Ultra Wideband: Applications, Technology and Future perspectives

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***Abstract*— Ultra Wide Band (UWB) wireless communications offers a radically different approach to wireless communication compared to conventional narrow band systems. Global interest in the technology is huge. This paper reports on the state of the art of UWB wireless technology and highlights key application areas, technological challenges, higher layer protocol issues, spectrum operating zones and future drivers. The majority of the discussion focuses on the state of the art of UWB technology as it is today and in the near future.**

***Index Terms*—Ultra Wideband, wireless technology**

I. Introduction

Ultra Wide Band (UWB) wireless communications offers a radically different approach to wireless communications compared to conventional narrow band systems. Global interest in the technology is huge. Some estimates predict the UWB market will be larger than the existing wireless LAN and Bluetooth markets combined by the year 2007 [1]. This is due to the capability of these license exempt wide bandwidth wireless systems to yield low cost, low energy, short range, extremely high capacity wireless communications links. The actual achievable data rate naturally depends on the particular technology and propagation conditions. The use of UWB has already been deregulated in the U.S.A. Singapore is set to follow shortly with Japan, China and elsewhere not far behind. The European position on deregulation, at the time of writing, is unclear although substantive work is being undertaken by CEPT and others [2] to produce a co-ordinated approach across Europe. However Europe has considerable activity in UWB. In addition to ETSI developing regulations, the EU, as part of its IST (Information Society and Technologies) initiative, has funded a number of projects including UCAN (UWB Concepts of Ad-Hoc Networks), PULSERS (Pervasive Ultra-Wideband Low spectral Energy Radio Systems) and ULTRAWAVES (ULTRA Wideband Audio Video Entertainment System). This brings into focus the application and implementation of this exciting technology.

Although receiving a renascence, ultra wideband transmissions are not new. Heinrich Hertz produced the first UWB transmission in 1893 with his spark discharge experiment, which was the dominant wave generation technique for about the next 20 years. After this, familiar sinusoidal carrier techniques were employed since they gave more control of the occupied radio spectrum. Modern UWB research stems from the 1960's when the U.S. military considered using pulse transmissions (impulse radio) for covert imaging, radar and 'stealth' communications. In the 1990's key technologies and concepts were brought into the public domain and, simultaneously, sub-system and component technology had progressed enabling UWB systems to become commercially viable. Furthermore, the technology 'boom' of the 1990's opened up new market potential and applications for UWB in the home.

The remainder of this paper elaborates on the above discussion and is structured as follows. Section II describes perceived applications of UWB technology for communications. Section III then focuses on technological aspects of UWB. Medium Access Control (MAC) for UWB is discussed in section IV. Section V describes spectrum issues that relate to the transmission of UWB signals. Some future perceptions of UWB technology are presented in section VI, and the paper is finally summarised in section VII.

II. Applications

A. Low Data Rate (LDR) Applications

The use of very short pulses in impulse radio transmission, and careful signal and architecture design, facilitate the design of very simple transmitters, permitting extreme low energy consumption and thus long-life battery-operated devices, which are mainly used in low data rate networks with low duty cycles. Nevertheless, the receiver design remains the major challenge. Energy detection receivers are a promising approach to build simple receivers [3]. Energy management schemes may alleviate the strict energy bounds imposed by batteries [4].

Surveillance of areas difficult to access by humans can be achieved by the deployment of sensor networks [5]. The inherent noise-like behaviour of UWB systems makes robust security systems highly feasible. They are not only difficult to detect, but also excel in jamming resistance. These characteristics are essential, not only for traditional security alarm systems, but also for Wireless Body Area Networks (WBANs), which are envisaged for medical supervision.

Due to the simple transceiver architecture and the thereby expected low costs of transceivers, the number of devices to be employed can be over dimensioned. With this approach, a certain percentage of nodes may fail (due to device failure, bad transmission conditions etc.) without affecting the functioning of the system as such. Deliberately designing devices with higher failure probability will again lower the cost of a single device. For complementing smart homes, actuators can be controlled by a central operator, making human intervention unnecessary.

