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Experimental Impulse Radio IEEE 802.15.4a UWB Based Wireless Sensor Localization Technology: Characterization, Reliability and Ranging

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Abstract — **Ultra Wide Band (UWB) transmission has recently been the object of considerable attention in the field of next generation location aware wireless sensor networks. This is due to its fine time resolution, energy efficient and robustness to interference in harsh environments. This paper presents a thorough applied examination of prototype IEEE 802.15.4a impulse UWB transceiver technology to quantify the effect of line of sight (LOS) and non line of sight (NLOS) ranging in real indoor and outdoor environments. Results included draw on an extensive array of experiments that fully characterize the 802.15.4a UWB transceiver technology, its reliability and ranging capabilities for the first time. A new two way (TW) ranging protocol is proposed. The goal of this work is to validate the technology as a dependable wireless communications mechanism for the subset of sensor network localization applications where reliability and precision positions are key concerns.**

Keywords — **Ultra Wide Band, TW Ranging, Reliability, LoS, NLoS**

I Introduction

Ultra Wide Band 802.15.4a transceiver technology is emerging as an ideal fit for the requirements of the next generation wireless sensor network [1]. IEEE has recognized the need to standardize UWB technology for use in personal area networks (PANs) and has established the IEEE 802.15.4a standard specifying a new UWB physical layer for WSNs [2]. UWB technology promises to be low in cost, miniature in form factor, energy efficient and robust to interference, small-scale fading and shadowing thusly ensuring stringent quality constraints can be fulfilled. Furthermore as real-time localization is becoming a more important concept in WSNs the precise ranging and geolocation capabilities of UWB is proving to be a unique selling point for the technology. A Time of Arrival (TOA) ranging method by capturing the transmission time is applicable for impulse radio UWB signal from the nature of its impulse waveform in the time domain. The IEEE 802.15.4a standard based on a impulse UWB signal supports a TOA ranging mechanism [3]. Employing prototype fully IEEE 802.15.4a compliant transceiver technology the world's first IEEE 802.15.4a UWB wireless packet was transmitted and successfully coherently received in real time in March 2009 [4]. This impulse UWB prototype transceiver technology can easily be placed in the next generation Wireless WSN category.

However, the presence of factors such as crystal offset, system delay and obstructions leads to a significant challenge resulting in biased distance estimates. The goal of the paper is to examine the characterization, reliability and ranging precision of an impulse UWB based transceiver for both indoor and outdoor environments. A two way ranging algorithm employed as part of this work is described in detail. A theoretical analysis of impulse UWB radio for wireless communication and ranging is provided employing the Shannon Hartley theorem [5] and Cramer-Rao lower bound

(CRLB) [6] method.

To fully test the reliability of the UWB ranging system, we focus on a distance measuring experiment firstly at indoor environment considering the case LOS area with multi-path, and also the case NLOS with different materials, for instance, counters, chairs, door and walls; secondly, we consider the outdoor open field case where with reflections are presented at the receiver. Relevant signal characterization, the pulse response, and transmitting power are measured. We propose a new two way ranging protocol which increases the time delay between the first and strongest paths when employing the leading path algorithm. Finally some conclusion are included.

II Theoretical analysis of UWB ranging

A classical time of arrival based method called two-way ranging (TWR) was originally proposed in [3]. The practical ranging demonstration is described in Fig.1. The leader observes a round trip delay

