IEEE 802.15.4a UWB-IR Ranging with Bilateral Transmitter Power Control Methodology for Multipath Effects Mitigation

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Abstract — **IEEE 802.15.4a Ultra Wideband Impulse Radio (UWB-IR) measures the distance using the time-of-arrival (TOA) of the leading path signal. Multipath propagation in indoor environments can adversely affect the signal to noise ratio (SNR) resulting errors in leading path detection. In this paper, the multipath effects mitigation is in focus and method for bilateral transmitter power control. Measurements for SNR status of the 802.15.4a UWB-IR propagation in indoor buildings are reported. Relevant aspects of power control are discussed on practical issues, using an automatic control framework, which is integrated into the symmetric double-sided two-way (SDS-TW) ranging protocol. We evaluate the resulting performance and compare with existing non-power control techniques in Line-of-Sight (LOS) condition. Experimental results show that, with power control, ranging error below sub 10cm occurs in more than 90% of the 4800 measurements from 2.5m to 30m; without power control, ranging error below sub 10cm occurs in less than 20%. The use of transmitter power controlled ranging method is capable of mitigating the uncertain multipath effects, improving the ranging accuracy and stability in indoor multipath environments.**

Keywords — **IEEE 802.15.4a UWB Ranging, Multipath Propagation, Bilateral Transmitter Power Control, SNR.**

I Introduction

Global Positioning System (GPS) is a representative positioning system for tracking in outdoor environments. However, indoor environments have increased positioning challenges due to accuracy requirements (sub 10cm) and multipath propagation effects making GPS ineffective. Ultra Wideband Impulse Radio (UWB-IR) transmission provides robust signaling, as well as high resolution ranging capabilities [1]. Therefore, UWB represents a promising technology for ranging and localization applications in indoor environments through TOA technique [2], [3]. 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 [4].

In practical scenarios, however, a number of challenges remain before UWB ranging and communication can be deployed. These mainly include hardware issues, such as uncommon time reference, clock drift, low sampling rate; and environmental issues, such as multipath propagation and non-line-of-sight (NLOS) propagation. The hardware issues have been significantly solved by using Symmetric Double-Sided Two-Way (SDS-TW) ranging protocol [4] and Energy Detector (ED)-based subsampling TOA estimators [5], [6], [7]. The SDS-TW demonstrated in Fig.1(a) that needs three TOA values to get a distance measurement based on time-of-flight (TOF) calculations, $d = TOF \times \dot{c}$, $\dot{c}$ is the speed of electromagnetic waves. A two-step TOA estimator based on ED for leading path detection [7] is demonstrated in Fig.1 (b).

We validated the above ranging method in an anechoic chamber, where has no multipath disturbances. The ranging error below 15cm/10cm oc-

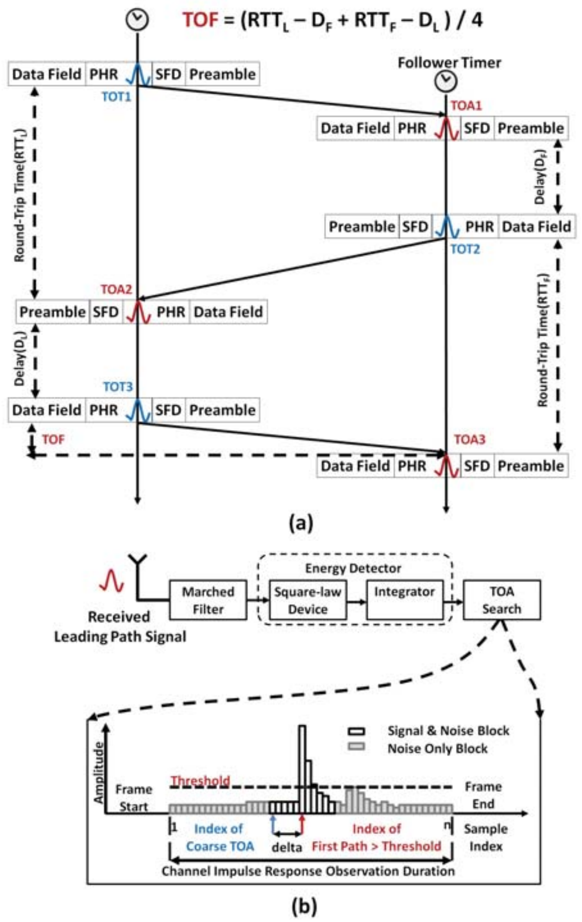

Fig. 1: (a) SDS-TW Ranging Protocol and (b) Two-step Energy Detector based TOA Estimator.