Positioning with previously unattained precision, tracking, and distance measuring techniques, as well as accommodating high node densities due to the large operating bandwidth is also possible [4]. Many routing protocols are known which reduce control-overhead using location information [6]. Today's indoor solutions use either infrared or ultrasonic approaches. The former requires line-of-sight-propagation which can not be guaranteed, and the latter has the disadvantage of propagating with limited penetration. Simple UWB radio technology may fill this gap between demand and physical constraints, and is currently under development [7]. For industrial needs, e.g. in the automotive field, distance measuring systems are yet another example for the deployment of UWB systems as logistics will also profit from highly precise location determination.

B. High Data Rate (HDR) Applications

High data rate applications of UWB wireless technology have initially drawn much attention, since many of the applications are suited to the consumer market. Hence, commercial interest in technology development, standards and regulation is very high.

The very definition of ultra wideband [7] – a bandwidth exceeding 500 MHz (for carrier frequencies above 2.4 GHz) and an extremely low power spectral density (75nW/MHz between 3.1-10.6GHz, according to FCC rules), makes UWB the perfect candidate technology for these kinds of scenarios. The problem of designing transceivers with reasonable complexity, also suitable for handheld devices, is one of the main challenges for high-rate applications. Robustness against jamming is also very important, as a large number of electrical devices emitting narrowband noise are usually found in home and office environments, as well as interfering signals from other wireless services operating in sections of the UWB bandwidth.

Main application areas include:

- *Internet Access and Multimedia Services*: Regardless of the envisioned environment (home, office, hot spot), very high data rates (> 1 Gbit/s) have to be provided – either due to high peak data rates, high numbers of users, or both.
- *Wireless peripheral interfaces*: A growing number of devices (laptop, mobile phone, PDA, headset, etc.) are employed by users to organize themselves in their daily life. The required data exchange is expected to happen as conveniently as possible or even automatically. Standardized wireless interconnection is highly desirable to replace cables and proprietary plugs [8][9]. It has to be emphasized, however, that wireless solutions in this context will be attractive mainly for battery-powered devices without the need for an external power supply.
- *Location based services*: To supply the user with the information he/she currently needs, at any place and any time (e.g. location aware services in museums or at exhibitions), the users' position has to be accurately measured. UWB techniques may be used to accommodate positioning techniques and data transmission in a single system for indoor and outdoor operation.

C. Home Networking and Home Electronics

One of the most promising commercial application areas for UWB technology is wireless connectivity of different home electronic systems. It is thought that many electronics manufacturers are investigating UWB as the wireless means to connect together devices such as televisions, DVD players, camcorders, and audio systems, which would remove some of the wiring clutter in the living room. This is particularly important when we consider the bit rate needed for high-definition television that is in excess of 30Mbps over a distance of at least a few meters.

D. Wireless Body Area Networks (WBAN)

WBANs are another example of how our life could be influenced by UWB. Probably the most promising application in this context is medical body area networks. Due to the proposed energy efficient operation of UWB, battery driven handheld equipment is feasible, making it perfectly suitable for medical supervision. Moreover, UWB signals are inherently robust against jamming, offering a high degree of reliability, which will be necessary to provide accurate patient health information and reliable transmission of data in a highly obstructed radio environment.

The possibility to process and transmit a large amount of data and transfer vital information using UWB wireless body area networks would enable tele-medicine to be the solution for future medical treatment of certain conditions. In addition, the ability to have controlled power levels would provide flawless connectivity between body-distributed networks. UWB also offers good penetrating properties that could be applied to imaging in medical applications; with the UWB body sensors this application could be easily reconfigured to adapt to the specific tasks and would enable high data rate connectivity to external processing networks (e.g. servers and large workstations).

