Precise Location Tracking System based on Time Difference of Arrival over LR-WPAN *

Hyuntae Cho
marine@pnu.edu
Dept. of CSE
Pusan National University
Busan, 609-735
Republic of Korea

Yeonsu Jung
rookie@embed.re.kr
Dept. of CSE
Pusan National University
Busan, 609-735
Republic of Korea

Hoon Choi
hara@juno.cs.pnu.edu
Dept. of CSE
Pusan National University
Busan, 609-735
Republic of Korea

Hyunsung Jang
fox@embed.re.kr
Dept. of CSE
Pusan National University
Busan, 609-735
Republic of Korea

Sanghyun Son
hyun0427@embed.re.kr
Dept. of CSE
Pusan National University
Busan, 609-735
Republic of Korea

Yunju Baek†
yunju@pnu.edu
Dept. of CSE
Pusan National University
Busan, 609-735
Republic of Korea

ABSTRACT

As the era of ubiquitous computing approaches, there is a growing need for a reliable, efficient positioning and tracking system. Localization involves continuous determination and tracking of the location of assets and personnel. Localization using time difference of arrival (TDOA) involves determining the location of a tag by calculating the time difference of arrival of the signal received from the tag. In order to calculate the time difference of the signal, TDOA-based methods require precision time synchronization of within a few nanoseconds. This paper presents a location tracking system(LTS), which consists of readers, tags, and an engine, based on TDOA in IEEE 802.15.4. In addition, we propose a precise time measurement method and a precision time synchronization protocol which provides a common clock with an accuracy of within a few nanoseconds. The proposed precision time synchronization protocol results in accurate locating services. The performance shows that readers achieve precision time synchronization of within 5 nanoseconds from a reference clock, and the location tracking system has a location error of within 2 meters.

*"This work was supported by the Korea Research Foundation Grant funded by the Korean Government(MOEHRD)" (The Regional Research Universities Program/Research Center for Logistics Information Technology).

†Correspondence to Prof. Yunju Baek.

MELT'08, September 19, 2008, San Francisco, California, USA.

Categories and Subject Descriptors

C.3 [**Special-purpose and application-based systems**]: Real-time and embedded systems; B.8.1 [**Performance and reliability**]: Reliability, Testing, and Fault-Tolerance

General Terms

Measurement, Design, Experiments

Keywords

LTS, IEEE 802.15.4, time difference of arrival, location tracking

1. INTRODUCTION

Currently, many applications are based on location awareness. Localization involves determining the position of personnel or assets. Basically, the location is calculated using the distance between nodes. A number of research[1-12] have been proposed for determining the location. Regarding location estimation, localization protocols are separated into two categories: range-based and range-free. A range-based protocol uses the direct distance between readers and a tag to estimate a tag's location. However, the range-free protocol does not rely on the assumption that nodes realize direct distance estimates. A range-based protocol has an accurate resolution for localization, while a range-free protocol provides large scalability. Although a number of methods have been proposed for estimating the location in LR-WPAN's, research about real-time locating and tracking in terms of analysis about characteristics of LR-WPAN's is inadequate. Despite these attempts at localization, deploying location-aware applications is arguably no easier.

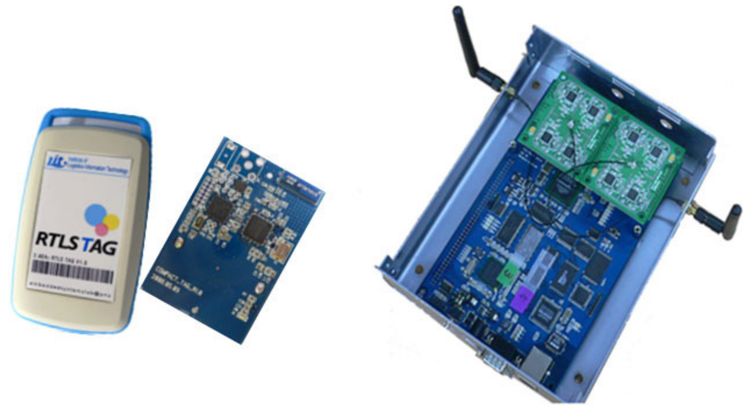
This paper presents a location tracking system(LTS) which considers characteristics of LR-WPANs and is based on time difference of arrival(TDOA). Our LTS consists of tags which are attached to personnel or assets and broadcast information, readers which measure the time of arrival of the signal and provide time synchronization, and an engine which finds and tracks a tag's location. Because a TDOA-based protocol uses the time difference between readers to provide location information, precise time measurements and exact time synchronization between readers is essential. In order to provide a time measurement method and precision time synchronization within a few nanoseconds, and accurate locating services, we developed a special purpose time stamping unit, which is embedded in the reader, and a multi-phase radio method. The time stamping unit can exactly measure the time that radio messages arrive, and the multi-phase radio method we proposed improves radio resolution dramatically. Readers in the network perform their own time synchronization without an external time server, and time stamp the time of arrival of the tag. The engine estimates a tag's location by computing the TDOA of the signal. Readers achieve precision time synchronization within 5 nanoseconds from a reference clock and the proposed LTS has a location error of within 2 meters.

