

Power Delay Profile Based Indoor Fingerprinting Localization System

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Abstract—Received signal strength (RSS) based fingerprinting localization technique has been researched widely for the indoor location based services (LBSs) in recent years. However, the accuracy performance suffers from the time-varying characteristic of RSS due to the multi-path and shadow effect. In this paper, we propose a fingerprinting positioning system based on power delay profile (PDP). The system extracts the PDP of the multi-paths from the cross-correlation result between the received signal and the reference signal. In the offline phase of the system, a PDP fingerprint database is constructed via calibrating the PDP of each access point (AP) at each reference point (RP). In the online phase, a PDP similarity matching algorithm is designed to mitigate the error caused by the time-variation of RSS, and further to obtain the final location estimation. Numerical experimental results show that the proposed system can obtain higher localization accuracy than other existing positioning systems.

Index Terms—fingerprinting localization, power delay profile, time-variation, vector cosine.

I. INTRODUCTION

In recent years, there has been an increasing interest in location determination of mobile terminal in indoor environments. Indoor location based services (LBSs), such as indoor positioning, tracking, navigation, advertising, logistics management and game development, are becoming more popular in our daily life. Obviously, the qualities of services mainly depend on the accuracy of positioning system. However, traditional systems, such as Global Positioning System (GPS), cellular network based positioning system, become invalid in the indoor environment because of the none-line-of-sight (NLOS) and multi-path propagation of the signal [1]. Fingerprinting localization technique has been promoted to overcome the multi-path problem in indoor environments [2].

Generally, fingerprinting localization system is divided into two phases, the offline phase and the online phase. The offline phase needs to calibrate the signal parametrics (also called fingerprint) from each access point (AP) at each reference point (RP) in the target area. All the fingerprints and the corresponding RP locations will be stored in a database. The online phase estimates the location information of the terminal via matching the real-time fingerprint calibration with the database. The signal parametrics mainly include the received signal strength (RSS) [3], channel impulse response (CIR) and power delay profile (PDP) [4–7]. The RSS based fingerprinting localization system is most widely adopted because it is easy to realize without any hardware modification [8, 9]. However, the RSS is time-varying due to the multi-path effects, which would

results in large location error. To mitigate the effect of time-variation of RSS, most researchers draw more attentions on the design of the online positioning algorithm. Some researchers introduced the probabilistic methods to mapping the location, including the histogram algorithm [10] and Kernel function based method [11]. Those approaches need to calibrate a large number of RSS samples to achieve the accurate RSS distribution model in the target area. Others adopted the artificial intelligence (AI) algorithms, such as artificial neural networks (ANN) [12] and support vector machine (SVM) [13], to carry out the pattern matching functionality. The computational complexity of AI algorithms is higher than traditional K-nearest node (KNN) or Weight-KNN (WKNN) algorithms [14].

CIR or PDP based fingerprinting localization is another good choice to improve the accuracy through characterizing the multipath channel [15]. CIR or PDP is extracted via a cross-correlation metric method, reflecting the multi-path propagation in indoor environment. CIR or PDP parametric fingerprint has the advantage of being reproducible, unique and location-dependent [16]. The extraction of the parametric is generally obtained from a wideband wireless system, like ultra wide band (UWB) system [6, 16]. Nerguizian et al. [16] proposed ANN based fingerprint matching algorithm to estimate the location information. The offline training of the neural network played the most significant role in the performance of the system. Mati et al. [17] proposed a subspace decomposition based super-resolution multipath fingerprinting localization system. However, the computational complexity increased dramatically. Khanbashi et al. [6] theoretically validated the performance improvement of the CIR based fingerprinting localization system.

PDP fingerprinting localization is actually based on the power-delay characteristics of the multi-path wideband signals. The characteristics will be more robust against interference and noise when the band of the signal increases. However, the band of most existing wireless network, such as WiFi and Long Term Evolution (LTE) network [18], is not as wide as UWB network. In this case, the robustness of power-delay parametric of each propagation path will decrease, and the power of each path tends to seriously vary with time, which would result in large positioning error. In this paper, we propose a PDP fingerprinting localization system based on narrow bandwidth system (such as 40MHz 802.11n and 160MHz 802.11ac). We extract the PDP of the signal via cross-correlation method

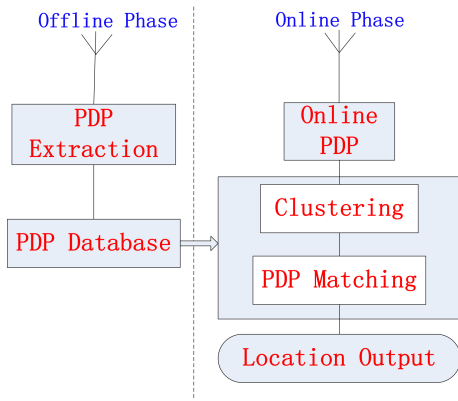


Fig. 1. Proposed positioning system structure

and propose a vector cosine based matching algorithm to estimate the location information. We validate the performance improvement through a real-world experimental platform.