III. Focus on Technology

A. Signal Propagation

Due to large signal bandwidths far exceeding the coherence bandwidth of the propagation environment, the UWB channel exhibits frequency-selective fading. Sub-nanosecond sampling intervals allow for fine resolution of the very large number of multipaths typically observed in UWB channels (depending on the propagation environment and spreading bandwidth). Rake reception makes use of this high temporal resolution and multipath propagation to yield enhanced operation, providing a gain of up to 4 dB in LOS environments [10]. Pulsed UWB systems count on temporal orthogonality of multipaths. Multicarrier (OFDM and CDMA) UWB systems rely on efficient energy distribution in the spectrum to prevent multipath and inter-symbol interference, ensuring that sufficient information is always presented to the receiver for reliable demodulation.

Similarly, two-branch transmit diversity using polarization orthogonality with space-time codes has been shown to provide a diversity gain of about 5 dB [11]. The use of multiple antenna techniques is especially useful in UWB communications since the small size of high-frequency antennas enables compact placement of multiple antenna elements within a mobile device.

B. Electronics and A/D Conversion

The performance of A/D converters has a major impact on the choice of receiver architecture in a digital wireless system. In UWB systems, this phenomenon is particularly exacerbated by the large operating bandwidth. In pulsed systems, high frequency A/D converters allow the implementation of correlation in the digital domain and enable new modulation and multiple-access concepts that exploit pulse shape. Conventional lower frequency converters that make use of analogue correlation are described in [12]. The dynamic range is usually relaxed, which ensures the feasibility of digital radio for UWB systems. These solutions have a promising future since they are particularly in line with the evolution of silicon technologies. Moreover, with the new concept of cognitive radio, all-digital architectures are becoming more and more attractive. However, the A/D converters that are required in such transceivers are not available off-the-shelf and need further development, for which possibilities exist [13].

C. Single- and Multi-band Techniques

As mentioned previously, impulse radio was the initial form of UWB technology. Research effort is continuing in the investigation of UWB schemes based on impulse radio which has maintained a hold in niche markets, with applications ranging from imaging radars to location systems and wireless sensor networks.

On the other hand, multiband techniques have reinterpreted the UWB concept to allow for the application of, in effect, multiple narrow- or wide-band approaches. They provide a natural evolution from existing narrowband and wideband designs that can be readily adapted to operate in UWB configurations by utilising a parallel architecture. They are based on conventional radio technologies such as OFDM and DS-CDMA. They can achieve bit rates of the order of 2 Gbps in an indoor dense multipath environment [14]. They also permit adaptive selection of sub-bands to minimise interference and enhance coexistence with other wireless services. Both multiband approaches provide a natural evolution from narrowband to ultra-wideband without the need to devise novel signalling techniques, thus facilitating reuse of existing expertise for rapid production of marketable products.

D. Antenna Design and Performance

Microwave signal propagation requires smaller antennas than those required for typical RF communication, which makes it easier to produce compact devices. Multi-antenna systems can also be produced with acceptable sizes. Many special designs suitable for efficient UWB signal radiation have been proposed in the literature, such as planar elliptical dipoles, balanced antipodal Vivaldi, D*dot, TEM horn, etc. These antennas have frequency dependent radiation patterns. Many frequency-independent antennas can also be used with UWB, such as the biconical, discone, bowtie, horn, log-spiral and trapezoidal designs. However, some of these antenna designs cannot be directly used for UWB systems, as they radiate distorted signal waveforms due to phase variation as a function of frequency and look-angle (i.e., they cause signal distortion). Thus, this distortion should be compensated for, or exploited as part of a cognitive radio architecture.

E. Interference

Recent theoretical and experimental investigations show that UWB emissions do not cause significant interference to other devices operating in the vicinity [15]. Low power-spectral-density causes UWB signals to lie below the unintentional emitter noise limits defined by the wireless regulations. As a consequence, a UWB system is deemed not to cause any more interference to a narrowband receiver than the spurious emissions from unintentional radiators. Also, since current applications use UWB technology for very short ranges, any detectable interference can usually only be caused by a particularly high spatial density of UWB devices near the receiver. However, even in such a case, the interference would be localised by the transmission range of the UWB devices. Conversely, the effect of narrowband interference from other closely located emitters to UWB receivers is not significant unless a very high interference power is radiated as discussed in [16].

