Real Time Locating System for Wireless Networks using IEEE 802.15.4 radio

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***Abstract*—Real time locating systems(RTLS) determine and track the location of assets and person using active tags. Two or more readers can estimate the tag's range from each reader and determine its location. In order to determine tag's location, there are several methods. This paper presents a real time locating system which is based on time difference of arrival(TDOA) of a signal, for wireless networks using IEEE 802.15.4 radio. In order to measure the time that a signal arrives at, exact time measurement is crucial. This paper proposes a multi-phase radio method to provide exact time measurement. In addition, to calculate the time difference, readers in the network should be synchronized with themselves. We also present a precision time synchronization protocol. This paper includes the performance evaluation. The performance shows that our RTLS has accuracy of within 3 meters.**

I. Introduction

As the era of ubiquitous computing is ushered in, there is a growing need for a reliable, efficient positioning and tracking system. Real time locating systems(RTLS) is the system for automatically locating and tracking men and objects. For real time locating systems, RSSI of arrival (ROA), angle of arrival(AOA), time of arrival(TOA), and time difference of arrival(TDOA) are best well-known methods[1]. The TDOA-based method is based on that signals propagating from the RTLS tag arrive at the readers at different time. Two or more readers receive the tag's signal, and then estimate tag's location by using the arrival time of the tag's signal which each reader receives.

This paper designs and implements a real time locating system for wireless networks using IEEE 802.15.4 radio. The real time locating system consists of readers, tags and an engine. TDOA over IEEE 802.15.4 radio includes a number of uncertainties in a network protocol stack. The measurement of time including uncertainties results in poor accuracy of location. In order to reduce uncertainties, we have analyzed the error factors of the protocol stack. In addition, the real time locating system based on TDOA requires accurate time synchronization between the RTLS readers to calculate the time difference. This paper also includes accurate time synchronization within few nanoseconds.

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In this paper we show how to synchronize RTLS readers' time with a reference clock, and how to find and track the RTLS tag's location. The result of performance evaluation is that we established for nodes in a network to maintain their clocks to within 10 nanoseconds offset from the reference clock and RTLS has accuracy of within 3 meters.

II. Real time locating system

This section demonstrates the real time locating system for wireless networks using IEEE 802.15.4 radio. The RTLS composed of tags, readers, and an engine. The RTLS readers synchronize their clock with a master reader which provides a reference clock. Upon receiving the RTLS tag's message, the RTLS tag's location is determined by the RTLS engine.

A. Hardware Prototypes

For accurate time measurement of IEEE 802.15.4 radio, we have designed a special hardware which includes a RTLS tag and a RTLS reader. First, the tag has designed for low power operation. TI's MSP430F2252 have been chosen as the processing unit of the RTLS tag. The tag uses TI's CC2420, which is an IEEE 802.15.4/Zigbee compliant RF transceiver, to radiate its information. In addition, the tag can adjust its blink period by using a motion sensor and an external real time clock and therefore can provide the extended lifetime. The RTLS tag can adaptively broadcast its location information and adjust its broadcast period.

The RTLS reader consists of a main processor, a time stamping unit, and a radio communication unit. Intel's PXA255 is chosen as the main processor which controls the gross task of the reader, and enables to communicate with the RTLS engine. Altera's Cyclone II FPGA, which operates at 160MHz, is used for the time stamping unit that provides accurate time stamping by hardware. For radio communication, the RTLS reader uses two IEEE 802.15.4 radio communication modules simultaneously. One is used for exchanging time synchronization messages between RTLS readers. The other is used for collecting tag's blink message. Figure 1 illustrates the hardware prototypes for the RTLS tag and the RTLS reader of the real time locating system. Figure 2 shows the architecture of the RTLS tag and the RTLS reader.

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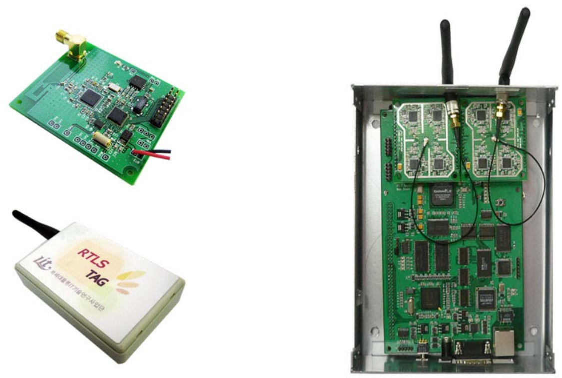
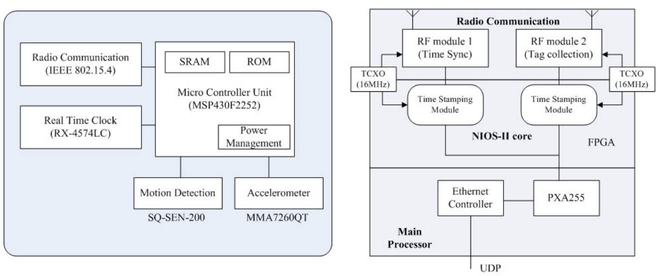


