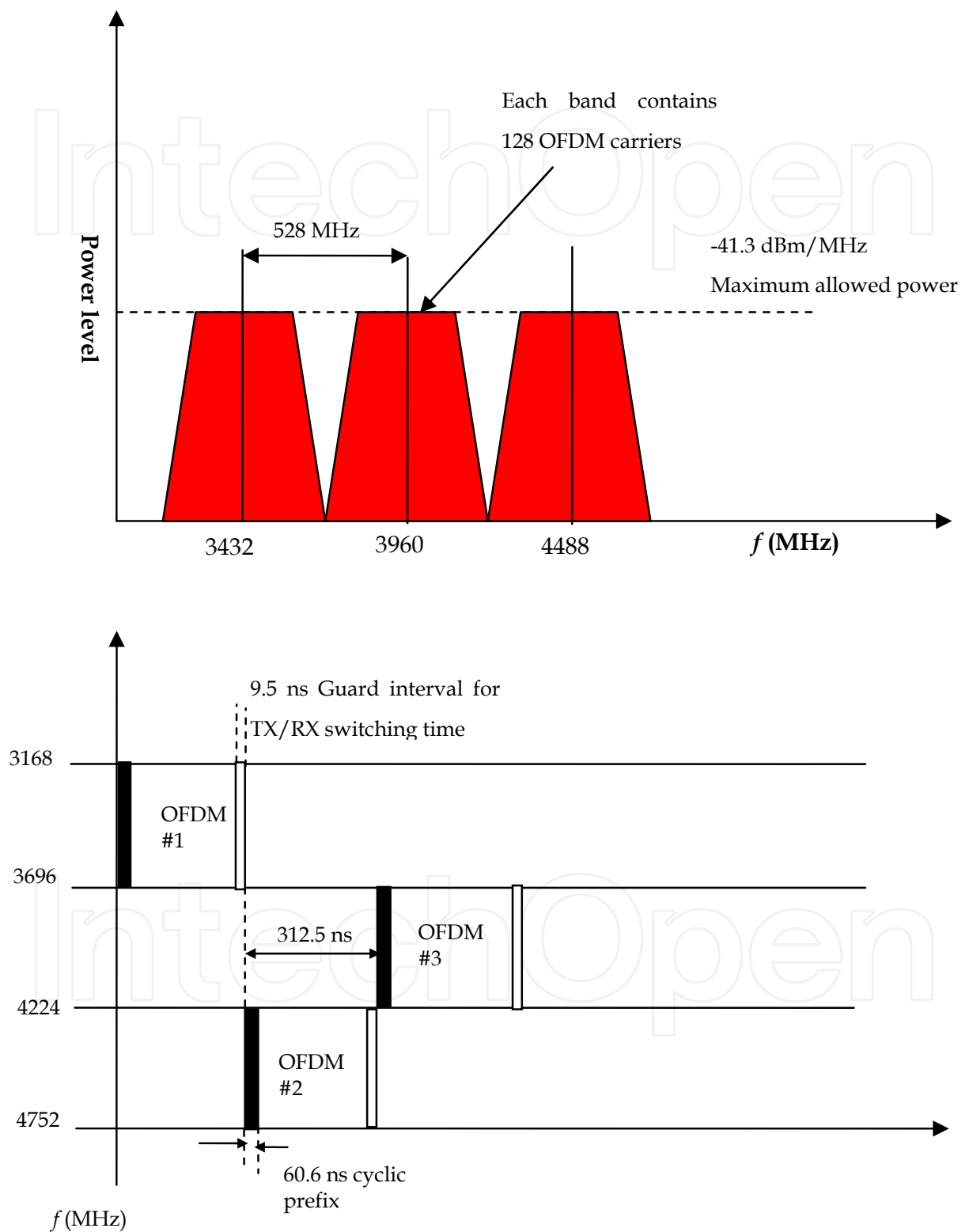

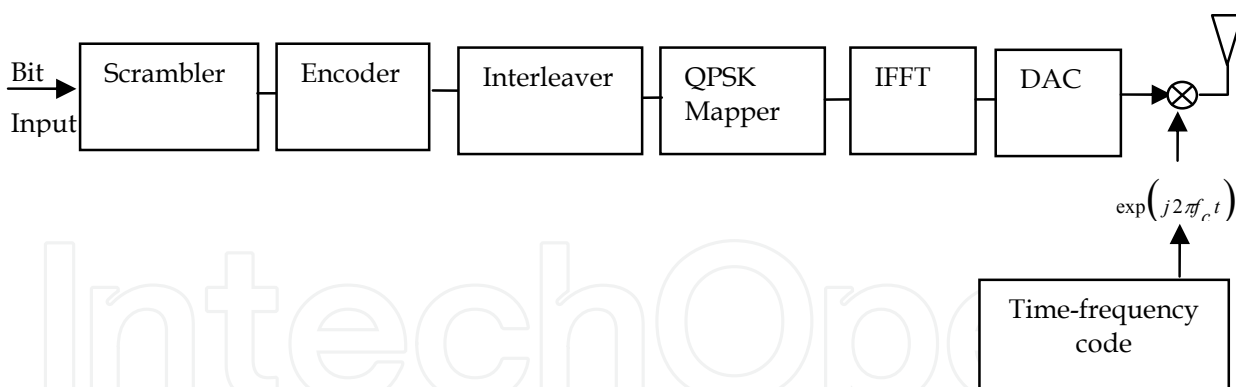Fig. 8. MB-OFDM system [Batra et al., 2004]