The rest of this paper is organized as follows. Section II describes the system structure. Section III introduces PDP extraction method and the positioning algorithm. Experiments and analysis are presented in Section VI. Finally, the concluding remarks and future work are provided in Section V.

II. OVERVIEW OF PROPOSED SYSTEM STRUCTURE

Without loss of generality, our fingerprinting localization system is also divided into two phases. As shown in Fig.1, the system consists of offline phase and online phase. In the offline phase, the system extracts the PDP of each AP at each RP, and then stores the PDP fingerprints in the database which would be used in the online phase for location estimation. Fig. 2 shows the PDP extraction system. The core of the system is a signal analyzer which is used for synchronization by triggering the signal generator to send the designed pseudo-noise (PN) sequence, and also used to receive the transmitted signal at the same time. As previous mentioned, the signal generator of the positioning system sends a $f_c = 1.525\text{GHz}$ carrier frequency and 40MHz bandwidth source. The source is then splitted into transmitting signal and reference signal via a power splitter. The received signal data via the signal analyzer is finally download to the PC for analysis.

Denoting the calibrated fingerprint at the i^{th} RP as

$$\mathbf{P}_i = \{p_i^1, \dots, p_i^j, \dots, p_i^n\}, \quad i = 1, 2, \dots, L, \quad (1)$$

where L is the number of RPs, n is the number of APs, $p_i^j \in \mathbb{R}^{N \times 1}$ is the PDP of AP_j at RP_i , N is the length of the correlation sequence. The location of RP_i is denoted as $l_i = [x_i, y_i]^T$. The final fingerprint database can be expressed as

$$\Omega = \{\mathbf{P}_1, \dots, \mathbf{P}_i, \dots, \mathbf{P}_L\}. \quad (2)$$

In the online phase, the mobile terminal to be located firstly calibrates the real-time fingerprint, denoted as $\hat{\mathbf{P}}$. Then, the terminal carries out the positioning algorithm to obtain the location information. The process of estimation consists of two steps. The first step, called clustering, is designed to locate

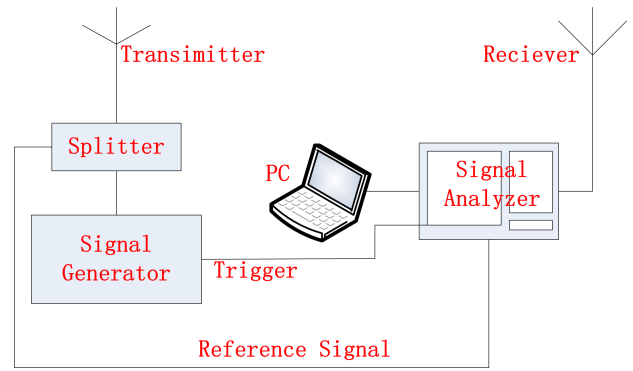


Fig. 2. PDP extraction system

the terminal into a rough area. The next step is to get the fine location information through PDP matching algorithm in the rough area. The detailed PDP extraction and positioning algorithm in mathematical expressions will be described in the next section.

III. LOCALIZATION ESTIMATION ALGORITHM

The traditional PDP or CIR based fingerprinting localization system obtains the PDP/CIR fingerprint from the multi-path impulse response of each AP, which can be defined as

$$h(t, \tau, d) = \sum_{i=0}^{m-1} a_i(t, \tau, d) \exp^{j\phi_i(t, \tau, d)} \delta(\tau - \tau_i), \quad (3)$$

where $a_i(t, \tau, d)$ and $\phi_i(t, \tau, d)$ are the amplitude and phase of the i^{th} multi-path, τ_i is the corresponding excess time delay, d is the distance between transceivers, m is the number of multi-paths. We extract the PDP of the j^{th} AP at the i^{th} RP through cross-correlation operation, which can be expressed as

$$p_i^j = \text{abs}(IFFT(FFT(x(t)) \times \text{conj}(FFT(r(t))))), \quad (4)$$

where $x(t)$ is the transmitting signal, FFT and $IFFT$ denotes the fast fourier transformation (FFT) and inverse FFT function. $\text{conj}(\cdot)$ is the conjugate of the vector, and $\text{abs}(\cdot)$ returns the complex magnitude of the corresponding element. $r(t)$ is the received signal which is expressed as

$$r(t) = \sum_{i=0}^{m-1} a_i(t, \tau_i, d) x(t - \tau_i) \exp^{j\phi_i(t, \tau_i, d)} + n_i(t), \quad (5)$$

where $n_i(t)$ is the additive Gaussian white noise of the i^{th} multi-path.

