Recent Advances in IR-UWB Transceivers: An Overview

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***Abstract*— Modern Ultra-Wide Band (UWB) regulations have recently been adopted worldwide allowing for unlicensed operation within 3.1 and 10.6 GHz, using an appropriate wideband signal format with a low Effective Isotropic Radiated Power (EIRP) level. UWB characteristics are suitable to transmit data using pulses instead of continuous-waves such as in narrowband radio links. It has the potential to be the right technology for high data-rate, low-power and short-to-medium range communication systems.**

We will focus on Impulse Radio-UWB (IR-UWB) systems and show their suitability for many different applications, including sensor networks, ad-hoc networks, cognitive radio, home networking, etc. We will also discuss the difficulties and challenges of designing IR-UWB systems.

We present a tutorial overview of UWB regulations and usable signals. We present the existing standards and recommendations, and we review recently published results, highlighting trends in UWB transceiver power consumption and the impact of CMOS scaling on performance.

I. INTRODUCTION

Before the emergence of ultra-wideband (UWB) radios, widely used wireless communications were based on sinusoidal carriers, and impulse technologies were employed only in specific applications (eg. radar). In 2002, the Federal Communication Commission (FCC) allowed unlicensed operation between 3.1 GHz and 10.6 GHz for UWB communication, using an appropriate wideband signal format with a low EIRP level (-41.3dBm/MHz). UWB communication systems then emerged as an alternative to narrowband systems and significant effort in this area has been invested at the regulatory, commercial, and research levels [1-3].

UWB signals can support high data rates due to the large bandwidth available, and low power due to the use of narrow pulses in time. There are presently two main competing technical approaches to the development of UWB systems: 1) multi-band (MB) OFDM UWB, and 2) impulse radio (IR) UWB. The MB-OFDM approach has been primarily used for applications such as streaming video and wireless USB with data rates of 480Mb/s. Because of the high-performance electronics required to operate a MB-OFDM UWB radio, these systems generally are not amenable to energy-constrained applications. IR-UWB radios, however, can be designed with relatively low-complexity and low power consumption. They have therefore found a niche in energy-constrained, short-range wireless applications including personal-area-networks, low-power sensor networks, and wireless body-area-networks. Because of the bandwidths that can be achieved with IR-UWB radios, they are also used in precise location systems and for dedicated high-data-rate communication links.

This overview paper is an introductory paper to the ISCAS Special Session on "Recent Advances in IR-UWB Transceivers". In section II we review the UWB regulations and standards. In section III we present IR-UWB characteristics and signals. In section IV we summarize proposed applications, recent trends and results, while introducing the Special Session selected papers. Finally, in section V, we draw some conclusions.

II. UWB REGULATIONS AND STANDARDS

Regulations

In 2002 modern UWB regulations were introduced by the FCC [4], for an unlicensed frequency band between 3.1 GHz and 10.6 GHz with an allowable EIRP of -41.3 dBm/MHz and a minimum bandwidth of 500 MHz. To put this power level in perspective, this is the same level allowed for the noise emissions of an electronic device. Therefore, UWB signaling can be thought of as reusing the "noise floor" for communication. The spectral masks depend on applications and regions; in Europe and in Asian countries the regulations tend to be more strict while in the US and Canada they tend to be more relaxed. Fig. 1 summarizes the bands in which UWB

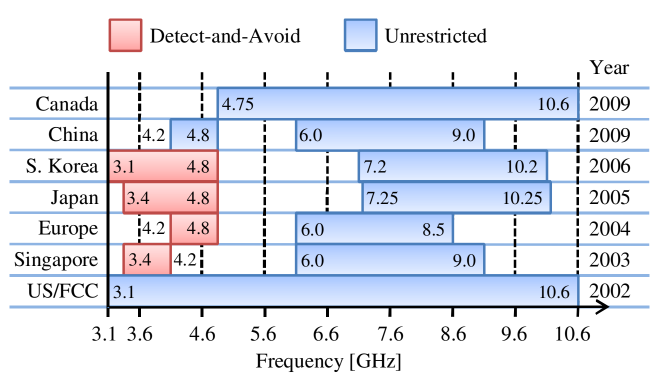

Figure 1. UWB intended bands for communications for different regions.

[1]Work partially supported by FCT and ENIAC (Se2A).

wireless communication is allowed, some of which require detect-and-avoid strategies in the UWB transmitter. Across these regulations, we see that the band from 7.25-8.5 GHz is the only common spectrum.