F. Waveform Shaping

Impulse Radio UWB communications may use any of a large family of signal waveforms that satisfy the regulatory spectral masks. More popular among them are the Gaussian pulse, Gaussian doublet, Gaussian monopulse, Mexican hat, Morlet, Rayleigh, Laplacian, prolate spherical wave functions and Hermite families of waveforms [17].

IV. UWB MAC CONSIDERATIONS

A. MAC Objectives

As discussed earlier, UWB holds great potential for wireless ad-hoc and peer-to-peer networks. This, coupled with the enormous bandwidth of UWB systems, means that specialized medium access control (MAC) mechanisms are required so that efficient operation is possible. Major MAC development activity is being undertaken in the IEEE standardisation [18] as well as European Union projects such as PULSERS [19].

Without dramatically changing the air interface, the data rate can be changed by orders of magnitude according to the system requirements. This means that high data rate (HDR) and low data rate (LDR) devices will need to co-exist. The narrow time domain pulse also means that UWB offers the possibility for very high location estimation accuracy. However, each device in the network must be "heard" by a number of other devices in order to generate a position from a delay or angle-of-arrival estimate. This, coupled with the fact that an individual low power UWB pulse is difficult to detect, offer some significant challenges for the multiple access (MAC) design. The main issues to be addressed by a UWB MAC include channel access, coexistence, inter-operability and support for positioning / tracking.

B. Coexistence

The potential proliferation of UWB devices of widely varying data rates and complexities will require coexistence strategies to be developed. Here, coexistence is in the context of coexisting UWB users, i.e., it is assumed that coexistence between UWB and other spectrum users does not form part of this discussion. This is, however, of paramount importance to the success of UWB and, under some circumstances, a MAC designed to account for this could provide part or all of a solution. Other aspects providing such solutions are: physical layer signal design and transceiver architecture with temporal/frequency/spatial or polarisation based filtering.

The assumptions of the physical layer will have implications on MAC issues. These are, for example, initial search and acquisition process, channel access protocols, interference avoidance/minimisation protocols, and power adaptation protocols. The quality of the achieved "channel" will have implications on the link level, which may necessitate active searching by a device for better conditions.

Within this context, other noteworthy developments include the Common Signalling Mode (CSM) initiative, an approach allowing different types of UWB to communicate with each other over the same wireless network [20].

C. Interoperability

The most common requirement of MAC protocols is to support inter-working with other devices of the same type. With the potentially wide range of device types, the MAC design challenge is to be able to ensure cooperation and information exchange between devices with differing data rates, QoS class or complexity. In particular, emphasis must be placed on how low complexity, LDR devices can successfully produce limited QoS networking with higher complexity, HDR devices.

D. Positioning/Ranging Support

Position estimation techniques are integrally linked to the MAC. This includes strategies for improving timing and therefore ranging accuracy and for exchanging timing information to produce positioning information. The provision of such support is a key requirement for many UWB wireless applications.

It is possible for any single device to estimate the arrival time of a signal from another device based on its own time reference. This single data point in relative time needs to be combined with other measurements to produce a 3D position estimate relative to some system reference. Exchange of timing information requires cooperation between devices. Being able to locate all devices in a system presents a variation of the "hidden node" problem. The problem is further complicated for positioning because multiple receivers need to detect the signal from each node to allow a position in 2- or 3-dimensions to be determined.

All of the following issues require MAC support: information exchange; device sampling rate; node visibility; and signal conditioning. These pose significant obstacles to existing WLAN and other radio systems offering reliable positioning/ tracking when added on to the MAC at the post-design. Hence, UWB system design has the opportunity to fully integrate positioning and tracking functionality much earlier in its design cycle.