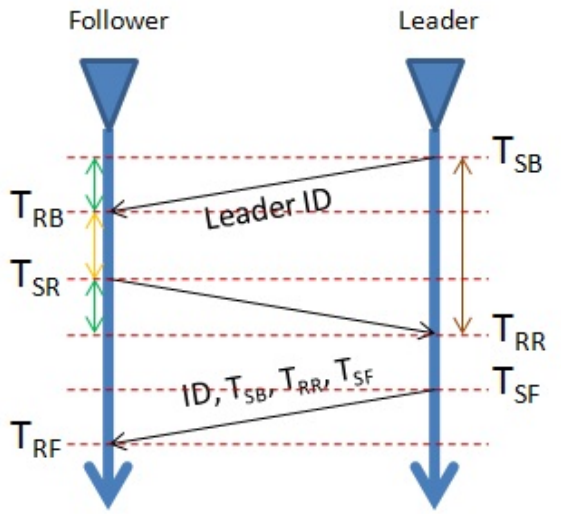

Fig. 1: TW-Ranging Method

$L_{RT} = T_{RR} - T_{SB}$ and a turn around time $L_{TA} = T_{SF} - T_{RR}$. The follower observes a round trip $F_{RT} = T_{RF} - T_{SR}$ and a turn around time $F_{TA} = T_{SR} - T_{RB}$. The value of transmission time T is computed at leader (T_l) and follower (T_f):

$$2T_l = (T_{RR} - T_{SB}) - (T_{SR} - T_{RB}) \tag{1}$$

$$2T_f = (T_{RF} - T_{SR}) - (T_{SF} - T_{RR}) \tag{2}$$

The follower can then combine these two resultant round trip times (by averaging) to remove the effects of clock differences. The result is then divided by 2 to get one way trip time.

$$T = \frac{2T_l + 2T_f}{2 \times 2} \tag{3}$$

Thus the distance between the two prototypes is:

$$d = T \times C \tag{4}$$

Here C is the speed of light.

When implementing the ranging method in a practical operation, reliable ranging depends on the system's ability to accurately determine the transmitting and receiving times of the signal messages at the antenna. The IEEE 802.15.4a defines specifically the time stamps reflecting the time instant the first ultra wide band pulse of the first bit of the physical layer header (PHR)of a ranging frame. Moreover, there are a number of challenges that remain before accurate ranging can be achieved in a harsh environment; these include multi-path, radio interference, and the NLOS propagations. Thus, the TWR requires the RF signal should have a good channel capacity and be robust to interference enable the detection of the first path of received signal.

An ultra wide band signal is defined by the FCC to have either a signal bandwidth exceeding 500MHz or a fractional bandwidth exceeding 0.2. UWB is broadly categorized into impulse UWB and multi-carrier UWB. It is most likely that signals formed by pulses with duration in the order of fractions of nanoseconds will be UWB signals. This paper is specific to impulse UWB. For any given RF radio, Shannon's theory [5] (equation 1) examines the characterization of the signal channel.

$$C = B \times \log_2(1 + S/N) \tag{5}$$

In equation (5), C is the maximum channel capacity, B is the channel bandwidth, and S/N is the signal to noise ratio. This equation indicates that for high frequency bands, large channel capacity is available despite a reduction in transmission power. If both UWB (500MHz) and narrow band signal such as IEEE 802.11n [7] (40MHz) has the same S/N, the channel capacity of UWB is approximately 12 times larger than IEEE 802.11n.

Impulse UWB pulse waveform can be easily generated from a Gaussian pulse and its derivatives. A Gaussian pulse in the time domain is described in [8] as:

$$P(t) = \pm \frac{\sqrt{2}}{\alpha} e^{-\frac{2\pi t^2}{\alpha^2}} \tag{6}$$

Here

$$\alpha^2 = 4\pi\sigma^2 \tag{7}$$

where α is the pulse form factor and σ^2 is the variance. The Gaussian pulse and its fist 15 derivatives are shown at Fig.2. These pulses are not directly used for practical applications because of

the need to meet the spectrum as mandated by the FCC. For instance, a Gaussian pulse can modulate a 500MHz signal with a center frequency at 4GHz. The first pulse is a Gaussian monocycle.

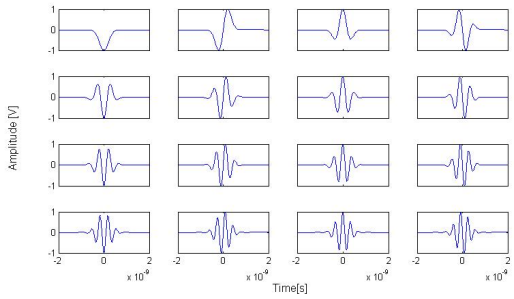

Fig. 2: The Gaussian pulse and its derivatives

From equation 6, it is clear that the bigger the α value is, the narrower the pulse width, but the wider frequency bandwidth. When the order of the Gaussian pulse derivative increases, its peak frequency increases as indicated in Fig.3.