Fig. 9. UWB multi-band OFDM transmitter

The MB-OFDM radio uses the standard coding, scrambling, and inverse fast Fourier transform (IFFT) to generate the signal to be transmitted. Fig. 9 shows UWB multi-band OFDM transmit architecture which is very similar to that of a conventional wireless OFDM system, except time-frequency code. The time-frequency codes are used not only to provide frequency diversity in the system, but also to provide multiple access. At the receiver, an FFT recovers the original signal. Consequently, digital signal processing lies at the heart of an MB-OFDM UWB radio. Nonetheless, a 128-point FFT isn't that complex and can be implemented with logic in a small space these days. The resulting radio can achieve a data rate of up to 480 Mbits/s at about 2 to 3 m and up to 110 Mbits/s at 10 m. The data rate dependent modulation parameters are listed in Table 3, which summarizes the technical parameters of UWB multi-band OFDM systems. For some reason, though, the industry hasn't adopted these techniques as standards. In fact, most companies already have abandoned the impulse approach and are diving head-on into DS-CDMA and MB-OFDM. These two will form the foundation for most of the coming UWB products.

Data Rate =640Mbps*Coding Rate/Spreading

Info. Data Rate (Mbps)	Modulation/ Constellation	FFT Size	Coding Rate (K=7)	Spreading rate
53.3	OFDM/QPSK	128	1/3	4
55	OFDM/QPSK	128	11/32	4
80	OFDM/QPSK	128	1/2	4
106.7	OFDM/QPSK	128	1/3	2
110	OFDM/QPSK	128	11/32	2
160	OFDM/QPSK	128	1/2	2
200	OFDM/QPSK	128	5/8	2
320	OFDM/QPSK	128	1/2	1
400	OFDM/QPSK	128	5/8	1
480	OFDM/QPSK	128	3/4	1

Table 3. Data rate dependent parameters [Batra et al., 2004]
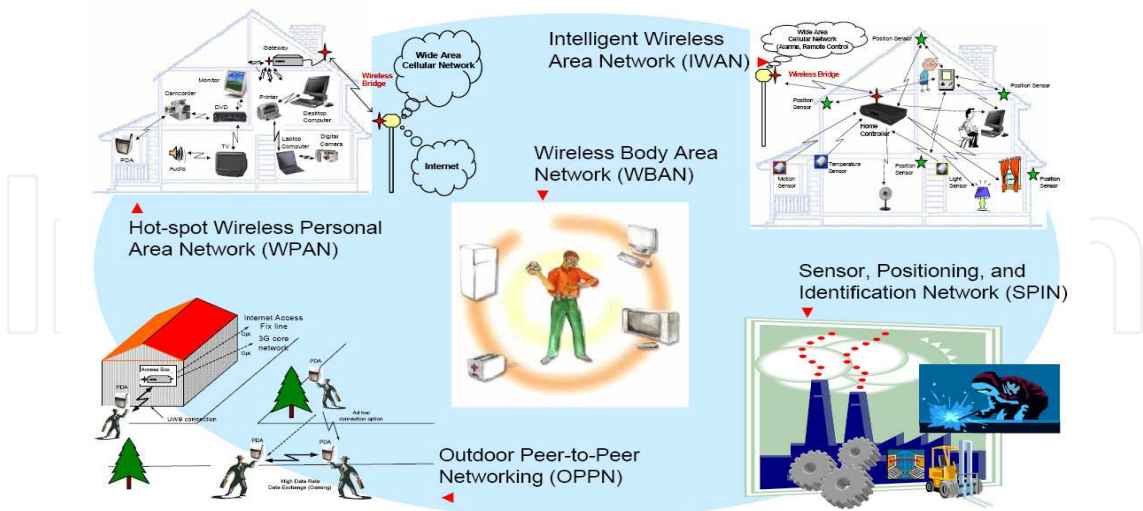
6. UWB applications

Fig. 10. Potential application scenarios [Oppermann, 2004]

The potential UWB applications scenario is shown in Fig. 10. As UWB allows high date rate throughput with low power consumption for distances of less than 10 meters, it is applicable to the digital home requirements. The digital home requirements are:

