Energy Detection Receiver with TOA Estimation Enabling Positioning in Passive UWB-RFID System

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Abstract—This paper presents a passive UWB-RFID system with Time-Difference-of-Arrival (TDOA) positioning from system to circuit perspectives. Wireless powered RFID tags with UWB transmitter transmit wideband pulses to readers, allowing high accurate Time-of-Arrival (TOA) estimation. Low power low complexity TOA estimations using energy detection receiver are investigated. Max Energy Select (MES), Threshold Comparison (TC), and MES-Search-Back (MES-SB) algorithms are evaluated and analyzed. As a special focus, a prototype of the proposed energy detection receiver is designed and implemented. It consists of a 3.1-4.8GHz IR-UWB analog frontend with high speed digital circuits in 90nm CMOS, and a flexible back-end with a TOA estimator on FPGA.

I. INTRODUCTION

Radio Frequency IDentification (RFID) with positioning capability is highly demanded in the era of the Internet-of-Things. Location information of radio tags attached on objects will bring emerging applications and new services in our daily life, creating added value in market space. Impulse Radio Ultra-Wideband (IR-UWB) has been recognized as a promising solution for the future RFID to overcome limitations of current RFID systems such as very short operating range, insufficient ranging resolution for accurate localization, sensitivity to interference and scarce multiple access capability.

As an attractive feature of IR-UWB, ultra wide signal bandwidth with fine resolution in time domain, allows accurate ranging and precise positioning. RFID using UWB technology has been introduced by *Ubisense* and *Time Domain* for positioning as commercial products. However, these system require active RFID tags as well as complex and expensive readers. One of the most challenging issues for UWB positioning is to perform accurate Time-of-Arrival (TOA) with low sampling rate and low complexity receivers. Recently, TOA estimation using energy detection (ED) receivers for low power low cost positioning system has been studied [1]. In [2], an ED receiver for MAX TOA estimation is implemented with relatively high power consumption (48mW). But it offers limited accuracy ($\pm 5ns$) and multi-path effects are ignored.

In this work, a passive UWB-RFID system with positioning capability is presented from system to circuit perspectives. Passive RFID tags with UWB transmitter [3] that are remotely powered by electromagnetic waves, transmit impulse signal to readers. It promises high accurate TOA estimation thanks to the UWB pulses. In order to reduce the system complexity, Time-Difference-of-Arrival (TDOA) is considered, which is

Fig. 1. The architecture of the passive UWB-RFID positioning system.

able to perform positioning without synchronization between tags and readers. Low power low complexity TOA estimations using ED receiver are investigated. Max Energy Select (MES), Threshold Comparison (TC), and MES-Search-back (MES-SB) algorithms are evaluated and analyzed. As a special focus, a prototype of the proposed ED receiver is designed and implemented. It consists of a 3.1-4.8GHz IR-UWB analog frontend with high speed digital circuits in 90nm CMOS, and a flexible back-end with a TOA estimator on FPGA. The remainder of the paper is organized as follows. Section II is a brief system overview of the passive UWB-RFID system with positioning capability. ED-based TOA estimation algorithms are discussed in Section III. This is followed by the circuit implementation of the ED receiver and the TOA estimator in Section IV. Final conclusions are given in Section V.

II. SYSTEM DESCRIPTION

A passive UWB-RFID system for identification and positioning is proposed in Figure 1. It consists of RFID tags, power source nodes, and readers.

A remote-powered RFID tag with IR-UWB uplink and UHF downlink has been presented in [3]. It captures electromagnetic energy from power source nodes and stores in a capacitor. After the tag is powered, the IR-UWB transmitter sends pulses

containing modulated information to readers. In order to avoid the inter-pulse interference, which is fatal for TOA estimation, a tunable pulse generator is designed. During preambles for TOA estimation, a higher pulse amplitude with a longer pulse repetition interval is employed, while a higher pulse rate is utilized for payload reception.

The power source node is deployed to emit RF signal in a frequency band fitting to the power converter on tags. In our work, both UHF and 2.4GHz ISM bands are adopted. In many cases, the power source node is combined with the reader. In some scenarios where active tags with internal power sources are applied, this power source node can be removed.

The reader is the key enabler for the passive positioning system. In this work, it is essentially an IR-UWB receiver with a TOA estimator. Each reader estimates the TOA and uploads it to a centralized node for TDOA calculation. TDOA requires accurate synchronization between readers. This could be done by either a centralized controller wired or wirelessly, or a 2-way synchronization scheme between readers.