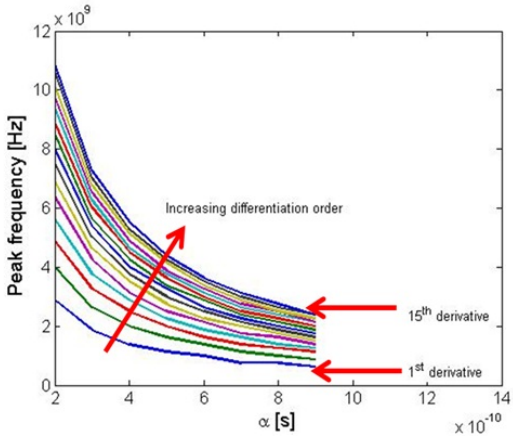

Fig. 3: 15 order derivative verus pulse Peak Frequency and α

An impulse UWB signal is a discrete signal which can be easily generated by Time-Hopping (TH) modulation and Direct Sequence (DS) modulation. The DS modulation is selected to generate a UWB signal whose transmitting signal is indicated as follows:

$$S(t) = \sum_{j=-\infty}^{+\infty} d_j P(t - jT_s) \tag{8}$$

Here, j is integer, d_j is the pseudo random sequence, T_s is the pulse duration, $P(t)$ is signal pulse. A simulation of a DS UWB signal is shown in Fig.4, pulse repetition period $2e^{-9}$s, 10 pulses per bit, periodicity of the DS code is 1 0, and pulse duration is $0.5e^{-9}$s. From equation 8 and Fig.4, it is clear that the UWB system architecture

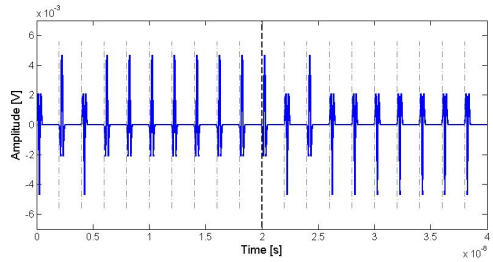

Fig. 4: Direct Sequence UWB Signal Simulation

is more simple when compared to the Direct Sequence Spread Spectrum (DS-SS) system with Binary Phase Shift Keying (BPSK) carrier modulation. The discrete UWB signal is narrow in width and can be distinguished from multi-path reflections, making accurate pulse timing more strength forward when compared with conventional RF radios for indoor environments.

For ranging applications, the system captures the transmitting time employing the time of arrival method. The Cramer-Rao lower bound states that the variance of any unbiased estimator would not be lower than the inverse of the Fisher information. Where, the Fisher information is defined as a way of measuring the amount of information that an observable random variable X carries about an unknown parameter θ upon which the probability of X depends. The CRLB for impulse UWB signal time delay estimate is given by Kay [6] as follows:

$$Var(\tau) \geq \frac{1}{SNR \times \beta^2} \tag{9}$$

In the equation 9, τ is the transmission time, SNR is the system signal to noise ratio, and β is the the effective bandwidth. Therefore, the wider signal bandwidth or the better the SNR, the more accurate the ranging precision.

Impulse UWB is therefore a promising technology for location aware sensor networks, due to its high quality communication and accurate ranging. Owing primarily to the fine time resolution in the order of sub-nanoseconds pulses, accuracy of few centimeters in distance measurement can be obtained.

III Experimental Activities

The goal of this experiment is to validate the characterization, reliability and ranging of the UWB transceiver technology in indoor and outdoor environments. The measurements were made using two FCC-compliant UWB radios obtained from Decawave, a company [9]. The primary focus is to characterize the electrical properties of these UWB transceivers. The two radios, a leader and a follower, generate impulse UWB signal resulting in a signal with a bandwidth of 500MHz and center frequency 4GHz.

