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IEEE 802.15.4a CSS-based mobile object locating system using sequential Monte Carlo method

Seungwoo Lee [a], Hyojeong Shin [a], Rhan Ha [b], Hojung Cha [a,*]

[a] Department of Computer Science, Yonsei University, Seodaemun-gu, Shinchon-dong 134, Seoul 120-749, Republic of Korea
[b] Department of Computer Engineering, Hongik University, Mapo-gu, Sangsoo-Dong 72-1, Seoul 121-791, Republic of Korea

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ABSTRACT

With the widespread use of mobile devices equipped with various types of sensors, the need for location awareness in mobile environments is increasing. Many range-based approaches focus on localization accuracy but are vulnerable to ranging noises. In this paper, we propose a practical mechanism for a mobile object locating system. The mechanism applies the bootstrap particle filter and likelihood functions to the IEEE802.15.4a Chirp Spread Spectrum (CSS) ranging functionality. Based on the empirical characteristics of the prototype hardware, we developed an accurate and practical localization mechanism by using a CSS-specific adaptive likelihood distribution in real environments. The simulation and experiment results show that the proposed scheme outperforms previous techniques.

1. Introduction

Mobile object locating systems in the ubiquitous computing environment have been widely studied over the years. Off-the-shelf mobile devices such as PDAs or smartphones, are already equipped with various communication modules as well as MEMS- (Micro-Electro-Mechanical Systems) based sensors. Accordingly, a new category of services that combine sensing and locating information is wide open to the next generation of handset usage. Location-based services (LBS) [1] and a real-time location system (RTLS) [2–4] are good examples of such development.

As the necessity for location awareness in the mobile environment increases, the IEEE 802.15.4a Task Group recently standardized an alternative physical layer for the IEEE 802.15.4 standard, to provide precise distance information directly from radio signals [5–6]. Chirp Spread Spectrum (CSS), one of the two IEEE 802.15.4a signaling formats, has a 2.45-GHz frequency band. The CSS encodes data using chirp pulses for transmission over air. A chirp is a frequency-modulated pulse that changes monotonically from low to high value (Upchirp) or from high to low value (Downchirp) by Linear Frequency Modulated signals with constant amplitude [7,8]. By utilizing a wide spectrum band, CSS is robust to external radio noise, multi-path fading, and the Doppler Effect [9]. Hence, the technique is appropriate for communication among mobile nodes. The IEEE 802.15.4a RF transceiver can solve many environmental difficulties, and obtains accurate distance information directly from the radio signal without additional sensors. In IEEE 802.15.4a standard, the CSS-based systems can measure distance based on time-of-fight (TOF) measurements obtained by accurate time-of-arrival (TOA) estimation. The CSS ranging calculates the distance between two nodes within 10 ms by estimating the propagation time based on Symmetric Double Sided Two Way Ranging (SDS-TWR) methodology [7,10].

Although CSS is a promising technology for the successful development of mobile object locating systems, the CSS ranging functionality is considered less robust than expected in indoor environments where many obstacles may exist between measuring nodes. In fact, our preliminary experiments in Section 3 show that the measurement noise of CSS is fluctuated, biased, and dynamic in noisy environment.

To locate a mobile object accurately, many localization techniques have been suggested. However, the non-linear characteristic of CSS-based ranging in noisy environments significantly degrades the accuracy of conventional location estimators, such as lateration-based techniques [11–12] and Gaussian distribution-based systems [13–15]. To solve this problem we employ a particle filter, which is a recursive implementation of Monte Carlo based statistical signal processing [16–18]. The key observation is that the ranging functionality of IEEE 802.15.4a CSS is significantly influenced by many factors such as node mobility, signal interference, and stationary or mobile obstacles.

* Corresponding author. Tel.: +82 2 2123 5711; fax: +82 2 365 2579.
E-mail address: hjcha@yonsei.ac.kr (H. Cha).

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In this paper, we propose a mobile object locating scheme that can be practically deployed in real environments. Based on the experimental analysis of the CSS ranging functionality, we devised a CSS-specific probability distribution model to solve the non-linear problem of CSS ranging and to develop a pragmatic localization system that can be used in real environments. Our contributions are as follows: (1) modeling of the CSS ranging for indoor environments, (2) proposing the state transition density and dynamic likelihood function of CSS-ranging based Monte Carlo estimation, and (3) evaluation of the scheme in real environments.

The rest of the paper is organized as follows. We describe related works in Section 2. Section 3 discusses the preliminary experiments and the results. Section 4 states the problems and the proposed solutions. The performance of our algorithm is evaluated in Section 5, and Section 6 concludes the paper.

2. Related work

Received Signal Strength (RSS) fingerprinting-based positioning systems is one of the most widely used indoor localization technologies [4,19–21]. The RSS fingerprinting-based approach consists of training phase and locating phase. In the training phase, the RSS vectors from several nearby anchors are measured at every location, and RSS vectors and corresponding location are stored in fingerprinting database. After construction of RSS fingerprinting map, the current location is obtained with the most similar RSS vector from the database. However, the radio fingerprint map in database should be constructed in off-line to generate location information. The off-line training process is time-consuming and laborious. Moreover, to obtain accurate location, a lot of anchor installation and access process to database server is required. Finally, periodical re-training is required to manage the changes of radio signal characteristics [22].

