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Conference Paper · October 2009

DOI: 10.1109/IMWS2.2009.5307895 · Source: IEEE Xplore

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IEEE MTT-S International Microwave Workshop on
Wireless Sensing, Local Positioning, and RFID (IMWS 2009 - Croatia)

Recent Trends and Advances in UWB Positioning

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***Abstract* — Since the ruling of the Federal Communications Commission (FCC) in the United States to open up the spectrum from 3.1-10.6 GHz for ultra wideband (UWB) applications in 2002, interest in the use of UWB for localization outside of military applications has skyrocketed. The multi-purpose nature of UWB for localization and also high or low data rate communication make it robust and attractive in many indoor applications including wireless sensor networks, medical body area networks (BANs), surgical navigation, etc. A push towards integrating UWB with global positioning systems (GPS), wireless local area networks (WLANs), Wi-Fi, and inertial measurement units (IMUs) help to mitigate localization errors with redundancy and increase interoperability with existing technologies. A look at the current trends both in the research community and industry highlight future applications of UWB positioning and the technologies which will serve as the building blocks in these systems.**

***Index Terms* — UWB positioning, real-time location systems, indoor positioning, ultra wideband.**

I. Introduction

The Federal Communications Commission (FCC) opened up the 3.1-10.6 GHz and 22-29 GHz bands for ultra wideband (UWB) use in 2002 with a maximum equivalent isotropically radiated power (EIRP) level of -41.3 dBm/MHz in either band [1]. Fontana provides an excellent overview of the history of UWB starting from the development of time domain electromagnetics in the 1960s [2]. As discussed by Fontana, the initial use and interest in UWB was for low probability of detection radar and communications applications with commercial interest starting much later in 1998 when the FCC released its Notice of Inquiry, culminating in the official decision to open up the bands in 2002 [2]. The attractiveness of UWB for high accuracy indoor applications is illustrated in Fig. 1, which summarizes the results of the experiments from

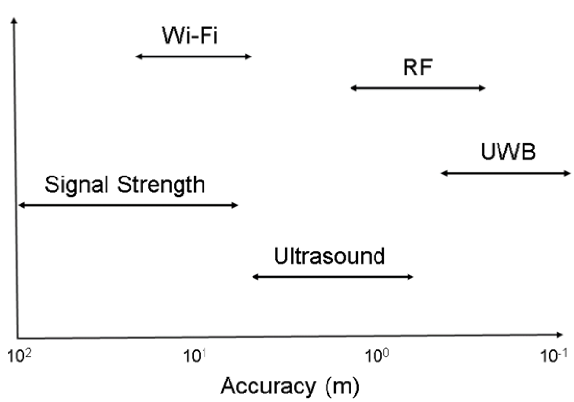

Fig. 1. Summary of indoor experiments run by Clarke et al. [3].

Clarke et al. [3] where five commercial real-time location systems (RTLS) which utilized competing technologies (signal strength, Wi-Fi, ultrasound, narrowband radio frequency (RF), and UWB [4]) were tested in an operating room and intensive care unit in a hospital. The UWB system noticeably outperformed the other four systems in terms of reliability and accuracy [3]. Starting around the year 2000, there has been extensive research and development of UWB localization systems for a plethora of different applications including indoor short range, outdoor urban environments, asset tracking in manufacturing, biomedical-related tracking and navigation, hospital tracking of personnel and assets, low power, integration with UWB high data rate (HDR) and low data rate (LDR) digital communication, etc. Given the wide range of technologies and applications of these systems, it is necessary to look at the overall evolution of UWB positioning both commercially and in the research community to gain perspective on its future trends and the technologies which will drive these new systems.

This paper is organized as follows: Section II looks at current applications of UWB localization both in industry and in the research community. This eclectic mix includes asset tracking for manufacturing, logistics, and military applications, ad-hoc wireless sensor networks (WSNs), biomedical sensors, and surgical navigation. Section III focuses on the technologies that have been utilized in developing UWB systems both in the past and in the future including microwave integrated circuits (MICs), monolithic microwave integrated circuits (MMICs), and radio frequency complementary-metal-oxide-semiconductors (RF/CMOS). Finally, Section IV looks at future trends in UWB localization which include small tag size, low power, integration with HDR UWB systems, and coexistence with existing wireless technologies.