The organization of this paper is as follows. We present traditional approaches for localization in the next section. Then, in Section 3, we describe a location tracking system(LTS) based on time difference of arrival(TDOA) in IEEE 802.15.4. Section 4 includes experiments and the performance evaluation of our system, which includes time synchronization and LTS accuracy. Finally, in Section 5, we conclude this paper with plans for future work.

2. RELATED WORKS

There are attractive solutions for estimating the distance between nodes. Received signal strength indicator (RSSI) is the most conventional approach. The RSSI approach is based on the radio path loss model in which radio signals attenuate exponentially during transmission. RADAR[2], in which distance is estimated by received signal strength, is one of approaches in WLAN. Cricket[3] utilizes radio communication and ultrasonic sounds to estimate distance. Cricket achieved a location granularity of tens of centimeters using ultrasound transceivers. Some research methods used time based techniques such as time of flight(TOA)[4], and time difference of arrival (TDOA)[5] between readers and a tag. The angle of arrival (AOA)[6] approach was also proposed to estimate position. AOA requires an antenna array of receivers. Recently, chirp spread spectrum(CSS)[7] and ultra wide band(UWB)[8] have emerged, which provide precise location services.

During past years, several research methods for range-free protocols have emerged, to achieve localization in LR-WPAN's. Because these range-free solutions only use COTS radio transceivers as the basis of localization, they do not require additional hardware. DV-HOP[9] is one of the most well known range-free protocols. In DV-HOP, readers broadcast their location over a network with a hop count. Nodes calculate their position based on the received reader locations, the hop count from the reader, and the average distance per hop. APIT[10] resolves the localization problem by partitioning the environment into triangular regions between anchor nodes. The Amorphous Positioning algorithm[11] performs estimation via a neighbor information exchange. However, range-free protocols have poor accuracy in finding and tracking assets. In order to provide accurate locating services in IEEE 802.15.4, this paper attempts to find the means to achieve location tracking of assets.



(a) LTS Tag (b) LTS Reader

Figure 1: LTS hardware prototypes

3. PRECISE LOCATION TRACKING SYSTEM

This section demonstrates a location tracking system(LTS) over IEEE 802.15.4 radio. An LTS is composed of tags, readers, and an engine. Basically, readers synchronize their clocks with a master reader, which provides a reference clock. When a reader receives a tag's signal, the reader records the time that the signal arrives and the engine calculates the time difference between readers. Hence, the engine determines a tag's location.

3.1 Hardware Prototypes

For accurate time measurements in IEEE 802.15.4 radio, we designed special hardware which includes an LTS tag and an LTS reader. First, the tag was designed for low power operation. The processing unit of the tag was an MSP430F2252 (TI) . The tag uses a CC2420 (TI). which is an IEEE 802.15.4/Zigbee compliant RF transceiver, to propagate its information. In addition, the tag can adjust its blink period using a motion sensor and an external real time clock, which enables an extended lifetime.

The reader consists of a main processor, a time stamping unit, and a radio communication unit. The main processor controlling the low level processing of the reader and enabling it to communicate with the engine was a PXA255 (Intel). A Cyclone II FPGA (Altera) operating at 160MHz was used as the time stamping unit that provides accurate time stamping via hardware, and precision time synchronization. For communication, the reader uses two IEEE 802.15.4 radio communication modules simultaneously. One exchanges time synchronization messages between readers and the other collects a tag's blink messages. Figure 1 illustrates hardware prototypes for the tag and the reader in the LTS.