Regulations for UWB are being established worldwide, and are often updated. In Europe the new regulations announced by the European Commission (EC) through the European Technical Standards Institute (ETSI) in 2007, set the EIRP at -41.3 dBm/MHz in the frequency bands 4.2 to 4.8 GHz (up to year 2010) and 6.0 to 8.5 GHz. These can be extended to 3.1 to 4.8 GHz and from 8.5 to 9 GHz subject to the implementation of mitigation techniques [5]. In Singapore to stimulate the study and development of UWB usage, a technical park is considered as an UWB Friendly Zone (UFZ) and allows the much more relaxed EIRP limit of -35.3dBm/MHz from 2.2 GHz to 10.6 GHz.

Standards

The UWB bands are unlicensed and can be used freely, but there have been efforts to establish standards to provide compliance between devices from different origins. One of the most important standardization organizations is the IEEE LAN/MAN Standards Committee.

IEEE 802.15 Task Groups 3 and 4 established standards for wireless personal area networks (WPAN) which led to IEEE-Std 802.15.3 for high-data rate [6] and IEEE-Std 802.15.4 for low-data rate [7]. Amendments to [6] and [7] were attempted to contemplate UWB. The IEEE-Std 802.15.3a proposal for high-data-rate has led to the multi band (MB)-OFDM UWB approach which became the *de facto* standard for high-data-rate UWB communication, and was later adopted by the WiMedia Alliance for certified Wireless-USB. MB-OFDM is a carrier based communication protocol that divides the 3.1-10.6GHz UWB spectrum into 14 bands of 528 MHz [8, 10-12]. A second outcome of the 802.15.3a task group was a Direct Sequence (DS) UWB standard, supported by the UWB Forum (this is more in the original spirit of UWB transmission of very narrow pulses, from 100 ps to 1 ns, and considering a low band from 3.1 and 5.15 GHz and a high frequency band between 5.825 and 10.6 GHz).

The IEEE-Std 802.15.4a proposal for low-data rate [9] also considered the division into a low band from 3.1 and 5 GHz and an upper band between 6 and 10.6 GHz. This frequency division approach is useful when the regulations are not universal, but share some common features. The IEEE 802.15 Task Group 6 (IEEE 802.15.6) was formed in Nov. 2007 and is currently developing a communication standard for body-area networks (BAN). A more heterogeneous approach of IR-UWB signaling paired with narrowband signaling is being considered for this standard.

III. IR-UWB CHARACTERISTICS AND SIGNALS

Narrowband communication is widely used and occupies most of the usable spectrum. Transceiver architectures, modulation schemes, circuit topologies, antennas, and transmission channels for narrowband radios are well known. In contrast, modern IR-UWB communicates by using short pulses in the time domain with their energy spread over a wide bandwidth in the frequency domain. Many of the common design practices do not apply to UWB signaling. This imposed new constraints on the design across all layers of the system.

Examples of IR-UWB signals are illustrated in Fig. 2, representing a rectangular and a Gaussian pulse in the time domain. The spectrum of the rectangular pulse (a *sinc* curve) has side lobes that cannot be disregarded. A Gaussian pulse however is Gaussian in the frequency domain as well, and its energy is confined into a narrower band. These two types of pulses have energy at low frequencies so their spectrum is often shifted upwards by mixing the pulses with a sinewave, resulting in the pulses shapes in Fig. 2 in the time and frequency domain. In practice the resulting output pulses are somewhere between a square and Gaussian shape.

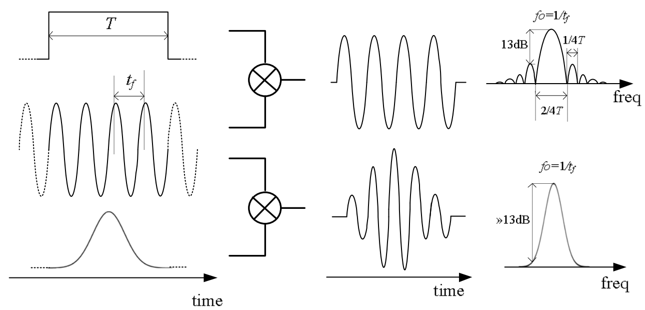

Figure 2. Modulated rectangular and Gaussian pulses.

A narrower pulse in time occupies a larger bandwidth for a shorter period of time. The energy in each pulse can still be high, being limited by the bandwidth and the peak power specification. The energy allowed for each pulse also depends on the data rate, therefore there is a tradeoff between range and data rate. The data rate can then be increased by increasing circuit complexity, using several channels and wider-band circuits, but this will lead to an increase in power consumption.

The architectures and the circuits for UWB have important changes with respect to narrowband communication transceivers. Instead of the transmitter power amplifier the receiver is responsible for most of the transceiver power consumption.

IV. RECENT TRENDS AND APPLICATIONS

IR-UWB receivers cannot rely on conventional PLL circuits for synchronizing, but require precise timing synchronization. Receivers also require fast analog-to-digital conversion, and they should be able to cope with large channel delay spreads and strong narrowband interferers. In this section we will briefly review approaches that have been used to overcome or mitigate these problems. System design and its challenges are covered in this special session in the paper "Recent Advances in IR-UWB Transceivers: An Overview".