On the other hand, many range-based localization techniques for wireless sensor network have been proposed. Range-based approaches are based on estimated distance and favored in a real-time tracking system since they can detect sensitive changes in mobile states. Distance measurement is achieved in various ways: acoustic sound [23], ultra-sound [12], radio signal strength (RSS) [24], time-difference of arrival (TDOA) [25–26], RFID [27], and angle of arrival (AOA) [28–30]. In range-based localization techniques, the lateration-based techniques [11–12] are commonly used. Multi-lateration techniques are based on distances simultaneously acquired from more than three anchors. Therefore, the mobility of nodes or lack of estimated distances can increase the position error. In addition, the noise of range measurement significantly reduces the accuracy of the system.

Sequential Monte Carlo–based localization is a representative technique for mobile nodes. MCL [31] is designed for mobile sensor networks based on the sequential Monte Carlo method only with the connectivity of nodes. Baggio et al. [32] proposed MCB, an enhanced version of MCL that applies box-shaped filtering to reduce the cost of computation and sampling area, hence improving accuracy. These techniques use the RSS of the IEEE 802.15.4 nodes to estimate distances. Therefore, these schemes are based on transmission range, rather than actual distance between nodes. Another range-based version of MCL was proposed in [14], and [17] introduced various methods for particle filter-based navigation and tracking. Hightower et al. [15] used diverse sensors to provide probability distributions to higher-level applications. These techniques use static likelihood function and the observation model is assumed to follow Gaussian distribution. However, Gaussian distribution is not suitable for some of ranging techniques such as CSS and UWB radio, because measurement distribution highly depends on environmental condition such as Non-Line-Of-Sight (NLOS) propagation, and ranging measurement does not follow the Gaussian distribution. Here, noisy environment is defined as a place where Line-Of-Sight (LOS) between two nodes is not guaranteed because of environmental factors such as obstacles and indoor layout; hence, a node often receives RF signal that is propagated through indirect path. In noisy environments, localization schemes using Gaussian distribution do not show good performance. In fact, many research has recently tried to improve localization accuracy in noisy environments [30,33,34]. In this paper, we propose an adaptive localization technique with the consideration of the non-linear characteristics of CSS measurements and environmental factors.

3. CSS ranging functionality

We conducted a series of preliminary experiments to evaluate the characteristics of CSS range measurements using prototype hardware equipped with an IEEE 802.15.4a CSS-compatible radio transceiver. Fig. 1 shows the Ymote hardware that consists of an MSP430F1611 microcontroller, NanoLOC TRX transceiver [35], and a rechargeable Li-polymer battery.

To evaluate the effects of node mobility and obstacles on the accuracy of IEEE 802.15.4a CSS ranging, we conducted experiments to measure the distance among static nodes and mobile nodes when the line of sight is guaranteed. We also performed experiments with various obstacles on the site. Fig. 2(a) shows the range measurements between two static nodes in an obstacle-free corridor where the line of sight is preserved as shown in Fig. 2(b). The CSS devices were placed at 1 m above the ground. The result validated the high accuracy of distance measurement; both the average and standard deviation of distance error were lower than 1 m. The result shows that distance information was obtained with an average error of 0.86 m.

The experiment in Fig. 3 is conducted to reflect a real noisy indoor environment. Fig. 3(a) shows the result of range measurements conducted at a site shown in Fig. 3(c). Fig. 3(d) further illustrates the experimental scenario and obstacles at this site. Here, one node is moving (a mobile node) and the other node is stationary (an anchor node). The anchor node is installed at 2.1 m above the ground whereas a mobile node is carried by person. While the mobile node is moving around by maintaining a constant distance of 15 m, obstructive objects may exist between two nodes. In other words, the direct path of radio propagation is randomly blocked by walking person, pillar, flower pots, tables, chairs, and so on. The value zero on the y axis denotes the failure of range measurement. About 28% of the ranging frame was not measured because of blockage caused by several objects and human body. Also, in this experiment, the ranging error has a large

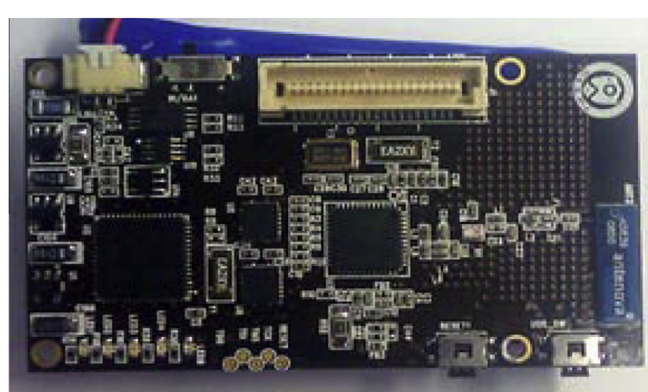

Fig. 1. Ymote which is equipped with IEEE 802.15.4a CSS radio.