In measuring the arrival time of a tag message and a time sync message, there is substantial uncertainty in the radio frequency transceiver. The encoding and decoding times of IEEE 802.15.4 radio are the times required for the radio chip to encode/decode a message to/from electromagnetic waves. While the Chipcon CC2420 radio, which supports IEEE 802.15.4/ZigBee, has no jitter uncertainty at the transmitter side, there is an uncertainty of ± 0.125 microseconds at

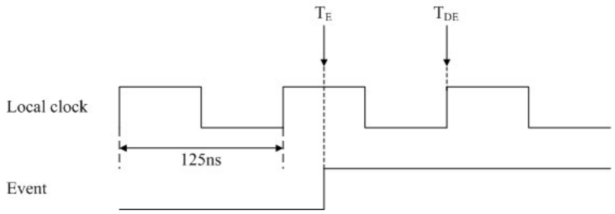


Figure 2: Time representation error

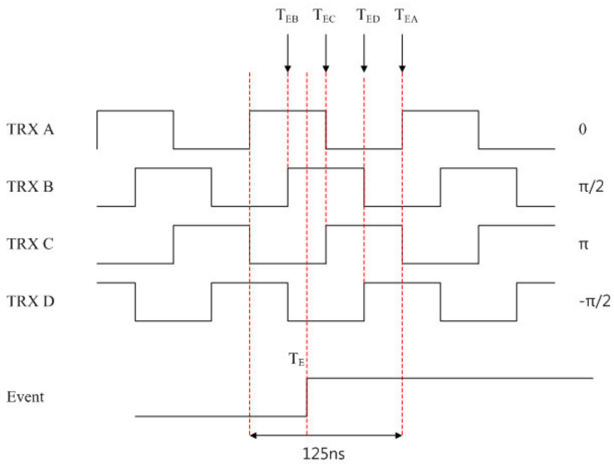


Figure 3: Input clocks for a multi-phase radio

the receiver side. This is because it has 8M chip/s. Figure 2 shows the uncertainty in the decoding time. When the system uses a rising edge clock, the processor timer is also counted at the rising edge. If there is an event at T_E, the processor timer does not record the time of the event, but counts at the consequent rising edge T_{DE}. The RF transceiver has the same problem. When the RF transceiver receives a radio signal, the consequent rising edge is the basis for decoding electromagnetic waves to binary data. The maximum time error is 1/f. A radio message travels at a velocity of 300 meters per microsecond. For an IEEE 802.15.4 transceiver, an accuracy of 37.5 meters(125 nanoseconds) is an achievable resolution limit.

It is impossible to remove the uncertainty at the receiver side. To reduce the decoding time, we propose a multi-phase radio method, in which four radio transceivers are used. Figure 3 depicts a multi-phase radio method that dramatically reduces the uncertainty in the decoding time of a single communication. Each radio transceiver has a unique input clock which has a shifted phase of exactly 90 degrees, as shown in Figure 3. Each radio transceiver operates at a clock frequency of 16MHz by the shifted phase. The 8MHz chip rate of the radio transceiver is derived from the 16MHz clock. When the antenna of the LTS reader receives a tag's radio signal, every radio transceiver simultaneously detects and decodes the signal, then generates the start of delimiter (SFD). The time stamping unit, operating at 6.25 nanoseconds per clock cycle, records all time stamps according to the number of radio transceivers. The earliest time among four time stamps is chosen as the arrival time of the radio signal. So, a 0.125 microsecond uncertainty at the receiver side is reduced to 0.03125 microseconds(1/4 resolution). For