(a) RTLS Tag (b) RTLS Reader

Fig. 1. RTLS tag and reader prototype



(a) RTLS Tag (b) RTLS Reader

Fig. 2. Architecture of the RTLS tag and the RTLS reader

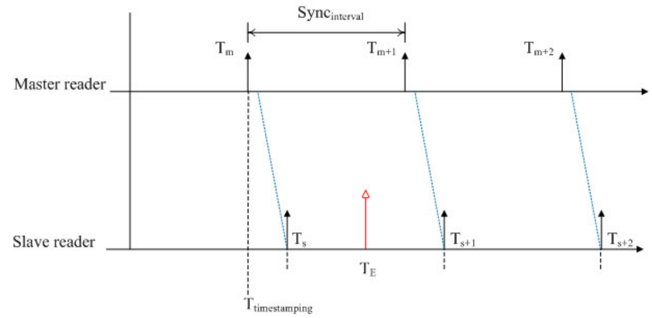


Fig. 3. RTLS protocol

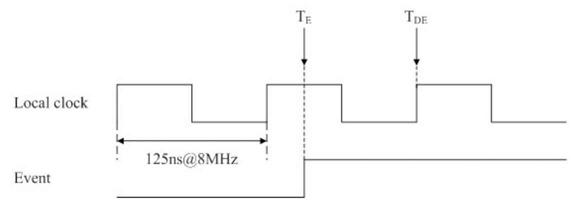


Fig. 4. Uncertainty of decoding time

B. RTLS Protocol

In the real time locating system based on TDOA, accurate time synchronization to calculate the time difference of RTLS readers precedes all other things. One of the RTLS readers is chosen as a master reader which provides a reference clock. Basically, time synchronization between RTLS readers is achieved by message exchanging. Figure 3 shows the time synchronization procedure by message exchanging. The master reader periodically broadcast a sync message. The slave reader receives the sync message and calculates the arrival time and the offset from the master as below.

$$offset = clock_{slave} - clock_{master} = T_s - T_m$$

The propagation delay is included in uncertainty of the protocol stack. However, in static networks it has no jitter. Because a distance between the master reader, which provides a reference clock, and the slave readers is known in the reader setup phase, the propagation delay can be calculated.

Although the slave reader knows the offset from the master reader, it does not adjust its local clock. The slave reader maintains sync messages in its internal buffer. The slave reader only calculates the offset and search for the offset of the nearest the sync message to arrival time of the tags blink message when it receives the blink message from the RTLS tag at T_E. And the slave reader does not correct the offset but transfer the offset and the time received the blink message to the RTLS engine The RTLS engine can determine TDOA value of the tag message using the offset and the received time of the tag message. Calculating TDOA in the RTLS engine can dramatically reduce the traffic between the RTLS engine and the readers.

In measuring the arrival time of the signal of the tag, there is a big uncertainty in a radio frequency transceiver. The encoding and the decoding time of IEEE 802.15.4 radio which do not be removed by hardware assistant time stamping, are the time required for the radio chip to encode and decode the message to electromagnetic waves or vice versa. While the Chipcon CC2420 radio, which supports the IEEE 802.15.4/ZigBee, has no jitter uncertainty at the transmitter side, 0.125s of uncertainty at the receiver side. This is because it has an 8M chip/s. Figure 4 shows uncertainty of decoding time. When the system uses the rising edge clock, the timer of the processor is also counted at the rising edge. If an event occurs at T_E, the timer of the processor does not record the time at which the event occurs, but counts at the consequent rising edge T_{DE}. The maximum time error is 1/f.

It is impossible to remove the uncertainty at the receiver side. To reduce the decoding time, we have proposed a multi-phase radio method which four radio transceivers are used for. Figure 5 depicts the multi-phase radio method that dramatically reduces the uncertainty of decoding time.