It is reported that the CIR is shown to be essentially time-invariant for UWB signal[19, 20]. However, the PDP trends to be time-varying when the bandwidth decreases, especially for the amplitude of each multi-path as shown in Fig.3. In the Fig.3, the signal bandwidth is set to be 28MHz , and the signal is received at a different time from the same AP to the same RP. It can be seen that the resolvable multi-path time delays have little change. However, the corresponding amplitude of

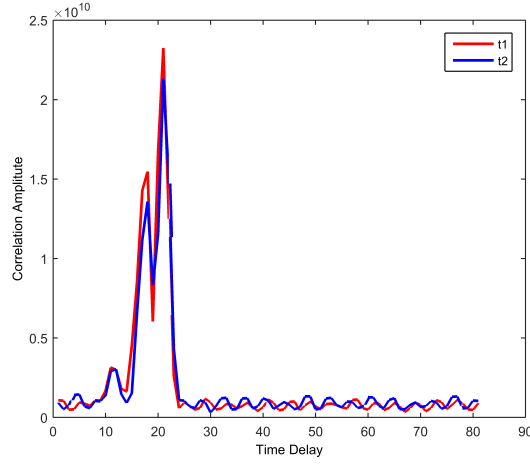


Fig. 3. Cross correlation results at different time

each multi-path varies with time. In this case, the accuracy of positioning system will suffer from the time-variation.

To mitigate the effect of the time-varying amplitude of multi-path, we proposed a vector cosine based PDP matching algorithm. The location estimation includes two steps, clustering and PDP matching. In the first step, we extract the time delay of the first multi-path in the PDP database Ω , and denote the first time delay of AP_j at RP_i as τ_{ij}^0 . Then, a sub-database of first time delay at each RP is constructed by the following set of vectors

$$\Psi = [\Gamma_1, \Gamma_2, \dots, \Gamma_L], \quad (6)$$

where $\Gamma_i = [\tau_{i1}^0, \dots, \tau_{ij}^0, \dots, \tau_{in}^0]^T$, $i = 1, 2, \dots, L$. The online vector of first time delay is assumed to be $\Gamma_{\tilde{l}}$. Then, all the RPs that satisfy the following condition can be selected into a cluster (denoted as $\mathcal{C}$). The condition is defined as

$$\text{norm}(\Gamma_i - \Gamma_{\tilde{l}}) \leq n \times \frac{1}{f_s}, \quad (7)$$

where $f_s = 56\text{MHz}$ is the sampling frequency in this system, $\text{norm}(\cdot)$ is the Euclidean norm of the vector.

The fine positioning algorithm will be carried out in step two after the terminal has been located into the cluster. The fine location is obtained through a vector cosine based PDP matching algorithm. In other words, we measure the similarity between two PDP vectors (or two cross correlation curves as shown in Fig. 3) via calculating their vector cosine value. In order to mitigate the effect of noise on the vector cosine value, we extract the principal component of cross correlation results (as shown in Fig.4) to get the similarity metric. The metric is calculated as

$$s_i^j = \frac{(\tilde{p}^j)^T \cdot p_i^j}{\text{norm}(\tilde{p}^j) \times \text{norm}(p_i^j)}. \quad (8)$$

where $\tilde{p}^j$ and p_i^j are the principle components of the AP_j at the location to be located and at the RP_i . Denoting $S_i = [s_i^1, s_i^2, \dots, s_i^n]^T$ as the vector of similarity metrics between the online fingerprint and the fingerprint at RP_i .