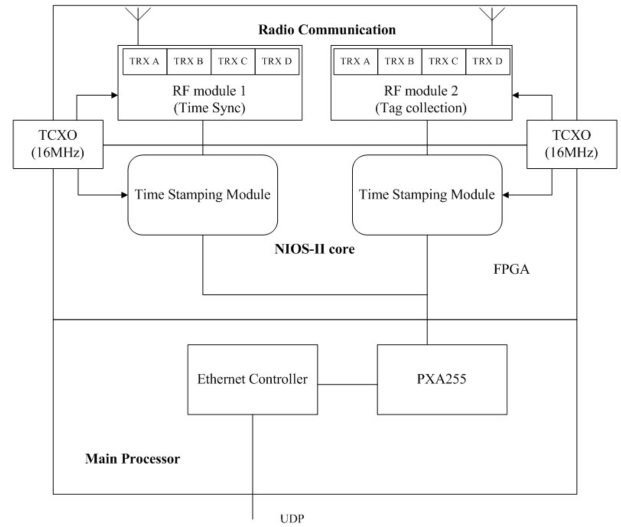


Figure 4: Architecture of the reader

example, if a micro wave arrives at the antenna of the reader at T_E, while radio transceiver A (TRX A) detects it at T_{EA}, which is the next rising edge of TRX A, radio transceiver C(TRX C) detects it at T_{EC}, which is the consequent rising edge of TRX C. Because TRX C has the earliest rising edge relative to the event, the micro wave has the earliest time stamp, thus it is chosen as the arrival time of the radio signal. This multi-phase radio method can simultaneously reduce not only time synchronization uncertainty but also uncertainty of a tag's collection at the receiver side.

Figure 4 shows the architecture of the reader for LTS, which includes a multi-phase radio and a time stamping unit. The multi-phase radio technique apply to both of time synchronization and tag collection.

In TDOA-based LTS, precision time synchronization to calculate the time difference of the LTS readers takes precedence. One LTS reader is chosen as the master reader, which serves as a reference clock. Basically, time synchronization between LTS readers is achieved by message exchanging. Figure 5 shows the time synchronization procedure by message exchanging. The master reader periodically broadcasts a sync message. The slave reader receives the sync message and calculates the arrival time and the offset from the master, as shown by Equation (1).

$$offset = clock_{slave} - clock_{master} = T_s - T_m \quad (1)$$

The propagation delay is included in the protocol stack uncertainty. However, in static networks there is no jitter. Because the distance between the master reader and the slave reader is determined in reader configuration, the propagation delay is easily 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 searches for the offset of the nearest sync message to the arrival time of a tag's blink message, when it receives a blink message from an LTS tag at T_E. And, the slave reader does not correct the offset, but transfers the offset and the time it received the blink message to the LTS engine The LTS

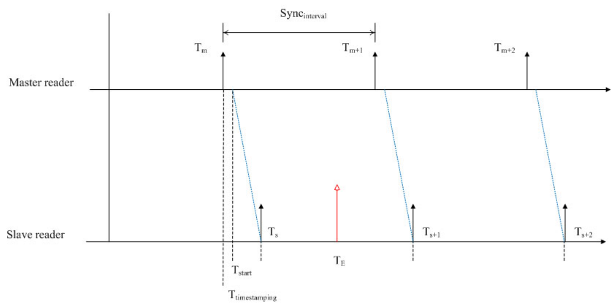


Figure 5: Location tracking system protocol

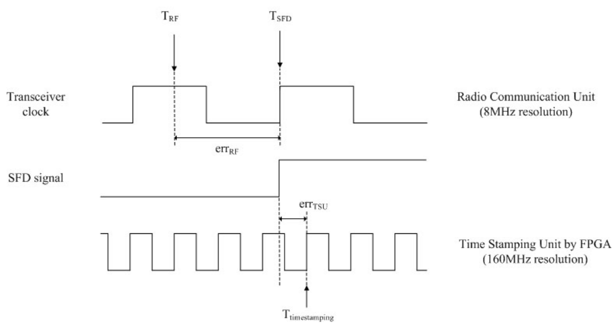


Figure 6: Uncertainty between the RF transceiver and the time stamping unit

engine determines the TDOA of the tag message using the offset and the arrival time of the tag message. Calculating the TDOA in the LTS engine can dramatically reduce the reader load and the traffic between the LTS engine and the readers.

The sync message interval affects the performance of the LTS. The message interval for the correction of clock drift between two readers is defined by Equation (2).

$$Sync_{interval} = \frac{err_{tolerance} \times 10^6}{f_{drift}} \tag{2}$$

Where, f_{drift} is the drift rate of a crystal oscillator including its stability, and $err_{tolerance}$ is the time error tolerance between two readers.

