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Crowdsensing-based Wi-Fi radio map management using a lightweight site survey

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ABSTRACT

Localization based on Wi-Fi fingerprinting (WF) necessitates training the radio signals of target areas. Manual training enables good accuracy but requires service providers to conduct thorough site surveys to collect the radio signals of target areas periodically. Several systems are capable of eliminating the training phase by collecting radio signals from users, but these schemes are unable to provide location-based services until enough data are collected from the participatory users. Moreover, the accuracy of such systems is generally worse than that of systems that conduct manual training. In this paper, we propose a radio map management scheme in which the two methods are combined to achieve high accuracy with reduced management costs. The proposed scheme entails only a lightweight site survey for the construction of the initial radio map and does not necessarily require coverage of the entire area of interest. The quality of the radio map is enhanced in terms of both coverage and accuracy through user collaboration. In our system, mobile users conduct automatic war-walking with smartphone-based pedestrian dead reckoning (PDR), and to match the war-walking path to the radio map accurately, we employ a particle filter using both WF and PDR. We also consider the received signal strength variance problem caused by the device type and environmental changes. The proposed scheme is elastic since the service provider can adjust the costs required for the initial site survey depending on the quality of the crowdsensing-based radio map, which would compensate for the lack of coverage and accuracy of the initial radio map. The experiment's result validates that our scheme achieves competitive accuracy and coverage in comparison with systems that conduct full site surveys.

1. Introduction

The diverse location-based services (LBS) on offer today, such as location tagging on photos [1], life-logging [2], and social networking, provide convenient technology for people to use in their daily lives. With the widespread use of smartphones, localization is now available for both indoor and outdoor spaces. Most outdoor spaces are covered by the global positioning system (GPS) [3], but indoor LBS systems employ different localization techniques because GPS signals cannot penetrate indoor spaces. Indoor LBS solutions use a variety of sensors, such as radio-frequency identification [4], ultra-wideband [5], the global system for mobile communications [6], and Wi-Fi [7]. In particular, Wi-Fi fingerprinting (WF) has been extensively applied because this technology estimates indoor locations with meter-level accuracy. Moreover, additional infrastructures are not required because the system uses existing access points (APs) and most smartphones are Wi-Fi enabled.

The WF training process generally incurs high costs because the surveyor has to create a radio map by collecting received signal strength (RSS) information from every location in a target area. Periodic re-training is also inevitable because the characteristics of radio signals change over time. Much of the recent research on WF has focused on overcoming the problems presented by user collaboration. Park et al. [8] proposed WF systems that construct radio maps by collecting RSS measurements and location information that are manually provided by users. These systems require the active participation of users who have knowledge of the layouts of buildings and their current locations. We previously developed a WF system that constructs radio maps by user collaboration in a non-intrusive way [9]. In the system, mobile users report RSS measurements with location information tracked via pedestrian dead reckoning (PDR). The accuracy of the system is lower than that of a manual training system because of the drift error from PDR. Rai et al. [13] proposed Zee, which improves the accuracy of PDR with information extracted from floor plans, such as the locations of walls, rooms, and obstacles. However, detailed floor plans are not always available in practice, and the

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accuracy of PDR is low in large, open spaces due to the absence of walls and obstacles.

To achieve high-accuracy WF at a reduced cost, in this paper, we propose an elastic radio map management scheme that constructs a partial radio map using a lightweight site survey. In this system, the radio map is updated and expanded with PDR-based non-intrusive user collaboration. The proposed scheme is elastic since service providers can readily adjust the coverage of the initial site survey. Nevertheless, the proposed system presents a number of challenges as users collect radio fingerprints with different types of devices at different times. The system should therefore ideally consider the RSS variance problem [10] when the radio map is updated with user data. Since the initial map may not cover the entire area, the system should be able to add radio fingerprints for places that have not been covered with the correction of location errors from the smartphone-based PDR.

We overcame these challenges by developing an algorithm that combines WF and PDR with a particle filter. To solve the RSS variance problem, we considered particles based on a series of RSS measurements rather than a single RSS measurement. To reduce PDR errors, we designed a mobility model that has the bias error of a gyroscope at each turn point to reflect the characteristics of smartphone-based PDR. We also reduced the localization error caused by RSS variances by updating the radio map with a median fingerprint that was highly similar to all the other fingerprints collected at the same location.