In the system configuration, a PRF of 16MHz, a preamble length of 1024, preamble code 4 and data rate 850kbit/s is selected for both transceivers. The system delay which is the key factor for ranging measurement is tested and determined to be 277.850ns. However, the system delay may need to be tuned if operating modes are changed, for instance, changing the PRF value might mean that the delay needs to be changed up or down. Shorter system delay will produce larger error in the operational ranging value due to the crystal offset in ranging method, while larger system delay will lead to the time of arrival to be a negative value. The prototype has no Automatic Gain Control (AGC) unit, thus, setting of the transmission attenuation value is needed which is 13.5dB to insure the transmitting power is complaint to the FCC emission limits.

The UWB radio signal spectrum captured by an agilent spectrum analyzer is shown as Fig.5. The effective bandwidth about 500MHz from lower frequency 3.75GHz to upper frequency 4.25Ghz is observed with 1MHz resolution bandwidth. The Power Spectrum Density(PSD) is approximately -41.3dBm/MHz which meets with FCC emission limits as shown in Fig.6. The band power measured -13.31dBm at the 4.22GHz point, from which, the antenna gain is calculated resulting in a value of 3.1.

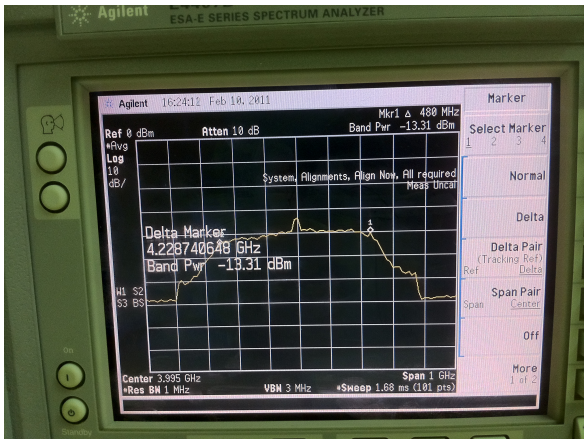

Fig. 5: UWB Signal Spectrum

The TWR ranging algorithm (equation (1),(2),(3),(4)) is embedded in the system IC for each of the prototype boards. As this is a digital hardware, the frame time adjustments at both the transmitter and the receiver can not be avoided. In some multi-path channels, the first arriving signal component might not have the largest energy when compared with multi-path reflections. Therefore, in those channels, the time difference between the first and strongest paths appears as a positive bias in the range estimate. Assume that both leader and follower

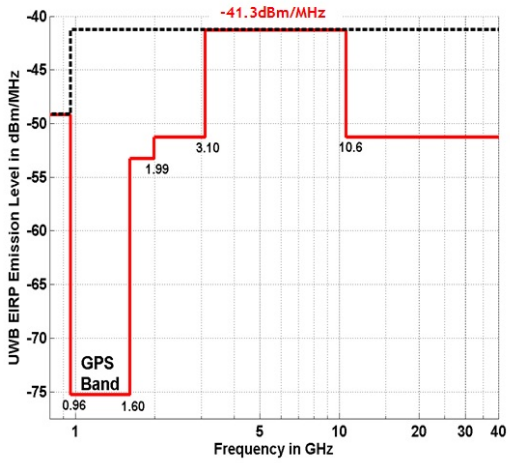

Fig. 6: Indoor Emission Mask

have no clock frequency offsets. According to the original TW ranging protocol in [3] as equation 1 and equation 2, we propose a new TW ranging protocol as follows:

$$2T = T^L_{RTT} - T^F_{TAT} - T^L_{off} - T^F_{off} \tag{10}$$

Here, the RTT^L is round-trip-time of the leader, the T^F_{TAT} is the turn around time of the follower, the T^L_{off} is the time interval between the first path and the strongest paths at the leader, similarly the T^F_{off} at the follower. The leading path software which is used to find the first in time arriving receive signal defines a time delta is added onto the receive-time stamp reference. If the channel is assumed to be symmetric, and the leader and follower are identical devices, than $T^L_{off} \approx T^F_{off}$. The range estimate d can be obtained as

$$d = \frac{C}{2}(T^L_{RTT} - T^F_{TAT} - 2T^L_{off}) \tag{11}$$

The system delay is added to the time stamp of the frame transmit-time, while it is subtracted at the frame receive-time. The pulse to pulse delay time present at start of frame delimiter (SFD)to the PHR transmission generated by pulse repetition frequency (PRF)is added. Compensation for the clock offset is achieved by adding the relevant offset. Thus, the total ranging time is the summation of ranging count and clock offset.