To reduce the system complexity, there is neither IR-UWB receiver on the passive radio tags nor synchronization protocol between tag and readers in our proposed system. Hence, TOA based ranging and positioning schemes which require synchronization among the target and the reference nodes are infeasible in our proposed system. TDOA, on the other hand, is able to measure the position even in absence of the synchronization between the reference node and the target node [4]. It is based on estimating the difference in the arrival time of the signal between the synchronized reference nodes. In our specific system, IR-UWB signal transmitted from a tag is received by different readers. Therefore, the TDOA is measured as $\tau_{TDOA} = \tau_1 - \tau_2$, where τ_1 and τ_2 denote the TOA estimates at the first and second readers, respectively. Consequently, the position of the tag can be calculated as by three reference nodes for 2D position and four readers for 3D position.

III. TOA ESTIMATION USING ENERGY DETECTION

All time-based ranging and positioning schemes require TOA estimations of the received signal. Conventional coherent estimations such as matched filter (ML)-based or correlation-based estimations require Nyquist rate sampling and complex DSP blocks. This approach is impractical for the UWB RFID positioning system which is constrained by energy and complexity. In this section, low power low complexity TOA estimations based on energy detection receiver is investigated.

A. Energy Detection Receiver

An energy detector shown in Figure 2 consists of a square law device followed by a finite time integrator. The output of the integrator $Z[n]$ is the energy of the input signal over time interval T_{int} in the past. This is to say, the output could be either the energy of the noise, or energy of noise added on signal (pulse). A symbol-spaced sampler results in low complex and low power implementations. In UWB communications, either OOK or PPM is applied. In OOK,

Fig. 2. The energy detection scheme.

integrated energy is compared to a pre-defined threshold, while in PPM, decision is made by comparing energy in two successive time intervals.

B. ED-based TOA Estimation

ED-based TOA estimation has been extensively studied in [1]. It is considered as a problem of leading edge detection of the energy sample (direct path detection). Theoretically, the accuracy of this approach is bounded by the resolution of the integration window T_{int} , as $T_{int}/\sqrt{12}$. In free spaces where AWGN channel is applied, sources of the error is contributed by the noise and quantization error in time domain. Simulation results show that 0.3 ns mean absolute error (MAE) at 24dB Eb/No can be achieved using ED receivers with 1ns integration window, corresponding to 10 cm accuracy approximately.

However, in many practical cases especially in the none line-of sight (NLOS) scenario where rich of multipath exists, detection of the direct path (first arrived path) is challenging. Several threshold-based algorithms have been proposed to detect the first path. Maximum energy selection (MES), normalized threshold comparison (TC), and MES-based search-back (MES-SB) are considered in this work. In MES, the strongest energy block in a pulse interval time is chosen as the leading edge. TC uses a threshold, and the first energy block exceeding the threshold is corresponded as the TOA. As opposed to TC where searches the energy block forward, the MSE-SB firstly finds the maximum block then search back blocks in a certain number of blocks W_{sb} and selects the first (earliest) one that exceeds the threshold as the TOA.

C. Simulation and Discussion

Simulations using IEEE 802.15.4a CM1 and CM2 channels [5], with 1500 channel realizations are performed. The 5th order Gaussian pulse with 1ns pulse width at 300ns pulse repetition interval is employed. The maximum delay, known as time of flight is 200ns. In Particular, some issues related to hardware implementation is discussed.

Threshold: A fixed threshold is simple but the performance is dramatically degraded in a dynamic environment. The optimal threshold is changing depending on different channel models, SNRs, and integration windows. A normalized threshold is written as $\eta_{norm} = \frac{\eta - \min\{Z[n]\}}{\max\{Z[n]\} - \min\{Z[n]\}}$, where η is the threshold and $Z[n]$ is received energy blocks in a pulse repetition interval. By sweeping the normalized threshold, the optimal value under different parameters can be obtained. It is shown that the performance is irrelevant to the η in low SNR, but with moderate to high SNR, the optimal threshold is decreased along with the increasing of SNR. This is because the source of estimation error moves from noise into multipath during the increasing of SNR. Mapping this to the hardware,

Fig. 3. Simulation results of MAE respects with E_b/N_o under CM1 and CM2 for $T_{int} = 1ns$, $W_{sb} = 30ns$, and $\eta_{norm} = 0.2$: (a) MES, TC and MES-SB comparisons. (b) and (c) Processing Gain under CM1 (method 1 and 2) using 1, 10, and 50 pulses respectively. (d) Comparisons using floating-point, 3-bit ADC and 1-bit ADC.

SNR estimation is needed before TOA calculation. A look-up table (LUT) is designed to set a proper threshold according to the channel estimation.

Comparison of MES, TC, and MES-SB: As can be seen in Figure 3-(a), MES hits the highest error floor because in many cases the strongest sample is not the leading edge block. Comparing TC and MES-SB, both can achieve the error floor on the same order, but MES-SB can reach the floor earlier. In the implantation aspects, MES is the simplest one. Both TC and MES-SB require SNR estimation and threshold calculation, but extra banks of memory are needed for MES-SB to keep all block samples.