Although using a multi-phase radio reduces the decoding time, there is still remaining uncertainty. Assume a radio signal from the master reader arrives at the slave reader at T_{RF}, as shown in figure 6. The RF transceiver of the slave reader decodes the electromagnetic wave to binary data and generates an SFD signal at T_{SFD} instead of T_{RF}. Jitter err_{RF} between T_{RF} and T_{SFD} is minimized by the multi-phase method. However, the time stamping unit must time stamp the SFD signal of the RF transceiver. There is also uncertainly in the time stamping unit, because it is also operated by a local clock. Although the SFD signal is generated at T_{SFD}, the time stamping unit records the event time at $T_{timestamping}$. The jitter of the time stamping unit, err_{TSU}, between T_{SFD} and $T_{timestamping}$ depends on the frequency of the time stamping unit.

The RF transceiver and the time stamping unit operate at different frequencies, because they are operated by unique crystal oscillators. In our system, while the RF transceiver operates at 16MHz, the time stamping unit operates at 160MHz. If the RF transceiver and the time stamping unit are not synchronized, the SFD signal cannot be detected at exactly T_{SFD}. The jitter between T_{SFD} and $T_{timestamping}$ is easily eliminated with the use of an identical clock, while the jitter between T_{RF} and T_{SFD} can severely affect the accuracy of time synchronization. It is difficult to eliminate the jitter between T_{RF} and T_{SFD} without modifying the RF transceiver. In this paper, we attempted to find the means of reducing this uncertainty. In this paper, we used a Kalman filter[12] to minimize encoding/decoding uncertainties in the RF transceiver and the time representation error in the time stamping unit. The Kalman filtering method has heavy overhead. Operation of the Kalman filter is performed on the main processor to reduce the overhead of the time stamping unit.

The effect of time synchronization is the realization of nodes in a network which maintain their clocks to within a 5 nanosecond offset from the reference clock.

In tag location estimation, a single measurement of the arrival time includes many error factors, such as measurement errors, multi-path propagation etc. We minimize error factors not only by the multi-phase radio method, but also by multiple measurements of a tag's messages using sub-blinks. Every reader receiving a tag blink message transfers the arrival time and the offset between the master reader and its local clock to the LTS engine. The LTS engine determines a tag's location by a calculation of the time difference between readers at the spherical intersection(SX)[13] which is 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 by Equation (3).

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

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

$$(xy)^T = \frac{1}{2} \begin{pmatrix} x_j - x_1 & y_j - y_1 \\ \vdots & \vdots \\ x_j - x_n & y_j - y_n \end{pmatrix}^{-1} \left[\begin{pmatrix} k_j - k_1 + r_{1j}^2 \\ \vdots \\ k_j - k_n + r_{nj}^2 \end{pmatrix} + \begin{pmatrix} r_{1j}^2 \\ \vdots \\ r_{nj}^2 \end{pmatrix} \right] \tag{3}$$

In addition, for higher accuracy 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.

4. PERFORMANCE EVALUATION

This section includes the performance evaluation of t LTS in IEEE 802.15.4. The evaluation is separated into two phases: time synchronization between LTS readers, and accuracy of LTS.

4.1 Accuracy of Time Synchronization

This section evaluates precision time synchronization between LTS readers. The system of evaluation consists of a master reader and a slave reader, a reference pulse generator, and a connecting LAN technology as shown in figure 7.

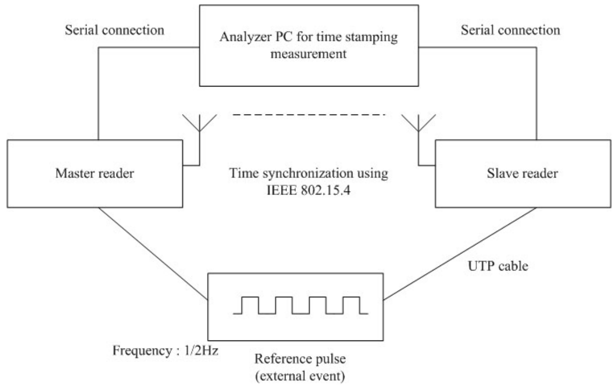


Figure 7: Environment for performance evaluation

The master reader serving as the global clock periodically sends a synchronization message. The slave reader receiving a message from the master reader synchronizes its clock with the global clock. In order to compare two clocks, a reference clock generator periodically sends an external event to the master reader and the slave reader. Two readers record the times that the event is detected and stores them.