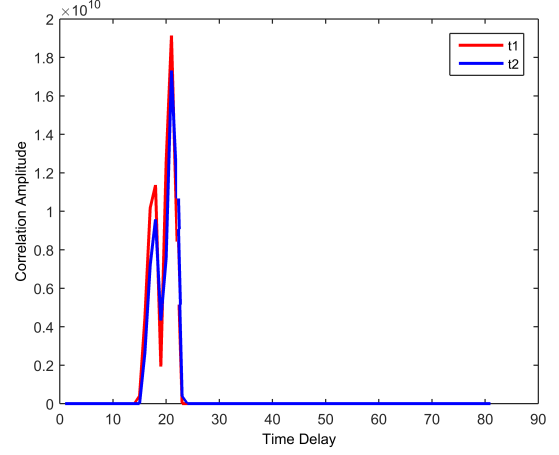


Fig. 4. Principal components of cross correlation extraction results

Finally, we estimate the location via a weighted linear equation of K RP locations which have the largest $\text{norm}(S_i)$ values. The equation can be expressed as

$$\tilde{l} = \frac{1}{\sum_{i=1}^K w_i} \times \sum_{i=1}^K w_i l_i, \quad \text{s.t. } RP_i \in \mathcal{C}, \quad (9)$$

where $w_i = \text{norm}(S_i)$, and the value of K is usually set to be $3 \sim 5$ in literature. Without loss of generality, we set it to be 3 in our test.

IV. PERFORMANCE EVALUATION

A. Experimental setup

To evaluate the accuracy performance of the proposed PDP based fingerprinting positioning system, we carry out numerous experiments in a real indoor environment, i.e. Fujitsu R&D Center (FRDC) office, as shown in Fig.5. In the testing area, we calibrate the fingerprints at total 143 RPs as showed by the dot marks in Fig.5, and calibrate another 108 testing points, as showed by the cross marks in Fig.5, to evaluate the performance. Both the grid size of the RPs and that of the testing points are set to be $1\text{m} \times 1\text{m}$. Fig.6 shows the experimental equipments in our positioning system. As shown in Fig.6, the signal generator in Fig.2 is Agilent MXG N5182B vector signal generator, and the signal analyzer in this system is Agilent PXA N9030A signal analyzer. The transmitting antenna sends a carrier frequency $f_c = 1.525\text{GHz}$ and bandwidth 28MHz signal to the receiving antenna. It should be point out that the accuracy of the positioning system would be further improved when the bandwidth increases, such as 40MHz and 80MHz in WiFi and 4G communication standards[4]. However, with a limited number of transmitting antennas, we have only calibrated the signals from two APs at each RP and testing point. Due to the advantage in exploiting the multi-path, the PDP fingerprinting localization system can also provide high accuracy with only one AP [4]. Hence, it is available for us to evaluate and demonstrate the performance of the proposed system in the following subsection.

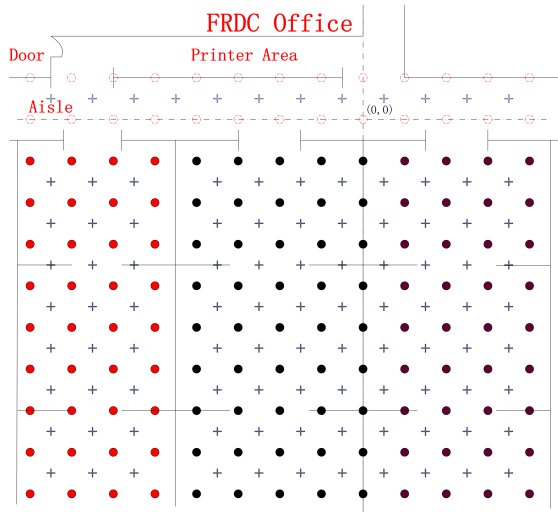


Fig. 5. Map of testing area in FRDC office

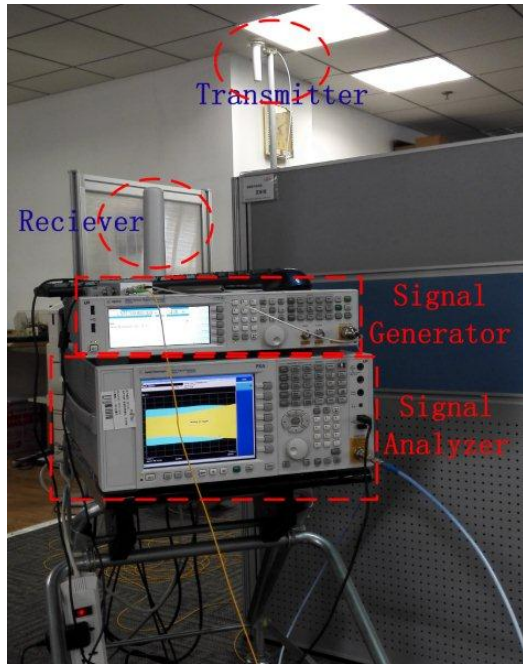


Fig. 6. Equipments for PDP extraction

B. Experimental results

We carry out two groups of experiments to evaluate the positioning performance of the proposed system. First, we compare the accuracy performance of the proposed system with the traditional PDP based fingerprinting positioning system[4, 17]. In order to demonstrate the efficiency of our proposed system on mitigating the error caused by RSS time-variation characteristic, the fingerprint of the traditional system is denoted as

$$\bar{p} = [a_0, a_1, \dots, a_{m-1}, \tau_0, \tau_1, \dots, \tau_{m-1}]^T, \quad (10)$$

where a_i and τ_i is the amplitude and time delay of the i^{th} path, $i = 0, 1, \dots, m - 1$. The fingerprint matching algorithm