E. Constraints and Implications of UWB Technologies on MAC Design

Some qualities of UWB signals are unique and may be used to produce additional benefit in terms of MAC design. For example, the accurate ranging capabilities associated with UWB signals may be exploited by the higher layers for location-aware services. Conversely, some aspects of UWB signals pose problems which must be solved by the MAC design. For example, using carrier-less impulse signals does not assist in the implementation of carrier sensing capability needed in popular approaches such as Carrier-Sense, Multiple Access/Collision Avoidance (CSMA/CA) MAC protocols.

Another aspect that impacts MAC design is the relatively long synchronisation and channel acquisition time in UWB systems. In [21], the performance of the CSMA/CA protocol is evaluated for an UWB physical layer. CSMA/CA is used in a number of distributed MAC protocols. It is also adopted in the IEEE 802.15.3 MAC and is being considered as the IEEE802.15.3a MAC.

The time required to achieve bit synchronization in UWB systems is typically high, of the order of few milliseconds [21]. Considering that the transmission time of a 10000 bit packet on a 100 Mbit/s rate link is only 0.1 milliseconds, it is easy to understand the impact of synchronization acquisition on CSMA/CA based protocols. The efficiency loss due to acquisition time can be minimised by using very long packets. However this may impact performance in other ways.

Acquisition preambles are typically sent at a higher transmit power than data packets [22]. This impacts both the interference level and the energy consumption in highly burst traffic. This must be taken into account when determining the efficiency of the system.

F. State-of-the-art

No standard currently exists for a UWB MAC. There is work in standardization bodies to adapt and possibly optimise and enhance existing MAC's for use with UWB systems. The reason for not simply adopting an existing MAC is partly due to the inherent complications of using a physical layer signal which is difficult to detect and difficult to synchronise to for intended users. Efforts have been made to develop MAC's which allow efficient operation for large numbers of devices, however, this work is still at an early stage.

An example is IEEE 802.15.3 MAC. This MAC has been developed for high speed ad-hoc applications and has been targeted for UWB by interested groups, however its suitability for UWB, either impulse based or for other physical layer UWB solutions, is yet to be proven.

Research into MAC solutions for UWB is needed and is on-going in industrial research centres and in universities. However, the research rarely takes into account the peculiarities of UWB signalling. As shown, limitations due to specific characteristics of the UWB physical layer do exist and attention must be paid to these in the MAC design.

V. Spectrum Landing Zones

A. Regulatory Bodies

One of the important issues in UWB communication deployment is the frequency allocation. Due to the implicit use of a very wide spectrum range, there are lots of existing and planned wireless systems operating under allocated bands within the UWB signal band. Some companies in the USA are working towards removing the restrictions from the FCC's regulations relating regulating the applications able to utilise UWB technology. These companies have established an Ultra Wideband Working Group (UWBWG) to negotiate with the FCC. Some other companies and organizations in the USA are willing existing narrow band allocated services to be well protected from possible interference generated by UWB systems. Similar discussions on frequency allocation and protection of other radio services from interference have also emerged in Europe. Currently, there are no dedicated frequency bands for UWB applications identified in the ETSI (European Telecommunications Standards Institute), in the ECC (European Communication Committee) decisions or in the ITU (International Telecommunications Union) Radio Regulation treaty.

The spectral mask associated with the FCC UWB regulation was designed to protect other spectrum users from undesirable levels of interference caused by UWB transmissions. Many of these users are considered by introducing a "notch" in the spectrum mask of an additional 35dB between 960MHz and 1.61GHz. In addition, the proposed European spectrum mask has approximately 20dB between 1.61GHz and 3.1GHz for protection to 3G services, as shown in figure 1. The figure shows spectrum masks for both communications and radar devices. It should also be remembered that the total allowable average EIRP from a UWB device is -2.5dBm or 0.56mW, which is a fraction of power compared to many other wireless services.

ITU-R Study Group 1 has established Task Group 1-8 to carry out relevant studies concerning the proposed introduction of UWB devices and the implications of compatibility with radio communication services. The mandate of TG 1-8 is focused in the study of

- compatibility between UWB devices and radio communication services (Question ITU-R 227/1);
- spectrum management framework related to the introduction of UWB devices (Question ITU-R 226/1); and
- appropriate measurement techniques for UWB devices.

