WinIPS: WiFi-based Non-intrusive IPS for Online Radio Map Construction

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***Abstract*—Existing WiFi fingerprinting-based Indoor Positioning System (IPS) suffers from two major bottlenecks. One is that the offline site survey process is extremely time-consuming and labor-intensive. The other is that the offline calibrated received signal strength (RSS) fingerprint database is vulnerable to environmental dynamics. To address these issues comprehensively, in this paper, we propose WinIPS, a WiFi-based non-intrusive IPS that enables automatic online radio map construction and adaptation for calibration-free indoor localization. WinIPS is able to capture data packets transmitted in the existing WiFi traffic and extract the RSS values and MAC addresses of both access points (AP) and mobile devices (MD) in a non-intrusive manner. By leveraging APs as online reference points for radio map construction, we can completely remove the needs of laborious offline site survey process. The constructed radio map is more robust to environmental dynamics since it is updated automatically in real-time. Extensive experimental results verify the superiority of WinIPS in terms of RSS estimation accuracy and localization accuracy, and these merits make it more suitable for practical large-scale implementation.**

I. Introduction

In recent years, great efforts have been devoted to developing IPSs. Among the proposed techniques, WiFi is acknowledged as the most promising alternative to GPS for indoor localization because the commercial WiFi devices and infrastructures have been extensively available in indoor environments. Fingerprinting-based localization algorithm is widely adopted for existing WiFi-based IPS. It localizes the MD by comparing the RSS readings with a pre-established RSS fingerprint database, (a.k.a. radio map). However, two major drawbacks restrain it for large-scale implementation: 1) the offline site survey process is extremely time-consuming and labor-intensive; 2) The offline calibrated database is vulnerable to environmental dynamics. Serious localization errors will be introduced if the radio map is not updated adaptively.

In this paper, we propose, WinIPS, a WiFi-based non-intrusive IPS that enables automatic online radio map construction and adaptation for calibration-free indoor localization. It can overhear data packets transmitted in the existing WiFi traffic and extract the RSS values and MAC addresses of both APs and MDs in a non-intrusive manner without introducing any extra hardware. By employing the real-time RSS readings and the physical coordinates of APs, all the APs are becoming natural online reference points for radio map construction, so we could discard the tedious offline site survey process. By modeling the RSS distribution in two dimensional surface, the proposed Gaussian Process Regression with Polynomial

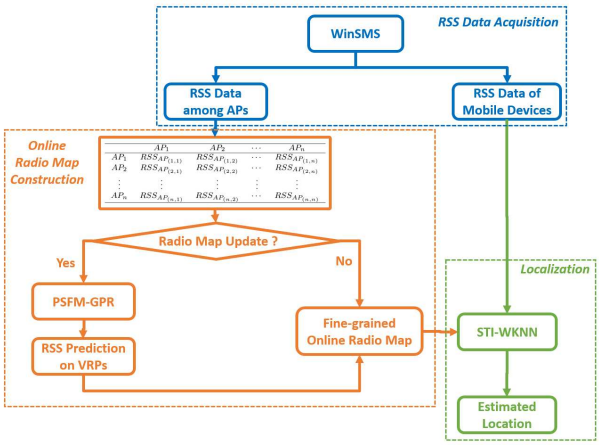

Fig. 1. System architecture of WinIPS.

Surface Fitting Mean (PSFM-GPR) can capture the irregular RSS distribution over complex indoor environment precisely and build up a fine-grained radio map. Furthermore, WinIPS is more tolerable and robust to various environmental dynamics because the radio map is updated automatically in real-time. We prototype WinIPS and test it in real complex indoor environment. Promising results indicate that WinIPS makes substantial progress towards fortifying WiFi fingerprint-based IPS for feasible large-scale commercialization.

II. System Design

Fig. 1 illustrates the system architecture of WinIPS. For RSS data acquisition, with the upgraded firmware, each AP is able to overhear the 802.11 data packets transmitted in the existing WiFi traffic and uses Libpcap to extract the RSS values of both MDs and APs and their corresponding MAC addresses from the packets without any intrusiveness on the user side. All the data is forwarded to a back-end server and the server constructs the online RSS fingerprint database and employs it to estimate locations of MDs. All the APs become natural online reference points for radio map construction and adaptation since we have their physical coordinates and real-time RSS readings. For online radio map construction, the limited number of APs may be not good enough to describe the odd RSS distribution in complex indoor environment. To construct a more fine-grained radio map, we first divide the area into grids and treat each grid point as virtual reference point (VRP) and then use Gaussian process regression (GPR), which is an appropriate method for capturing the noisy nature of RSS, to predict the RSS values of

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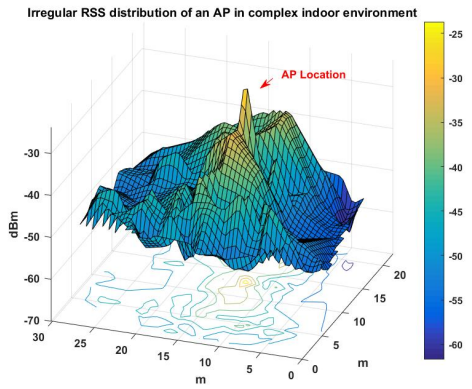

Fig. 2. Irregular RSS distribution of an AP in complex indoor environment.