Processing Gain: Two methods of iterations for processing gain are studied shown in Figure 3-(b) and (c). The first one makes use of noise gain by accumulating energy blocks of multi-pulse before TOA estimation, as (1), where N_s is the number of pulses and $Z_j[n]$ is the n^{th} block sample of the j^{th} pulse. This hits error floor earlier using more iterations. The second method calculates the TOA each of pulse then averages them, as (2). It offers little improvement compared to the first one. Longer length of data representation is needed to increase the dynamic range for the first approach.

$$\tau_{ToA} = f\left(\sum_{j=0}^{N_s-1} Z_j[n]\right) \quad (1)$$

$$\tau_{ToA} = \frac{1}{N_s} \sum_{j=0}^{N_s-1} f_j(Z[n]) \quad (2)$$

ADC Resolution: Figure 3-(d) shows the performance degradation due to the quantization error. It implies that a 3-bit ADC is adequate for threshold-based TOA estimations.

IV. HARDWARE IMPLEMENTATIONS

In order to enable the positioning capability in our proposed passive RFID system, a 3.1-4.8 GHz IR-UWB ED receiver with a TOA estimator is implemented (Figure 4) according to the algorithm described in previous sections. This prototype

is composed by analog front-end and timing-critical digital blocks in UMC 90nm CMOS process, and an Altera Cyclone III FPGA development kit for back-end processing and TOA estimation, connected by a High Speed Mezzanine Card (HSMC). This approach is featured by high programmability and multi-mode operations thanks to the flexible back-end on FPGA. The implementation result is summarized and compared in table I.

A. Analog Front-End

A common-gate LNA is designed to achieve $<3.5dB$ noise figure, and $>15dB$ gain. A 4-stage VGA chain following the LNA provides maximum 36dB-gain in total. It is vital to TOA estimations where requires high dynamic range and accurate SNR estimation. Squarer is a fully differential four-quadrant multiplier with 2GHz output bandwidth, and the integrator applies the gm-C continuous low pass filter with two interleaved integrating capacitors. Two integrators are driven by two independent clocks. This interleaved integrate scheme relaxes the implementation of digital circuits, and increases time domain resolution for TOA estimations. Figure 5 is the output of each stage in the analog front-end.

B. Timing Circuit and High Speed Digital Block

A timing circuit and a high speed digital block for real time control are key enablers for TOA estimation. It contains a high speed clock divider for fine tune that is designed in mixed signal process. It provides 1.1ns resolution, allowing tens of center meter estimation accuracy. Other parts are designed in the standard cell-based flow, offering vast of programmability such as integration window length, phase, processing gain and other trimming for the analog front-end. During TOA estimation, the timing circuit is operated in a sliding mode: energy blocks in a pulse interval are searched serially. Figure 6-(a) shows the measured waveform of the timing circuit.

C. Digital Back-end and TOA Estimator

A flexible digital back-end is implemented in FPGA. In general, it is responsible for estimation, synchronization, symbol

Fig. 4. Block diagram and the photo of the ED receiver

detection, and real-time control [6]. A TOA estimator that supports MES, TC, and MES-SB is developed. It is composed by a peak detector, comparators, buffers, and control logic. The digital back-end and TOA estimator is developed using VHDL and synthesized on FPGA. The design is validated by comparing to the Matlab simulation result. The possibility of sub-meter accuracy estimation (ranging error < 1 meter) using our proposed hardware architecture is illustrated in 6-(b). At 25dB SNR, the MES-SB implemented in our hardware can achieve 80% and 70% confidence level of sub-meter accuracy under CM1 and CM2, respectively.

Fig. 5. Simulated waveform at each stage of the analog front-end using 2ns integration window in interleaved mode.

Fig. 6. (a) Screenshot of the high speed digital circuit measurement. (b) Simulation result: probability of ranging error less than 1 meter.

V. CONCLUSION

A passive UWB-RFID positioning system is introduced in this paper. Low complexity TOA estimations using ED receiver are examined. An ED receiver including a 3.1-4.8GHz analog front-end as well as high speed digital circuits is implemented in 90nm CMOS process, with a flexible back-end and a TOA estimator on FPGA. Simulation and implementation results demonstrate that 10cm and sub-meter ranging accuracy can be achieved in free space, and dense multipath (CM1,2) environments, respectively.

TABLE I
IMPLEMENTATION RESULTS OF THIS WORK

	This Work	[2]
Power	21mW	48mW
Gain	51dB	38dB
Noise Figure	8dB	7.3dB
TOA Accuracy	10cm(free space), <1m(CM1,2)	$\pm 5ns$

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