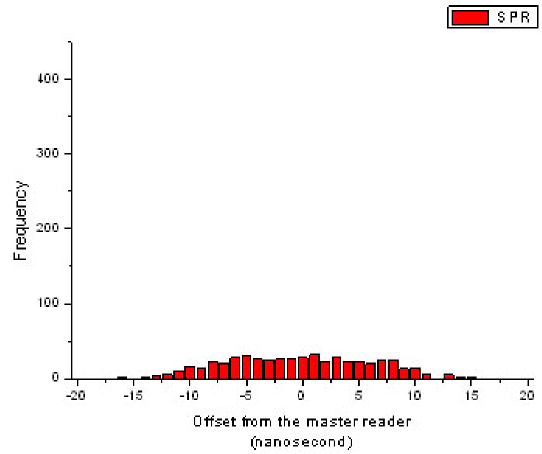
Figure 8 shows the results of the performance evaluation of the general transceiver (SPR: single-phase radio) and the multi-phase radio (MPR) which do not include the Kalman filter, where there are 500 sync messages per second. This graph also implies that the closer the offset is to zero, the more precise the synchronization. A positive value implies that the slave reader runs slower than the master reader. A negative value implies that the slave reader runs faster than the master reader. This figure shows that MPR has a standard deviation of 19.74 nanoseconds, while SPR has a standard deviation of 38.75 nanoseconds. The hardware assisted time stamping can achieve sub-microsecond time synchronization, but it has some limitations for TDOA-based RTLS which requires an accuracy on the order of nanoseconds. To achieve this level of precision, the filtering mechanism should be used. Figure 9 depicts the performance of the MPR with the Kalman filter. The standard deviation of the MPR with Kalman is 4.76 nanoseconds. This is sufficient for time synchronization in a TDOA-based location tracking system.

4.2 Accuracy of Location Tracking System

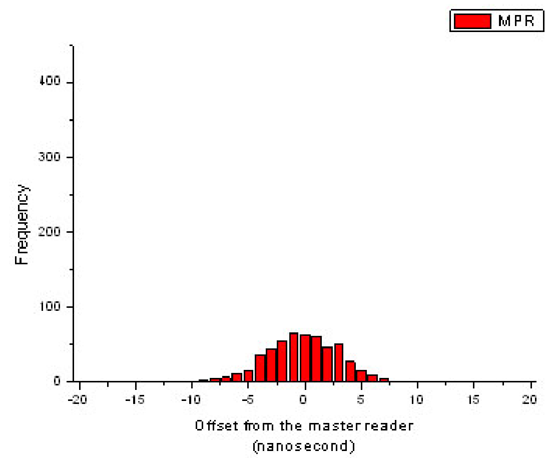
This section evaluates the performance of our LTS. The system configuration used in the evaluation is shown in Figure 10. Three LTS readers are located in a 19 x 22 (meters) parking lot. LTS readers are synchronized with the master reader. An LTS tag is embedded in three LTS readers. The tag periodically sends a message. LTS readers and the engine determine the tag's location. The experiment is repeated 300 times. Figure 10 also shows the location accuracy of LTS. We determined that the circular error probability(CEP) is 1.74 meters, and the distance root mean square (DRMS) is 2.14 meters. Our approach for location tracking is based on TDOA. So, location accuracy will be the same in case distances among readers enhance.