After setting these parameters, we start to do the ranging measurement. Firstly, we check the pulse response and system delay from both radios to make sure the system working.

The channel response is captured from a ranging GUI as shown in Fig.7, in which the red line is the plot of the real pulse response, the green line is the imaginary response and the blue line is the computed magnitude values. The vertical cyan line is the leading path which is used to

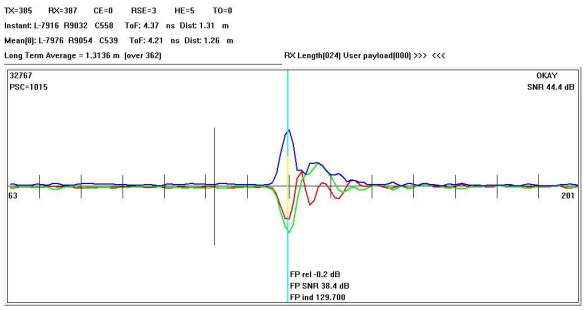

Fig. 7: Received UWB Signal Response

find the first in time arriving receive signal. The system SNR (44.4dB), first path SNR (38.4dB), and the real time distance (1.31m) is tested and recorded. This distance is firstly measured in a office with fewer obstructions and subsequently less reflections. Compared with the true value 1.30m measure physically using a tape, the measured instant and average distances are very accurate with only 1cm error. The round trip time value L, R, of both local and remote prototypes and their average value C are calculated in device time units [3]. The device time units follow the definition of time contained in the IEEE Std 802.15.4a, which states the LSB of a time value represents 1/128 of a chip time at the mandatory chipping rate of 499.2MHz. After dividing C by 128 and multiplying by the speed of light, the distance is finally calculated.

IV EXPERIMENTAL RANGING RESULTS

After testing the UWB system, we aim to validate the reliability of the UWB transceiver ranging in cluttered indoor and outdoor environment. We firstly characterize the effects of obstructions and define 3 scenarios as shown in Fig.8. according to the different channel models (LOS, Soft-NLOS, Hard-NLOS). Several offices, hallways, and yards (in the open field) in the Tyndall National Institute constitute the setting of the campaigns. One prototype is located at the fixed origin, while the other moves to perform point-to-point measurements. The distance between two radios is varied from 1m up to 45m to capture a variety of operation conditions. The 30cm height radios mounted on the floor. In each measurement location, the received pulse response, instant and average distance estimates, SNR, as well as the actual distance from tape are recorded.

a) *LOS campaign*

The line of sight ranging campaign as shown in Fig.8(a,b) is conducted in a library, an indoor hallway, an outdoor hallway and in the open field. Testing Points are placed randomly but are restricted to the tape measured points. The points are grouped with no obstructions. Fig.9 shows

(a) Outdoor LOS (b) Indoor LOS (c) Soft NLOS (d) Hard NLOS

Fig. 8: LOS, Soft-NLOS, Hard-NLOS Ranging Campaigns

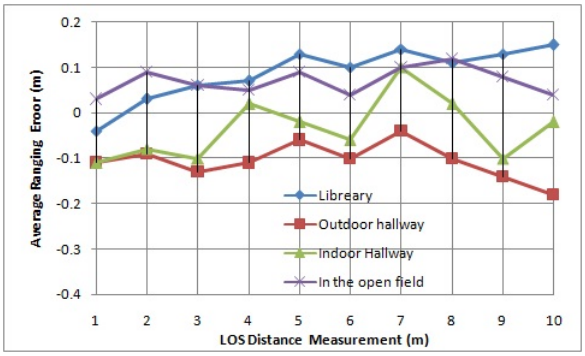

Fig. 9: Ranging Results of LOS Area Measurement

the average ranging results in the library which has some counters and chairs around the prototypes, the outdoor hallway in which the two boards are close to outside walls, the indoor hallway with some doors, walls on the both sides and in the open field where has fewer obstructions, if any, sources of signal reflection other than the operators, the equipment and the ground. The average ranging errors of these tested points are less than ±20cm regardless of the system error. The errors measured in the open field are less than 10cm, which is more accurate than the results of other conditions with more reflections and interferences in between.