The contributions of our work are as follows:

- We designed an elastic radio map management scheme that allows the coverage of a site survey to be adjusted.
- We proposed a radio map update algorithm that minimizes the RSS variance problem and the error distance of smartphone-based PDR.
- We validated the feasibility of our system with real experiments in different environments.

The remainder of this paper is structured as follows: Section 2 presents a background on the technologies used and an overview of the proposed system. Section 3 describes the radio map update algorithm, and Section 4 provides an evaluation of the system, which was achieved through experiments. Section 5 presents related work and Section 6 concludes the paper.

2. Background

2.1. Wi-Fi fingerprinting

WF involves two phases: a training phase and a localization phase. In the training phase, a radio map is constructed by a surveyor who conducts site surveys to collect the RSS measurements of all the locations in the target area. Radio map M is represented as follows:

$$M = \{F_1, F_2, \ldots, F_{n-1}, F_n\}$$

where F_i denotes the radio fingerprint of location i, and n is the number of locations from which the radio fingerprints are collected during the training phase. The radio fingerprint F includes the location information L and the RSS measurements R. The location L is represented by the coordinates of the x-axis and the y-axis in the 2D plane. R contains the RSS measurements from all the m APs deployed in the target area. Hence, F is represented as

$$F = (L, R)$$

$$L = (x, y), \quad R = (\mathrm{rss}^1, \mathrm{rss}^2, \ldots, \mathrm{rss}^m)$$

In the localization phase, mobile users report their current RSS measurements R' to the server. Then, the server identifies the F_i that has an RSS measurement most similar to R. Several kinds of similarity functions can be used for the two RSS measurements; these functions include the Euclidian distance [7] and the Tanimoto coefficient [12]. In this paper, we use the Tanimoto coefficient because it ranges from 0 to 1, while the Euclidian distance increases depending on the number of APs. Finally, the user location is estimated by using the location information on the selected fingerprint.

2.2. Received signal strength variance problem

Generally, WF suffers from an RSS variance problem because RSS values are monitored in different ways depending on the device type and environmental changes. According to our previous study [10], the RSS values measured in a single location can differ by more than 10 dBm under different conditions. Consequently, the accuracy of WF is significantly degraded due to RSS differences. Solving the RSS variance problem is important in user-collaboration scenarios because users report their RSS measurements at different times with different devices. In [11], the effect of device diversity was addressed via kernel density estimation with a wide kernel width, but the RSS variance caused by other conditions, such as user direction and environmental changes, was not explored in the work.

2.3. Smartphone-based pedestrian dead reckoning

PDR is a localization technique that tracks relative locations by estimating the moving distance and direction of pedestrians. We previously proposed a smartphone-based system that implements PDR by using the sensors that are built into commercial smartphones, such as an accelerometer and digital compass [9]. Moving distance is estimated by step counting with the accelerometer and direction is estimated by the digital compass. However, the compass reading cannot be aligned with the user's direction because of the smartphone's placement and magnetic distortion. According to [13], the difference between the compass reading and an actual user's direction might exceed 150°. We therefore did not use a digital compass for heading estimation but employed a gyroscope instead. Since the gyroscope provides only relative angular change, the PDR periodically reported relative mobility information (RMI) as follows:

$$D = (d, \theta_{\mathrm{gyro}})$$

where d represents the moving distance, and θ_{gyro} the relative directional change estimated with a gyroscope.

2.4. Limitations of map-based pedestrian dead reckoning

The main problem with PDR is that the start position is unknown and the positioning error is accumulated with the drift caused by sensor noises. To overcome this problem, researchers proposed a map-based PDR that exploits the layout information, such as the positions of pathways, doors, and obstacles. In particular, Zee [13] used a map-based PDR for radio map building based on crowdsensing. In the system, the moving path is estimated by finding a path that does not violate the physical constraints imposed by the layout, as shown in Fig. 1(a). However, map-based PDR fails to determine the moving path when there are multiple paths that do not violate the physical constraint, as illustrated in Fig. 1(b). The probability of failure increases when a user takes a short path or where few obstacles or walls exist that impose physical constraints.