curs in 100% and 85% of the 7500 measurements, respectively. Hence, we can say this practical ranging method is reliable and can get accurate and stable ranging measurements. When implementing ranging in a real indoor office in Line-of-Sight (LOS) condition, the ranging error below 10cm occurs in less than 20% of the 7500 measurements. The multipath propagation has a significant impact on the ranging accuracy. It is therefore critical to understand the impact of multipath propagation on ranging systems and to develop techniques that mitigate their effects.

The performance limits of time-based UWB ranging in multipath propagation and some TOA estimators designed to mitigate the multipath effects are studied. The performance of any TOA estimators can be bounded using theoretical bounds, like Cramer-Rao Lower Bounder (CRLB) [8]. It shows that, the SNR is a more accurate indication of the UWB ranging performance. In [9], a SNR model is proposed that the SNR is related to the received power, implementation loss, receiver noise figure and the noise spectral density. However, the multipath effects, like multipath fading, are not taken into account. In [10], super-resolution TOA technique is proposed to estimate the channel multipaths TOA and amplitude using root multiple signal classification (MUSIC). A pattern to identify closely-spaced direct path and ground reflection is given in [11]. The main drawbacks of existing multipath mitigation techniques are: (i) loss of information in SNR model due to the direct use of white noise instead of the total noise sources; (ii) difficulty in determining and mitigating the multipath components in the channel impulse response of leading path, as they may overlap.

We have performed an extensive indoor measurement campaign with FCC-compliant 802.15.4a UWB-IR radios to quantify the effect of multipath propagation. From these channel impulse responses obtained, we first extract features that are representative of the real multipath propagation channel of the IEEE 802.15.4a UWB-IR. Then, we consider a transmitter power control method to mitigate the multipath effects. Relevant aspects of power control on practical issues are discussed. Performance comparison is made with the non-power control scheme and some experimental ranging results published. Experimental results show that, the ranging error below 10cm occurs in more than 90% of 4800 measurements ranging from 2.5 to 30m when using bilateral transmitter power control algorithm; without power control, ranging error occurs in less than 20% of the measurements.

The rest of the paper is organized as follows. In Section II, we introduce the TOA estimation of leading path. In Section III, we analyze the multipath effects and the SNR features. Section IV describes bilateral power control algorithm. Numerical performance results are provided in Section V, and we draw our conclusions in Section VI.

II IEEE 802.15.4a UWB TOA Estimation

Considering a scenario in which a unitary energy leading pulse $p(t)$ is transmitted with duration T_p through a channel with multipath and thermal noise, the received signal can be written as:

$$r(t) = s(t) + n(t) \tag{1}$$

Where, $s(t)$ is the impulse response of transmitted leading path and $n(t)$ is AWGN with zero mean and two-sided power spectral density $N_0/2$. We consider frequency-selective fading channel, in which case [12]:

$$s(t) = \sqrt{E_p}\sum_{n=1}^{k}\alpha_n p(t-\tau_n) + n(t) \tag{2}$$

Where, n is the number of received multipath components with α_n and τ_n denoting the amplitude and delay of the n^{th} path, respectively. With

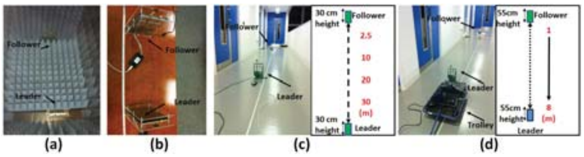

Fig. 2: Ranging Experimental Setup: (a) Anechoic Chamber; (b) Office (c) Hallway; (d) Hallway (mobile).

the normalization $\sum_{n=1}^{n} |\alpha_n|^2 = 1$, such that E_p represents the average energy. The goal is to estimate the TOA $\tau = \tau_1$ of the direct path by observing the received signal $r(t)$.