b) *Soft-NLOS campaign*

This campaign aims to validate the reliability of the UWB ranging system through a Soft-NLOS which occurs when the LOS path is obstructed by materials with relatively low attenuation or by a combination of these materials such as glass,doors, counters and chairs. We select 3m testing point for each experimental cluster and deploy different materials between the two radios as in Fig.8 (c). Some obstructions are combined as the actual conditions. All the results of clusters in the Fig.10 show that the error from different obstruction varies from 6cm (Glass) to 29cm (Door). However, this experiment conditions represent the most common channel model over the distances of interest in most European offices, the average results which are less then 30cm accuracy are acceptable to validate that the UWB signal can be utilized in indoor ranging measurements.

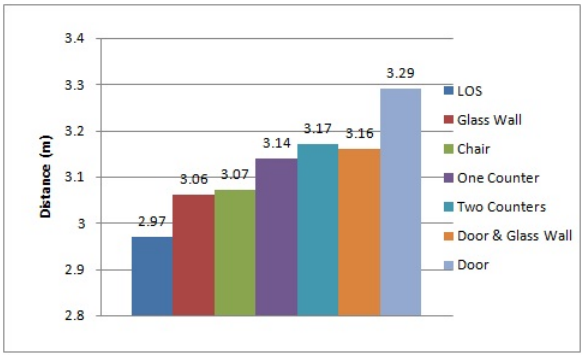

Fig. 10: Ranging Results of Soft-NLOS Area At 3m Point

c) *Hard-NLOS campaign*

This campaign (Fig.8 (d)) attempts to validate the capability of the UWB ranging system in a hard-NLOS channel which is severely attenuated due to multiple concrete Walls or multi-obstructions in the environment. Results in Fig.11 indicate that hard obstructions attenuate the UWB signal and generate large positive bias in the range estimates. The distance error varies widely from 26cm of one wall to 87cm of 4 walls. While at the 38m point, the receiver is unable to receive the signal. It is clear that localization in this hard NLOS rooms can not obtain high precision. Some methods, algorithms [3] are proposed to improve or solve the hard NLOS ranging problems, but this is still a challenging problem in indoor location area.

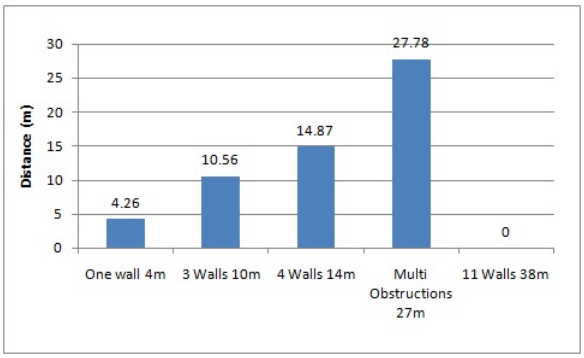

Fig. 11: Ranging Results of Hard-NLOS Area

V Conclusion

In this paper, we theoretically analyzed and realistically validated the reliability of an impulse based UWB transceiver point-to-point ranging system using a two way ranging algorithm in both indoor and outdoor environments. In theory, the UWB signal is very resistant to multi-path and reflections, the CRLB method proves that the UWB signal has a high precision in the order of several centimeters. In the practical operation, two UWB transceivers were evaluated in this study with a bandwidth of 500MHz satisfying the FCC emission limits of -41.3dBm/MHz. We proposed a new two way ranging protocol and implemented the algorithm in a ranging scenario. In most common channels, the time interval of the first and the strongest paths needs to be added into the TW ranging protocol to avoid the generation of a positive bias in the range estimate. Results of the ranging measurements in LOS, Soft-NLOS and Hard-NLOS channels show that UWB transceivers are capable of capturing accurate transmission time between two radios which can be used in turn to compute out the real distance. With features such as large channel capacity, robustness to interference and multi-path, energy efficiency and fine resolution, UWB transceiver technology is a dependable wireless communications mechanism for WSN localization applications.

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