Applications

Many IR-UWB applications concern short-to-medium range with low data-rate and are focused on achieving low power consumption. Applications that have been considered include wireless sensor networks, sensing and positioning [13,15] systems, inter-chip communication [16,17] contact less wireless [18], biological or biomedical networks [19,20], and imaging systems [21]. Most recently, health monitoring and body-area networks (BAN) have been candidates for UWB applications [22,23] and for the IEEE 802.15.6 standard. In this special session paper "System and Circuit Considerations for Low-Complexity Constant-Envelope FM-UWB" is on this topic.

Receivers

Receivers can be either coherent or non-coherent topologies. Coherent receivers have severe specifications on time alignment that are difficult to fulfill by the synchronization circuit. This has been mitigated by the use of quadrature correlation [24-31], or more complex schemes [32-34]. When the signal is strong enough receivers can be non-coherent, which are usually simpler but more susceptible to noise. Most non-coherent topologies are based on squaring and then integrating the signal [29,35-40], however other techniques using comparison [41] or super-regeneration [42-44] have been proposed. In this special session a hybrid method, combining both coherent and non-coherent methods, is presented in "Partially Coherent Signal Combination for Impulse Radio Synchronization".

Transmitters

In a narrowband system the PA is commonly the most critical block because its power consumption typically dominates the total power of the transmitter. In an IR-UWB transmitter, most of the power is consumed in the electronics that generate the pulse rather than in the PA. Implementations of pulse generators can be analog, based on derivatives [45], on multipliers [29,46-47], on filters, or, more recently, on oscillators which produce the UWB pulse based on start-up/fall-down time [48-51]. Digital implementations have also been used, which rely on multiphase ring oscillators and/or a combination of different path delays [52-59] to produce the wanted pulses. All-digital transceivers can take the maximum advantage of CMOS technology scaling. This topic is covered in this special session by the paper "IR-UWB Transmitters Synthesized from Standard Digital Library Components".

Published Results Trends

The plots in Fig. 3 compare the energy/pulse of recently published IR-UWB transmitters and receivers. Energy/pulse is a popular figure-of-merit (FoM) for IR-UWB transceivers because it directly relates to the energy required to transmit/receive a single bit of data, or the efficiency of the radio. The top plot in Fig. 3 graphs the E/pulse against the data rate, while the bottom plot graphs E/pulse against the process node. All results are measurements from fabricated custom integrated circuits. From the top plot, we first observe that IR-UWB transmitters consume on average 10x less energy than receivers at the same data rate. Additionally, the transmitter E/pulse does not have a strong dependence on data rate, while the receiver E/pulse generally decreases with increasing data rate. High-data-rate receivers are generally the most efficient, while transmitter efficiency is independent of the data rate. In the bottom plot, we observe that while IR-UWB receivers generally have not benefited from process scaling to 65nm, IR-UWB transmitters have. This trend of decreasing energy with process scaling is a result of IR-UWB transmitters being dominated by digital circuits.

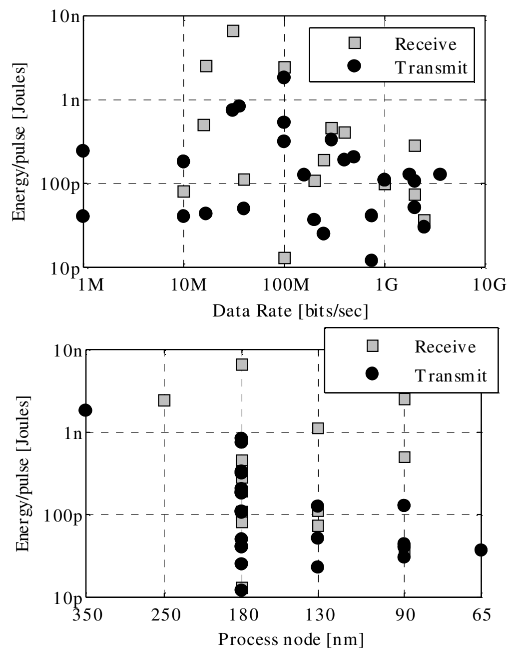

Figure 3. IR-UWB FoM relative to data rate (top) and process (bottom).

V. CONCLUSIONS

This paper reviews the evolution of UWB. It summarizes regulations worldwide, and discusses the nature of the pulses, the applications and transceivers topologies most widely used with IR-UWB. This is an introduction to the special session "Recent Advances in IR-UWB Transceivers". This session brings together authors from different countries and the combination of systems and hardware papers gives a bird's eye view of recent advances in IR-UWB communication.

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