TG1-8 is to complete its work in 2005 and will present to SG1 for new Recommendations on UWB characteristics, UWB compatibility with other radio services, UWB spectrum management framework and UWB measurement techniques.

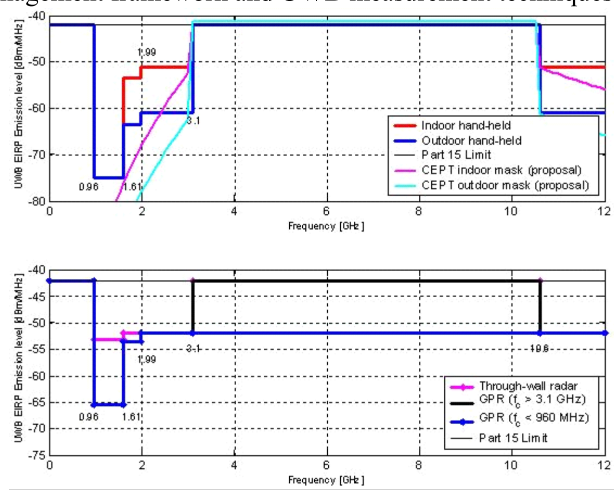

Fig 1. UWB Spectrum Mask as Defined by FCC and the current CEPT proposal

B. UWB Standardisation by IEEE

The IEEE established the 802.15.3a study group to define a new physical layer concept for short range, high data rate applications. This ALTernative PHYsical (ALT PHY) is intended to serve the needs of groups wishing to deploy high data rate applications. With a minimum data rate of 110 Mbps at 10 m, this study group intends to develop a standard to address such applications as video or multimedia links, or cable replacement. Whilst not specifically intended to be a UWB standards group, the technical requirements very much lend themselves to the use of UWB technology. The study group has been the focus of significant attention recently as the debate over competing UWB physical layer technologies has raged. The work of the Study Group also includes analysing the radio channel model proposal to be used in the UWB system evaluation.

The purpose of the study group is to provide a higher speed PHY for the existing approved 802.15.3 standard for applications which involve multimedia [23]. The main desired characteristics of the alternative PHY are:

- Co-existence with all existing IEEE 802 physical layer standards;
- Target data rate in excess of 100 Mbits/s for consumer a applications;
- Robust multipath performance;
- Location awareness; and

- Use of additional unlicensed spectrum for high rate WPANs (Wireless Personal Area Network).

The IEEE established the 802.15.4a task group to define a physical layer concept for low data rate applications utilising a UWB air interface. The task group addresses new applications which require only moderate data throughput, but requires a long battery life. Example applications are low-rate wireless personal area networks, sensors and small networks, as described in [4] and [24]. In most cases, centimetre accuracy ranging is the key feature brought by UWB to address these new applications. A baseline proposal was accepted by unanimous vote on March 2005 and the standard is now in a drafting stage.

VI. What Ever Next?

The majority of the discussion so far has focused on the state of the art of UWB technology as it is today and near future. However, future UWB developments and drivers that may shape future evolutions of this technology are:

- Integral part of 4G communications networks;
- Very high data rate requirements driven by the development of 3D imaging technology and applications;
- Digital implementation solutions; and
- Super-high density wireless sensor networks.

VII. Summary

This paper has reported on the state of the art of UWB wireless technology and highlighted key application areas, technological challenges, spectrum operating zones and future drivers. The simple transmit and receiver structures that are possible makes it a potentially powerful technology for low complexity, low cost communications. The physical characteristics of the signal also support location and tracking capabilities of UWB much more readily than with existing narrower band technologies.

The severe restrictions on transmit power have substantially limited the range of applications of UWB to short distance, high data rate, or low data rate, longer distance applications. The great potential of UWB is to allow flexible transition between these two extremes without the need for substantial modifications to the transceiver. Regulation of UWB technology outside the USA is still under discussion pending the outcome of compatibility studies with other radio services.