The first pulse of the physical layer header (PHR) is defined as the leading path for ranging [4]. We use a two-step TOA estimator based on ED to detect the TOA of the leading path, see Fig.1(b). The received signal is first passed through a marched filter (MF). The observed signal forms the input to the ED, whose output is sampled at every T_{int} seconds (the integration time of the ED); thus $n = T_{ob}/T_{int}$ samples are collected in each subinterval (with indices [1,2...n]). T_{ob} is the channel impulse response (CIR) observation duration. The TOA estimator firstly measures the coarse TOA of the leading pulse TOA_{coarse} with its relative index N_{coarse}, which is TOA of the first byte of the CIR read. Then, it picks of index N_{max}, whose amplitude is the first one above the calculated threshold. The distance *delta* between N_{coarse} and N_{max} is compensated to TOA estimation. The TOA of the leading path can be expressed as:

$$TOA = TOA_{coarse} + T_{int} \times delta + \frac{T_{int}}{2} \tag{3}$$

In the AWGN channel, TOA estimate is given by the time instant corresponding to the maximum absolute peak at the output of the matched filter over the observation interval. The performance of the estimator achieves the Cramer-Rao Lower Bound (CRLB) for signal SNR in AWGN channel as described in [8]. The mean square error of any unbiased estimate $\hat{\tau}$ of the true TOA τ can be lower bounded by:

$$V(\xi) \geq \frac{1}{2\sqrt{2}\pi B\sqrt{SNR}} \tag{4}$$

Where, the $V(\xi)$ is the variance of TOA error, $\xi = \hat{\tau} - \tau$ is the TOA error. B is the effective signal frequency bandwidth. Equation (4) shows that SNR is a more accurate indication of ranging accuracy.

III Multipath Channel Observation

To observe multipath effects, we investigated the received signal status using two IEEE 802.15.4a

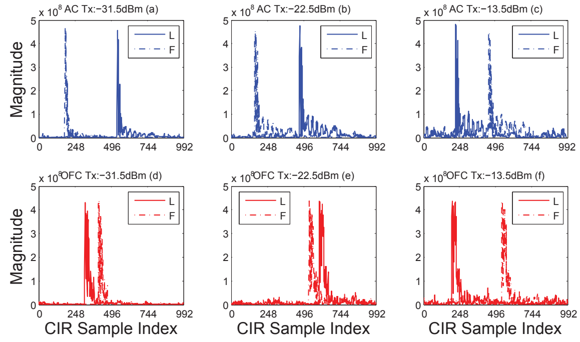

Fig. 3: Channel Impulse Response (CIR) in Anechoic Chamber (a), (b), (c) and Real Indoor Office (d), (e), (f).

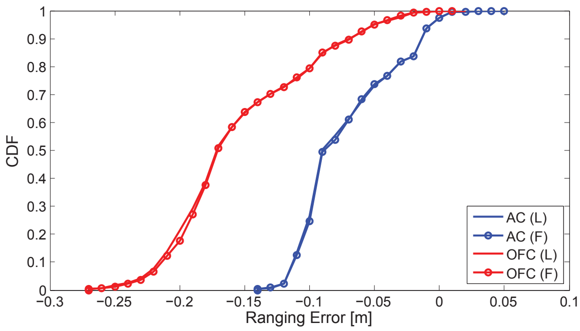

Fig. 4: CDF of the Ranging Error in AC and OFC.

compliant UWB radios. They are named as leader and follower, respectively, to implement the ranging measurement. The primary focus is to characterize the effects of multipath. Measurement was implemented in an anechoic chamber and in a real office in LOS condition, see Fig.2 (a) and (b). The signal parameters are outlined in Table 1 and they meet the 802.15.4a standard constraints and FCC limits [4]. The transmit-power is selected from -31.5dBm to -13.5dBm with an interval of 1.5dBm. The ranging error is shown using the empirical CDFs. The channel impulse response (CIR) observation duration is 992 indices. The LSB of a time value represents 1/128 of a chip time at the mandatory chipping rate of 499.2 MHz. Hence, 128 indices make up a signal cluster in which the TOA index exists.