II. Applications

UWB has gained widespread use in commercial and industrial applications and also in research endeavors. An overview of both these fields is provided to give a complete picture of the current and potential uses of UWB localization.

A. Industry

Commercial localization systems for indoor asset tracking applications are currently available from Multispectral Solutions Inc. [5], now owned by Zebra Enterprise Solutions, and Ubisense [4], which utilize time-difference-of-arrival (TDOA), and in the case of [4] a combination of TDOA and

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angle-of-arrival (AOA). The specified 3-D real-time accuracy of these systems is 10-15 cm with indoor operating ranges of over 50 m. Both of these systems operate in the 5.9-7.1 GHz range, which fall within the UWB spectrum regulations both in Europe (6-8.5 GHz) and the United States (3.1-10.6 GHz) while not falling within the standards set in Japan (7.25-10.25 GHz indoors). The Multispectral Solutions Inc. RTLS is now part of a family of RTLS from Zebra Enterprise Solutions which includes the RTLS from Navis™, which integrates radio frequency identification (RFID), GPS, and Wi-Fi for robust asset tracking solutions; the RTLS from Proveo which combines GPS and wireless local-area-networks (WLANs) for airport asset tracking; and the RTLS from WhereNet which utilizes RFID technology in the 2.4 GHz industrial, scientific, and medical band (ISM) for operation [6]. The use of passive and active RFID systems combined with a plethora of localization technologies including UWB, WLAN, Wi-Fi, GPS, and RFID provide a powerful and complete asset management solution for a wide array of applications including airport process optimization, marine terminals, aerospace, defense, automotive assembly optimization, etc. [6]. The Ubisense system is currently used in tracking automobiles as they are built in multiple stages at an assembly plant and also offers a military solution where personnel can be tracked both indoors and outdoors with the UWB technology seamlessly integrated with global positioning system (GPS) technology. Other asset tracking applications include tracking equipment and goods in a manufacturing facility and integration with other technologies (e.g. GPS, WiFi) in developing logistics solutions, in a similar mindset to the logistics solutions offered by Zebra Enterprise Solutions.

Additional players in the commercial market include Time Domain Corp. which offer the PLUS® RTLS for indoor asset tracking solutions, utilizing UWB in a similar manner to the Ubisense and MSSI systems by operating at a center frequency of 6.6 GHz with around 1 GHz bandwidth and an operating range near 50 m [7]. Figure 2 shows the use of the PLUS® RTLS for asset tracking in a hospital environment [8]. This allows tracking of patients, staff, and medical equipment which can be used to optimize workflow processes and provide better management of these different assets. Both the Time Domain Corp. and MSSI RTLS use UWB for digital communication while the Ubisense RTLS uses a more conventional digital communication technique (Bluetooth in the 2.4 GHz band).

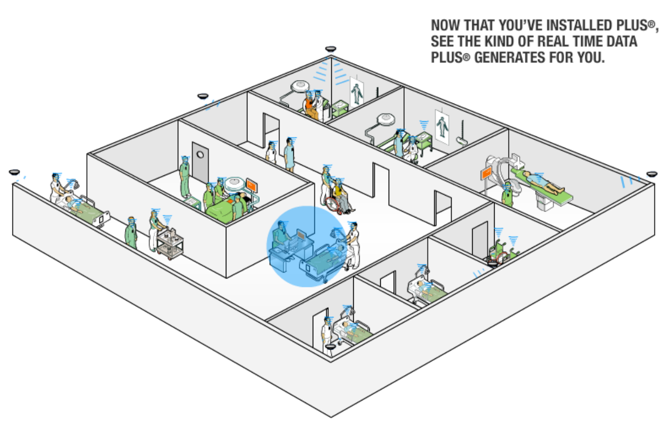

Fig. 2. PLUS® RTLS from Time Domain Corp. for asset tracking in a hospital [8].

More startup companies continue to enter the market of RTLS utilizing UWB technology. This includes the Israeli company Sandlinks Inc., which focuses on their system-on-chip (SOC) technology and ad-hoc network approach to provide robust localization and also drive down overall system costs. Their current applications focus on logistics and supply chains in various industrial sectors. It is also worth noting the use of UWB in 1-D ranging in autonomous cruise control and driver assistance and safety systems available in the Mercedes-S Class and operates at both 77 GHz and 24 GHz [9]. As mentioned in [10], the integration of UWB RTLS with other technologies is the current trend driving the technology behind future RTLS. With projected total revenue in the RFID market in 2009 of 5.56 billion USD, there are ample growth opportunities for UWB RTLS given its stark advantages over competing technologies in dense, indoor environments [11].