Whilst UWB is still the subject of significant debate, there is no doubt that the technology is capable of achieving very high data rates and is a viable alternative to existing technology for WPAN; short range, high data rate communications; multi-media applications, cable replacement and wireless sensor networks. Much of the current debate centres on which PHY layer(s) to adopt, development of a standard, and issues of coexistence and interference with other radio services.

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References

[1] G Brown, “Ultrawideband: Spectrum for Free”, Unstrung Insider (www.unstrung.com)W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.
[2] J Walko, “Ultra Wide Band”, The IEE Communications Engineer, Dec/Jan 2003/4B..
[3] Federal Communications Commission (FCC) “FCC NOI: Rules Regarding Ultra-Wideband Transmission Systems”, ET Docket No. 98-153, Sept. 1, 1998.
[4] B Allen, “Ultra Wideband Wireless Sensor Networks”, IEE UWB Symposium, June 2004.
[5] I. Akyildiz et al, “A Survey on Sensor Networks”, IEEE Comm. Magazine, August 2002.
[6] Y. Ko, N Vaidya, “Location-Aided Routing (LAR) in Mobile Ad Hoc Networks”, Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM ’98), August 1998.
[7] www.ubisense.net
[8] B Allen, M Ghavami, A Armogida, A.H Aghvami, “The Holy Grail of Wire Replacement?”, IEE Communications Engineer, Oct/Nov 2003.
[9] Intel.com: Industry Leaders Developing First High-Speed Personal Wireless Interconnect, Formation of Wireless USB Promoter Group Announced, http://www.intel.com/pressroom/archive/releases/20040218corp_c.htm
[10] W. Q. Malik, D. J. Edwards, and C. J. Stevens, "Experimental evaluation of Rake receiver performance in a line-of-sight ultra-wideband channel", Proc. Joint UWBST & IWUWBS. Kyoto, Japan, 18-21 May 2004.
[11] F. Argenti, T. Bianchi, E. Del Re, L. Mucchi, L. S. Ronga, “Ultra-wideband signal with polarization diversity for constant indoor QoS,” in Proc. 12th WWRF Meeting. Toronto, Canada, November 2004.
[12] D. Kelly et al., “Pulson second generation timing chip: enabling UWB through precise timing”, Proc. UWBST. 21-23 May, 2002.
[13] R. H. Walden, “Analog-to-Digital Converter Survey and Analysis”, IEEE J. Select. Areas Commun, vol. 17, April 1999.
[14] A. H. Tewfik, E. Saberinia, "High bit rate ultra-wideband OFDM", Proc. Globecom. Taipei, Taiwan, November 2002.
[15] L. Zhao and A. M. Haimovich, "Performance of ultra-wideband communications in the presence of interference," IEEE J. Select. Areas Commun., vol. 20, December 2002.
[16] X. Chu and R. D. Murch, “The effect of NBI on UWB time-hopping systems,” in IEEE Trans. Wireless Comm. vol. 3, no. 5, September 2004.
[17] B Allen, A Ghorishi, M Ghavami, "A Review of Pulse Design for Impulse Radio", IEE Ultra Wideband Workshop, June 2004.
[18] http://www.ieee802.org/15/pub/
[19] http://www.pulsers.net/main.shtml
[20] IEEE, “Draft Standard for Telecommunications and Information Exchange Between Systems – LAN/MAN Specific Requirements – Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPAN)”, Draft P802.15.3/D17, Feb 2003.
[21] Jin Ding, Li Zhao, S. R. Medidi, K. M. Sivalingam, “MAC Protocols for Ultra-Wide-Band (UWB) Wireless Networks: Impact of Channel Acquisition Time”, SPIE ITCOM Conf., Boston, MA, USA, July 2002.
[22] Federal Communications Commission (FCC) http://www.fcc.gov.
[23] http://www.ieee802.org/15/pub/
[24] I. Opperman et al., “UWB Wireless Sensor Networks: UWEN-A practical example, in IEEE Communications Mag., December 2004.