Fig.3 shows the different CIRs captured using different signal outputs (-31.5dBm, -22.5dBm and -13.5dBm). The responses, obtained in indoor office (OFC), exhibits more adjacent peaks with comparable amplitude to the largest peak than the response collected in anechoic chamber (AC). In AC, a ranging error below 10cm occurs in more than 80% of the 7500 measurements. However, in OFC, a ranging error below 10cm occurs in less than 20% of the measurements, see Fig.4. Clearly, multipath effect is a big error source in the TOA-based ranging.

The strength of received signal, which is related

Table 1: IEEE 802.15.4a UWB Signal Parameters

IEEE 802.15.4a Channel index	2
Preamble Length	1024
Pulse Repetition Frequency	16MHz
Data Rate	850Kbits/s
Signal Bandwidth	500 MHz
Center Frequency	4 GHz
Maximum Transmit-power	-13.5dBm

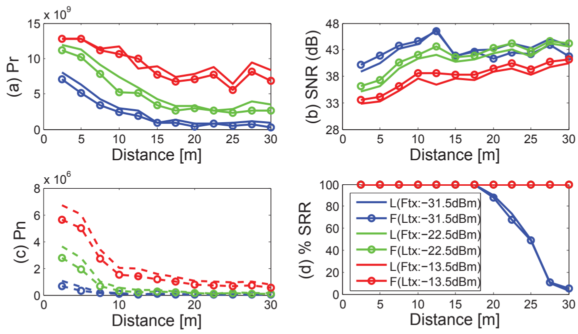

Fig. 5: Parameters measurements in different positions (a) Receive-power (Pr); (b) SNR; (c) Noise (Pn) and (d) PRR.

to the transmission distance, is another constraint of ranging performance. Fig.5 shows the multipath channel status ranging from 2.5m to 30m. With the distance increasing, the original receive-power (Pr) and noise values decrease, see Fig.5 (a) and (c), respectively. However, the SNR increases with distance increasing, see Fig.5 (b). It means that the multipath effects become less impact on the 802.15.4a UWB signal transmission with distance increasing. Due to the noise floor of the radios, the related percentage of pulse receive rate (PRR) decreases with distance increasing, see Fig.5 (d). The higher transmit-power,the higher PRR and better connectivity.

IV Bilateral Transceiver-power Control Methodology

With the multipath channel properties of IEEE 802.15.4a UWB transmission system observed, transmitter power control method is considered to optimize the SNR (and thus mitigating the effects of multipath propagation).

a) Power Control Aspects

Being subjective, some relevant aspects of the power control in 802.15.4a UWB ranging system should be considered.

• Ranging algorithm. This is the basic framework for UWB ranging system. Power control loop should be integrated into this framework.

• Power constraints. The transmission powers are considered due to the hardware limitations and

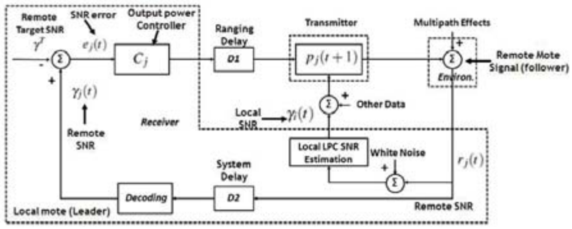

Fig. 6: Power Control Method when Employing an SNR-based Power Controller.

the FCC limits.

• Time delays. Measuring and control signaling take time, resulting in time delays are typically fixed due to standardized signaling protocols.