5. CONCLUSION AND FUTURE WORK

This paper presented a precision location tracking sys-



(a) Single-phase without Kalman filter



(b) Multi-phase without Kalman filter

Figure 8: Single-phase vs. multi-phase

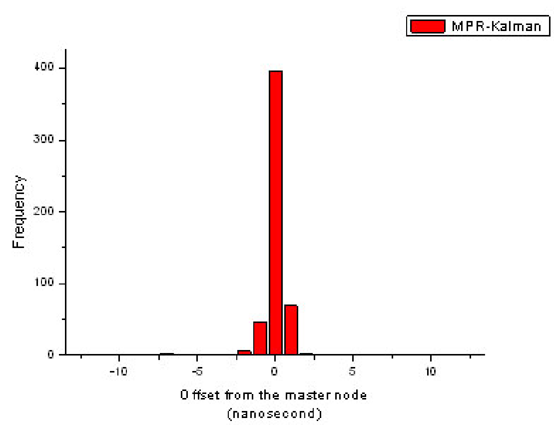


Figure 9: MPR with Kalman filter

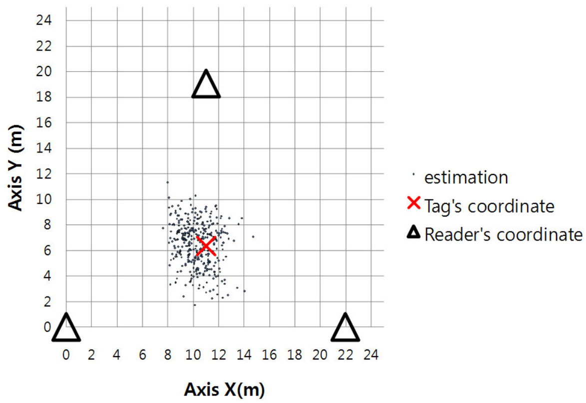


Figure 10: LTS performance

tem(LTS) based on the time difference of arrival in IEEE 802.15.4. Because a TDOA-based protocol uses the time difference between readers to provide location information, exact time measurements and time synchronization is essential. To measure the exact time that a message arrives, we designed special hardware which included a time stamping hardware unit and a multi-phase radio. The special hardware measures exact times, and provides precision time synchronization. LTS based on exact time measurements and time synchronization provides precise time calculations. Hence, LTS enables accurate location services. The performance shows that readers achieve precision time synchronization of within 5 nanoseconds from a reference clock, and the location tracking system has an accuracy of within 2 meters..

Our future work includes an LTS for multi-hop networks, a more accurate LTS, and a method for reducing traffic.

6. REFERENCES

[1] Jeffrey Hightower, and Gaetano Borriello, *A Survey and Taxonomy of Location Systems for Ubiquitous Computing*, IEEE Computer, vol. 34, no. 8, pp. 57-66, August 2001.

[2] Paramvir Bahl and Venkata N. Padmanabhan, *RADAR: An in-building RF-based user location and tracking system*, In INFOCOM 2000, pp. 775-784., 2000

[3] Nissanka B. Priyantha, Anit Chakraborty, and Hari Balakrishnan, *The cricket location-support system*, 6th ACM International Conference on Mobile Computing and Networking (ACM MOBICOM), pp. 32-43, 2000

[4] Andy Ward, Alan Jones, and Andy Hopper, *A new location technique for the active office*, In IEEE Personnel Communications 1997, pp. 42-47, 1997

[5] Andreas Savvides, Chih-Chieh Han, and Mani B. Strivastava, *Dynamic fine-grained localization in ad-hoc networks of sensors*, In Proceedings of the 7th annual international conference on Mobile computing and networking (2001), ACM Press, pp. 166-179, 2001

[6] D. Niculescu and B. Nath., *Ad hoc positioning system (APS) using AoA*, Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (IEEE INFOCOM), pp. 1734-1743, April 2003.

[7] A. Sikora, and V.F. Groza, *Fields Tests for Ranging and Localization with Time-of-Flight-Measurements Using Chirp Spread Spectrum RF-devices*, Instrumentation and Measurement Technology Conference Proceedings, 2007, pp. 1-6, May 2007

[8] W.C. Chung, and D.S. Ha, *An Accurate Ultra Wideband (UWB) Ranging for Precision Asset Location*, Ultra Wideband Systems and Technologies, 2003 IEEE Conference on, pp. 389-393. 2003.

[9] D. Niculescu and B. Nath., *DV based positioning in ad hoc networks*, In Journal of Telecommunication Systems, pp. 267-280, 2003.

[10] T. He, C. Huang, B. M. Blum, J. A. Stankovic, and T. F. Abdelzaher, *Range-free localization schemes in large scale sensor networks*, In Proceedings of the Ninth Annual International Conference on Mobile Computing and Networking (MobiCom '03), pp. 81 - 95, 2003.

[11] R. Nagpal, *Organizing a Global Coordinate System from Local Information on an Amorphous Computer*, A.I. Memo 1666, MIT A.I. Laboratory, August 1999.

[12] D. Simon, *Kalman Filtering*, Embedded Systems Programming, vol. 14, no. 6, pp. 72-79, June 2001.

[13] H. C. Schau and A. Z., *robinson, passive source localization employing intersecting spherical surfaces from time-of-arrival differences*, IEEE Trans. Acoust., Speech, Signal Processing, vol. ASSP-35, pp. 1223-1225, Aug. 1987