all the APs on these VRPs. As shown in Fig. 2, traditional GPR with zero mean (ZeroM-GPR) or Log-Distance mean (LDM-GPR) [1] fail to describe the irregular RSS distribution in complex indoor environment because they do not consider the orientation or the surrounding environmental property on each VRP. In order to capture this phenomenon, we first assume the RSS distribution of each AP to be a two dimensional polynomial function, and then propose PSFM-GPR, which utilizes a two dimensional polynomial surface fitting model to estimate a general mean of RSS and then employs GPR to estimate the residual RSS errors. The predicted RSS s_j by PSFM-GPR at VRP $\boldsymbol{l_j}$ is calculated by

$$s_j = m(\boldsymbol{l_j}) + K(\boldsymbol{l_j}, \boldsymbol{L})[K(\boldsymbol{L}, \boldsymbol{L}) + \sigma_\epsilon^2 I]^{-1}(\boldsymbol{S} - m(\boldsymbol{L}))$$
$$m(\boldsymbol{l_j}) = \beta_0 + \beta_1 x_j + \beta_2 y_j + \beta_3 x_j^2 + \beta_4 y_j^2 + \beta_5 x_j y_j$$

where (x_j, y_j) is the coordinates of location $\boldsymbol{l_j}$, $m(\cdot)$ and $K(\cdot,\cdot)$ represent the mean and covariance function, $\boldsymbol{S}$ and $\boldsymbol{L}$ denote the RSS values and coordinates of APs. In this way, a fine-grained radio map can be built up and update effectively to avoid cumbersome offline cite survey process. Due the device heterogeneity issue between APs and MDs, we leverage signal tendency index (STI) [2], which compares the similarities of the RSS curves' shapes between RSS vector of MD and those stored in the AP related fingerprint database instead of using the absolute RSS values for fingerprint matching.

III. Experimental Results

We conducted extensive experiments in a $600m^2$ multi-functional office to validate the performance of WinIPS in terms of RSS estimation accuracy and localization accuracy. The performance of PSFM-GPR is compared with ZeroM-GPR, LDM-GPR [1] and GWR [3]. The overall performance is summarized in Table I and Fig. 3. The average estimated RSS error of PSFM-GPR is only 4.68 dBm which is the smallest among the four methods because it performs two dimensional surface fitting for RSS prediction which precisely captures odd RSS distribution in different orientation. By leveraging the online radio map generated by PSFM-GPR, WinIPS can provide 1.718 m localization accuracy on average, which enhances the precision of indoor positioning by 45.52% over ZeroM-GPR, 33.16% over LDM-GPR and 35.23% over GWR

TABLE I
Comparison of RSS estimation accuracy and localization accuracy between different methods

Approach	Mean RSS Estimation Accuracy (dBm)	Mean Localization Accuracy (m)
ZeroM-GPR	18.16	3.153
LDM-GPR	6.55	2.570
GWR	6.64	2.652
PSFM-GPR	**4.68**	**1.718**

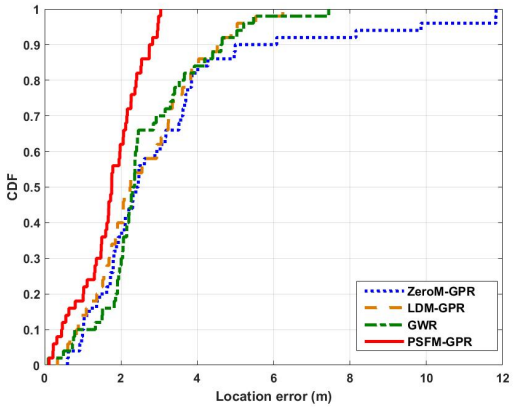

Fig. 3. Comparison of localization accuracy between different online methods.

respectively. We also compared it with traditional offline site survey method. When PSFM-GPR is compared with offline database constructed at the same day, the average localization accuracy of it is only a little worse by 8.67% than offline fingerprint database. However, it is impractical to perform the tedious offline calibration process every day. According to our experimental results, WinIPS can reduce the localization error by 26.17% than outdated offline fingerprint database and provide high localization accuracy consistently.

IV. Conclusion

In this paper, we proposed, WinIPS, a WiFi-based non-intrusive IPS that enables automatic online radio map construction and adaptation for calibration-free indoor localization. It can overhear the data packets transmitted in the existing WiFi traffic and extract vital information in a non-intrusive manner without any extra hardware infrastructure. Fine-grained radio map is constructed online using APs as online reference points, so we can completely get rid of the tedious offline site survey process. It is robust to environmental dynamics since the radio map is updated automatically in real-time. The experimental results verify the superiority of WinIPS and validate it is promising for large-scale practical implementation.

References

[1] M. M. Atia, A. Noureldin, and M. J. Korenberg, "Dynamic online calibrated radio maps for indoor positioning in wireless local area networks," *Mobile Computing, IEEE Transactions on*, 2013.

[2] H. Zou, B. Huang, X. Lu, H. Jiang, and L. Xie, "A robust indoor positioning system based on the procrustes analysis and weighted extreme learning machine," *Wireless Communications, IEEE Transactions on*, 2016.

[3] Y. Du, D. Yang, and C. Xiu, "A novel method for constructing a wifi positioning system with efficient manpower," *Sensors*, 2015.