• Tradeoff management. The one is the most correct BER expression [1] is:

$$BER = \frac{1}{2}erfc(\sqrt{\frac{1}{2}SNR}) \tag{5}$$

In equation (5), the $erfc$ is the error function. The BER here is used to manage the tradeoff between receive-power and SNR. A set-point SNR value can be selected and related directly to BER.

b) Fixed Step Size Power Control

According to the SDS-TW ranging algorithm, see Fig.1 (a), a TOF is calculated by the bilateral communication links between the leader and the follower. Hence, both 802.15.4a transceivers need to implement the power control loop integrated into the ranging algorithm.

Consider the arrangement of power control scheme at one UWB transceiver in Fig.6, the transmit-power level is increased/decreased depending on whether the SNR decoded ($\gamma_j(t)$) from the j^{th} remote signal $r_j(t)$ is above or below the target SNR (γ^T). The SNR error is:

$$e_j(t) = \gamma_j(t) - \gamma^T \tag{6}$$

The decision feedback where the sign of error $e_j(t)$ is fed back resulting in equation (7):

$$s_j(t) = sign(e_j(t)) = sign(\gamma_j(t) - \gamma^T) \tag{7}$$

We consider a fixed step size power control (FPC) where the power $p_j(t)$ is increased or decreased by βdBm depending on the sign of error $s_j(t)$ as equation (8):

$$p_j(t+1) = p_j(t) + \{^{-\beta, s_j(t)<0}_{+\beta, s_j(t)>0} \tag{8}$$

In the ranging architecture, see Fig.1, the delay, is set for mitigating the clock drift issue(about

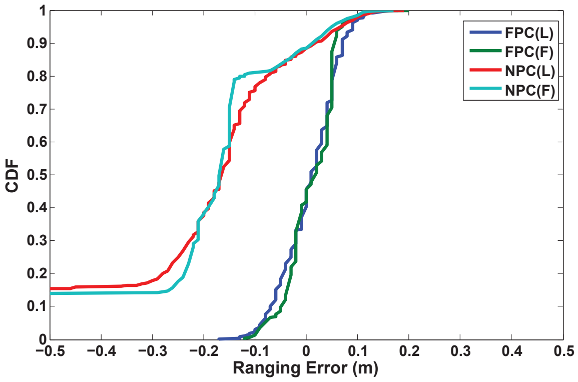

Fig. 7: CDF of the Ranging Error from 2.5m to 30m Using FPC and NPC.

Table 2: Comparison Ranging Performance of FPC, NPC and other experimental results

	FPC	NPC	Others [13]
Measurements	4800	4800	1024
Error<10cm	>90%	<20%	<5%
Error<5cm	>60%	<5%	<1%
Stability	0-20cm	0->1m	0-3m

300ms). Hence, cooperating with this ranging algorithm, there is enough time for measuring and control signaling delay ($D1$) in the power control loop. The other delay $D2$ is the system delay which is also considered into the ranging algorithm.

V Practical Implementation

The above bilateral power control method, with a fixed step size power control (FPC) scheme, and non-power control method (NPC), using the maximum transmit-power (-13.5dBm) of FCC limits, are critically assessed using a multipath propagation issue scenario. Stationary (from 2.5m to 30m) and mobile (from 1m to 8m with a trolley) ranging experiments are set up inside a real building, see Fig.2 (c) and (d).

In this work, a target SNR value of 43dB is selected for both UWB transceivers, guaranteeing a BER of $< 3e^{-11}$, verified using equation (5). The β is set to be 1.5dBm and the $e_j(t)$ is round to integer. The maximum transmit-power (MaxP:-13.5dBm) is selected at the beginning for strongest radio links. A frame is a record of the receive-time of the leading pulse according to the ranging algorithm. Basically, a frame-time is about 0.6s which is equal to 2 delays (300ms) plus 2 TOFs.

a) Stationary Ranging Test

Fig.7 shows that the ranging error below 10cm occurs in more than 90% of 4800 measurements when