- High speed data transfer for multimedia content
- Short range wireless connectivity for transfer data to other devices
- Low power consumption due to limited battery capacity
- Low complexity and cost due to market pricing pressures
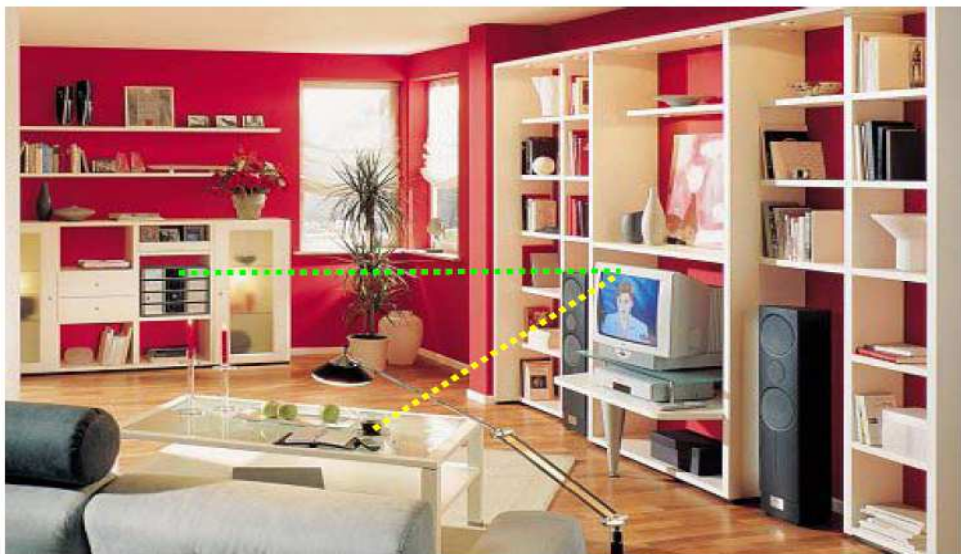
Fig. 11. UWB indoor communications [Manteuffel,2004]

For examples, the user will be able to stream video content from a PC or consumer electronics device- such as camcorder, DVD player or personal video recorder to a flat screen HDTV (high-definition television) display without the use of any wires, which is

shown in Fig. 11. Another model is the ability to view photos from the user's digital still camera on a larger display. Removing all wires to the printer, scanner, mass storage devices, and video cameras located in the home office is another possible scenario.

Due to high data rate, UWB can be used as an alternative to other wireless technologies, such as Bluetooth and WiFi, for Personal Area Network (PAN) applications.

6.1 UWB vs. Wi-Fi WLAN

UWB and Wi-Fi are seen as complementary technologies for the most part because Wi-Fi is a wireless local area network (WLAN) while UWB is a wireless personal area network (WPAN). The only area in which there is an overlap between these two technologies is in wireless video applications. Currently, Wi-Fi is not an effective method to distribute video applications wirelessly because the peak transfer rate of 54 Mbps is much too slow for video applications. UWB is a superior technology in video applications because peak transfer rates are in excess of 100 Mbps.

6.2 UWB vs. Bluetooth

Bluetooth data rates could reach 12 Mbps. This is only a fraction of UWB rates which can reach 480 Mbps. Bluetooth is sufficient for applications like mobile phones and ear phones but not sufficient for transfers of fast data and video between home appliance because of its high power consumption and poor data rates.

7. Challeges of UWB

There are several challenges that need to be considered and must be overcome to ensure the success of this technology in the wireless communication market such as multi-access code design, multiple access interference (MAI) cancellation, narrowband interference (NBI) detection and cancellation, synchronization of the receiver to extremely narrow pulses, accurate modeling of UWB channels, low-power transceiver design, RF component design and UWB tailored network design.

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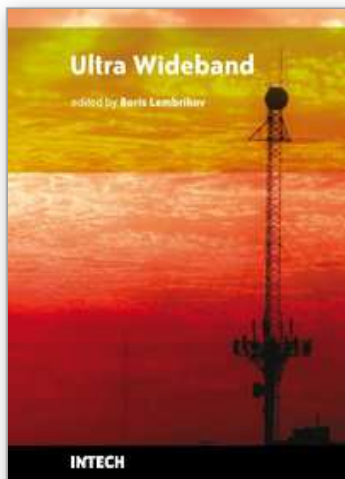
Ultra Wideband

Edited by Boris Lembrikov

Ultra wideband technology is one of the most promising directions in the rapidly developing modern communications. Ultra wideband communication system applications include radars, wireless personal area networks, sensor networks, imaging systems and high precision positioning systems. Ultra wideband transmission is characterized by high data rate, availability of low-cost transceivers, low transmit power and low interference. The proposed book consisting of 19 chapters presents both the state-of-the-art and the latest achievements in ultra wideband communication system performance, design and components. The book is addressed to engineers and researchers who are interested in the wide range of topics related to ultra wideband communications.

How to reference

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