B. Research

On the research side of UWB positioning applications, major advances have been made in the fields of high accuracy 3-D positioning for surgical navigation [12], low power, integrated UWB CMOS solutions for biosensors [13], and the development of the IEEE 802.15.4a standard for LDR WSNs which has resulted in a substantial amount of research and development on UWB CMOS transceivers [14-15] which comply to the standard. Startup companies have also begun to appear (DecaWave), integrating an IEEE 802.15.4a transceiver with RTLS, giving LDR communication (110 kbps to 6.8 Mbps), high location accuracy (10 cm), and large operating ranges (up to 500 m indoor LOS and up to 45 m indoor NLOS) [16]. The use of these WSNs for sensing, LDR communication, and positioning make them an excellent candidate for a wide variety of applications including telemetry of bodily vital signs in body area networks (BANs), which can be extended into personal area networks (PANs), process optimization in logistics and manufacturing, emergency services, military, and high security (assuming proper measures are taken on the network layers above the UWB physical layer).

The push taken by DecaWave in utilizing CMOS technology for ultra-low power UWB transceivers which comply to the IEEE 802.15.4a standard, are compact in size (a 4.5 mm x 4.5 mm ball grid array), work in NLOS conditions, and can be used for high accuracy localization, is a good summary of the current momentum in research for UWB positioning integrated with WSNs. Another new application currently being researched is the use of UWB positioning for short range (i.e. 5-10 m operating range) high accuracy 3-D positioning. As discussed in [12], non-coherent 3-D real-time accuracy of 5-6 mm was obtained in a range of experiments including tracking a robotic arm, freeform motion, and movement along an optical rail. Meier et al. achieved comparable results in a 1-D coherent experiment using a direct sequence spread spectrum technique at 24 GHz where use of a

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2000 sample Kalman filter resulted in static accuracies as high as 0.1 mm [17]. With the recent interest in UWB imaging for various applications including breast cancer detection [18] and see-thru-wall imaging [19], another integrated approach for future systems would be combining these imaging systems with UWB positioning technology to place them in a global coordinate system similar to orthopedic surgical navigation systems where portable magnetic resonance imaging (MRI), computed tomography (CT), and fluoroscopic imaging systems are tracked in 3-D with optical tracking technology for incorporation into a larger navigation framework [20].

III. TECHNOLOGIES

The landscape of UWB positioning systems has changed with the evolution of technologies used in designing microwave circuits. Starting with MICs, followed by MMICs, and more recently RF/CMOS, the power consumption, size, and overall performance of UWB RF front ends have drastically improved. Also, the advent of new technologies related to digital signal processing (DSP) such as the wide prevalence of field programmable gate arrays (FPGAs) which can be converted to an application specific integrated circuit (ASIC) has, in conjunction with the evolution of RF front-ends, propelled UWB positioning systems forward with greatly improved performance, opening up whole new fields of applications. A look at the evolution of technologies in the RF front-ends as well as the advancement of digital UWB detection techniques and the final positioning algorithms (e.g. TDOA or time-of-arrival (TOA)) helps in understanding the drastic improvement seen in the operation of these systems in dense indoor environments and even NLOS conditions. Moving forward, the integration of UWB with other RTLS technologies (e.g. WLAN, W-Fi, GPS, RFID) will play a larger role in the choice of how these base technologies are utilized.