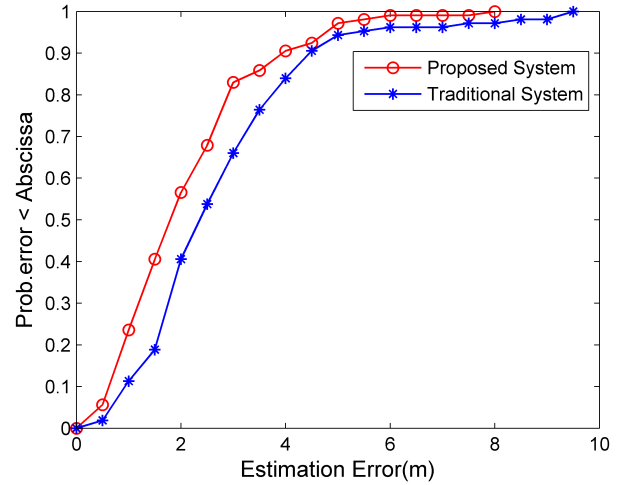


Fig. 7. Performance comparison in terms of accuracy

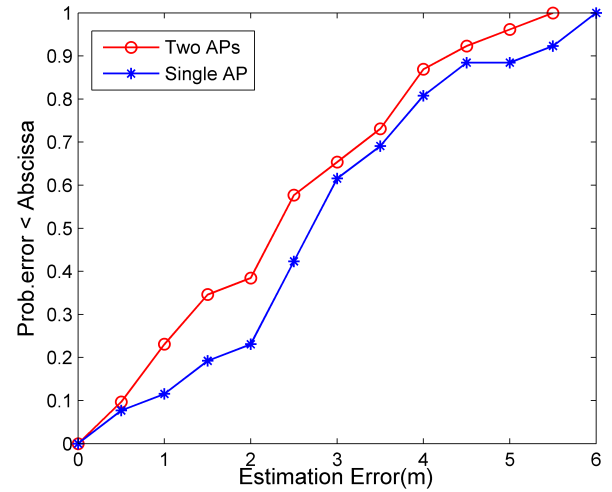


Fig. 8. Effect of AP number on accuracy performance

of the traditional system is based on WKNN algorithm [14].

Fig.7 shows the cumulative distribution function (CDF) of the estimation error of the two systems. In this group of experiments, we extract the fingerprint from only one AP in the testing area. As shown in the Fig.7, the proposed system outperforms the traditional system. The probability of estimation error within $4m$ of the proposed system is about 90.5%, whereas that of the traditional system is less than 84%. The largest positioning error of the proposed system is $1.5m$ less than that of traditional system. Hence, the results in Fig.7 also validate that our proposed algorithm can mitigate the effect of RSS time-variation on positioning error.

Then, in the second group of experiments, we compare the performance of the proposed system using two APs and single AP, respectively. Fig.8 demonstrates the effect of AP number on the accuracy of proposed system. As shown in Fig.8, the proposed system can obtain higher accuracy performance when we adopt more APs. In fact, the probability of the accuracy less than $4m$ is about 86.9% when the proposed system

extracts the fingerprints from two APs, and the probability is 6% higher than that of single AP based system.

V. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a PDP based fingerprinting localization system. In this system, we firstly locate the terminal into a cluster, and then obtain the fine location information through vector cosine based PDP matching algorithm. The experimental results demonstrate that our proposed system can effectively mitigate the error caused by RSS time-variation characteristic, and further achieves a higher accuracy performance. What is more, another advantage is that our proposed system could realize positioning functionality via single AP. Our proposed system can be easily realized in the existing wideband WiFi and LTE networks. It should be pointed out that the AP selection method in PDP based fingerprinting localization system is different from that in RSS based fingerprinting positioning system when numerous APs are available for terminal positioning. Hence, in the future work, we will concentrate on the study of AP selection method in our system to further improve the performance in terms of accuracy.

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