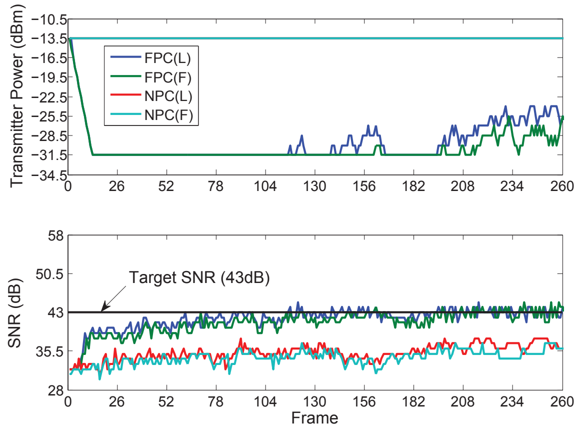

Fig. 8: Transmitter Power Updating (upper waveforms) and SNR Updating (lower waveforms) of FPC and NPC in Mobile Condition.

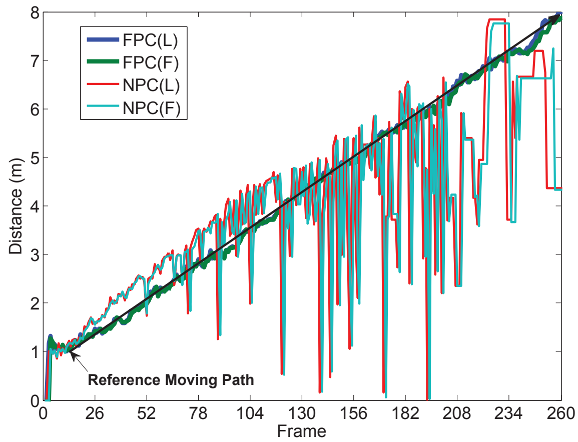

Fig. 9: Ranging Using FPC and NPC in mobile condition.

using bilateral transmit-power control algorithm ranging from 2.5 to 30m; however, without power control, ranging error occurs in less than 20% of the measurements. The Table 2 shows the performance comparison of the proposed methods for UWB ranging. The utilization of bilateral power control can get more stable and accurate ranging measurements.

b) Mobile Ranging Test

The mobile ranging test is made to observe the performance of the bilateral power control method in the real-world environment with uncertain factors such as the motion of the leader and time-varying wireless channel. The follower stands at a fixed position, the leader moves 7 meters using a trolley and the distance between the two devices is increased from 1m to 8m, see Fig.2 (d).

The FPC runs at the leader and the follower, adjusting output power according to whether the SNR is greater or less than the target SNR (43dB), see Fig.8 (upper waveforms). While the NPC method keeps the maximum transmit-power (-

13.5dBm). Before the 100^{th} frame point, the two UWB transceivers employing FPC use minimum transmit-power (-31.5dBm) and SNRs are less than 43dB. The minimum transmit-power is set by the device limits. With distance increasing, the value of the SNRs increases, see Fig.8 (lower waveforms). The power controller updates the transmitter power to get and maintain the target SNR (43dB). Whereas, the SNRs obtained from the NPC are always less than 38dB, but the value increases with distance increasing from the starting point (32dB).

In Fig.9, the leader moves from 1m (starting at about 13 frames point) to the end (8m test-point) with a approximate velocity (34frames/m). When employing power control method (FPC), the slopes of the ranging curves approximately meet reference moving path. The power controlled ranging channel is more stable than non-power control (NPC) which obtains highly variable ranging estimates (0$\sim$ 4m difference) during the moving period.

VI CONCLUSION

In this paper, we presented a novel approach to deal with multi-path propagation that relies solely on features extracted from the received waveform. This technique does not require changing the ranging protocol and time-of-arrival estimation method for the features. To validate this technique in realistic scenarios, we performed an extensive indoor measurement campaign using FCC-compliant IEEE 802.15.4a UWB radios. The bilateral power control method that is capable of dynamically controlling the outputs of the transmitters to reach and maintain the target SNR of leading path. Our results revealed that the proposed bilateral power control method outperforms pre-existing techniques, and the proposed bilateral power control method improves ranging accuracy and stability under LOS conditions. We observe that our bilateral power control method can: (1) cooperate with symmetric double-sided two-way ranging protocol; (2) deal with the uncertain multipath effects and (3) significantly improve the ranging performance in the realistic environments.

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