A. RF Front-Ends

Fontana provides an excellent overview of the evolution seen in UWB pulse generation starting with the use of step recovery diodes (SRDs) in MICs to produce high slew rate pulses [2] which can approach 300 ps in width [21]. More recent techniques include time-gated oscillators as well as time-gated power amplifiers combined with more conventional upconversion approaches [2]. Figure 3 shows an upconverted UWB pulse which meets the FCC requirements generated from a CMOS circuit where delayed rising edges were combined and then filtered to produce the UWB pulse [22]. A similar digital technique was used by Deparis et al. to generate UWB pulses as narrow as 60 ps using GaAs MMIC technology [23]. The prevalence of UWB CMOS transceivers which provide a complete solution continues to grow. Zheng et al. designed and tested a complete UWB transceiver which complies with the IEEE 802.15.4a standard [14]. A combination of burst position modulation and binary phase shift keying is used for the digital communication while the ranging is performed by calculating the time delay of the

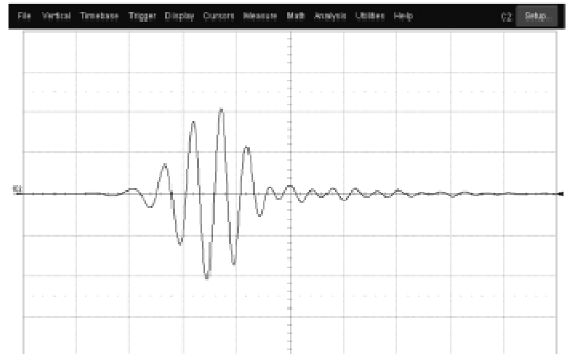

Fig. 3. UWB pulse which satisfies the FCC requirements and was generated by a CMOS circuit where different rising edges were combined in a delayed fashion, filtered to produce the UWB shape, and finally bandpass filtered to meet the FCC requirements [22].

baseband UWB pulse after low pass filtering. Two-way ranging of 3 cm is possible with this system [14]. The system draws a maximum current of 40 mA, although no final operating range is specified [14]. DecaWave provides a good example of a commercial company utilizing 90 nm CMOS technology for a complete UWB localization and communication solution which complies with the IEEE 802.15.4a standard [16]. SOC solutions implemented in the latest CMOS technology represent the future for UWB positioning systems in the 3.1-10.6 GHz band.

B. Digital Back-ends

Implementing the RF front-end in CMOS provides seamless integration of the RF front-end and the digital back-end since the digital processing can be performed on the same chip. The CMOS UWB transceiver in [14] provides an excellent example of this technique. If MIC or GaAs MMIC technology is used for the RF front-end, it is necessary to implement a separate digital backend. The tags in the Sapphire DART system [5] provide a good example where the RF front-end is implemented on one or multiple chips and even a separate substrate while the digital backend is implemented on a separate chip and possibly a separate substrate. It is possible to perform receiver-side processing of UWB signals with FPGAs, although the limiting factor in these systems is typically the sampling rate of the analog-to-digital converter(s) (ADCs). This can be solved by interleaving high speed ADCs together to achieve GSPS data rates. Another solution to achieve high sampling of UWB signals is the use of a periodic or sub-sampling technique which can be performed by either an analog circuit or digitally. An example of a microwave analog sampling circuit is given in [24]. Finally, it should be noted that graphics processing units (GPUs) are becoming more widespread in their use in real-time systems including UWB synthetic aperture radar [25]. The processing power available in GPUs opens up new real-time applications including hardware accelerated TDOA integrating iterative approaches and even extensions for NLOS situations. Methods have been developed for mitigation of NLOS effects in TDOA, ad-hoc scenarios [26]. The DecaWave system’s ability to operate up to 45 m in NLOS conditions shows the need to design UWB positioning systems for both LOS and NLOS environments [16].

IV. Future Trends

The prevalence of UWB RTLS has significantly increased since the FCC opened up discussion in 1998. The future trends in UWB positioning show its convergence with UWB digital communication in WSNs outlined by the IEEE 802.15.4a standard. CMOS technology is driving these new systems since it is low power, offers a small compact size for both the RF and digital portions of the system, and can be fabricated cheaply. Coexistance of UWB positioning systems with other technologies including IEEE 802.11a WLAN and Zigbee is a major concern which needs to be addressed at the design level of future positioning systems [12]. The seamless integration of UWB RTLS with existing technologies such as WLAN, GPS, and RFID presents another fundamental design concern for its incorporation into the larger RFID market. Next, a need exists for high accuracy UWB positioning systems (e.g. 1 mm 3-D accuracy) for a new set of applications including surgical navigation [12]. Finally, RF microelectromechanical systems (MEMS) present another exciting field for the future of UWB positioning [27] as well as the integration of UWB positioning systems with inertial measurement units (IMUs) for a redundant positioning strategy [28].

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