Each radio transceiver has a distinct input clock which has the exactly shifted phase of 90 degree shown in figure 4. Each radio transceiver operates at the clock by shifted phase. When the RTLS reader receives a RTLS tag' message, every radio transceiver will hear the message simultaneously and generate the start of delimiter (SFD). The earliest time value

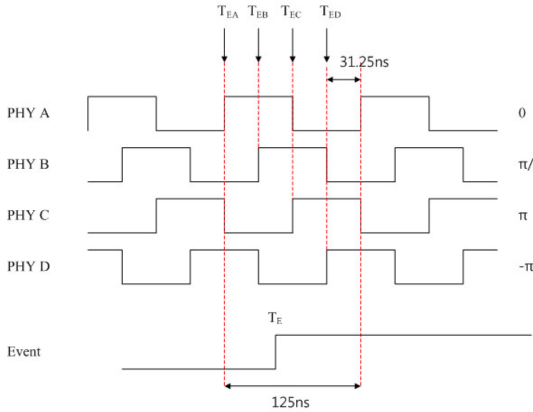


Fig. 5. Multi-phase radio method

is chosen as the arrival time of the radio signal. So, ± 0.125 microseconds of uncertainty at the receiver side will degrade into ± 0.03125 microseconds(1/4) of uncertainty. This multi-phase radio dramatically reduces the decoding time of the radio transceiver.

One measurement of the arrival time includes many error factors like a measurement error, a multi path propagation and so on. We have minimized error factors by multiple measurements using sub blinks. Every reader received the tag blink message transfers the arrival time and an offset value between the master reader and its local clock to the RTLS engine.

The RTLS engine determines tag location by calculating a time difference between readers in a spherical intersection(SX)[2] manner based on the least square method. Let the coordinate of the tag be (x, y) and the reader i be (x_i, y_i). the tag's location is determined as below.

$$r_i = [(x - x_i)^2 + (y - y_i)^2]^{\frac{1}{2}}$$

$$r_{ij} = r_i - r_j, \qquad k_i = x_i^2 + y_i^2$$

$$(xy)^T = \frac{1}{2} \begin{pmatrix} x_j - x_1 & y_j - y_1 \\ \vdots & \vdots \\ x_j - x_n & y_j - y_n \end{pmatrix}^{-1} \left[\begin{pmatrix} k_j - k_1 + r_{1j}^2 \\ \vdots \\ k_j - k_n + r_{nj}^2 \end{pmatrix} + \begin{pmatrix} r_{1j}^2 \\ \vdots \\ r_{nj}^2 \end{pmatrix} \right] \tag{1}$$

In addition, for higher accurate locating services, we use performance improvement techniques such as a 2.5D method, the alternation of the base reader for TDOA, and a tag location restriction approach based on the map.

III. Performance Evaluation

This section evaluates the performance of our real time locating system. The system setup used for evaluation is shown in figure 6. Three RTLS readers are located in a parking lot in which a space is 19 x 22 meters. RTLS readers is synchronized with a master reader. A RTLS tag is located in three RTLS readers. The tag periodically sends the its message. RTLS readers and engine determine the tag's location. Figure 6 also shows the result of the real time locating system. The result we established is that a circular error probability(CEP) is 1.74meters and a distance root mean square (DRMS) is 2.14 meters.

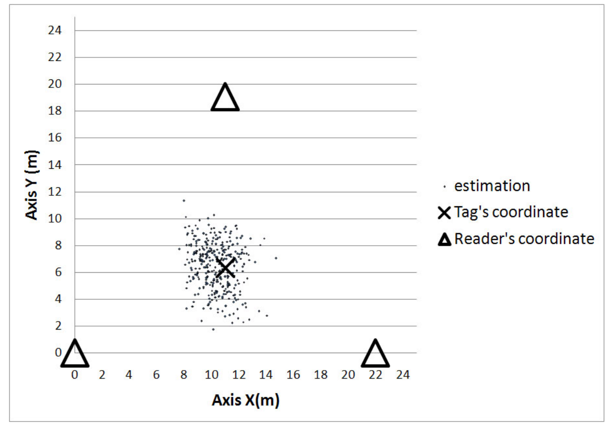


Fig. 6. Performance evaluation

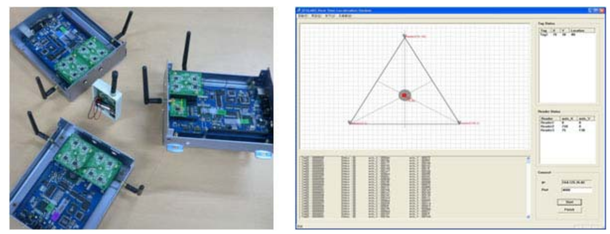


Fig. 7. Testbed for demonstration

IV. Demonstration Scenario

The RTLS tag is located at centroid of three readers and the tag periodically radiates its blink message to readers. Every reader received the tag message transfers the arrival time and the offset value between the master reader and its local clock to the RTLS engine. The RTLS engine determines the tag's location by calculating time differences between readers. The laptop computer installed the RTLS engine will display raw data of TDOA between readers. Because it is difficult to read raw data, we will provide graphic user interface for spectators' convenience. Figure 7 depicts the test bed deployment and the GUI interface. We will also provides a video which includes our outdoor demonstration.

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