Efficient Design of Scalable Indoor Positioning System Based on Wi-Fi Fingerprinting

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Abstract

Cyber-Physical Systems (CPS) are evolving and gradually building an ecosystem of smart homes, smart cities and automated systems. Indoor Positioning Systems (IPSs) play an essential part in providing location-based services to many demanded applications such as robots, UAVs, shopping malls, health care and more. Indoor positioning based on Wi-Fi is widely used to limit the complexity and cost of the Indoor Positioning System (IPS). This study aims to find an efficient design that makes IPS based on Wi-Fi fingerprinting more simple and scalable to enhance indoor positioning performance. Investigating the IPS system design in indoor settings tries to improve the positioning accuracy of Wi-Fi RSSI-based systems and reduce database-fingerprinting complexity by using cloud-computing architecture for efficient resource management and system scalability.

Keywords

Indoor Positioning Design, Cyber-Physical System, Model-based design, Cloud computing.

1. Introduction

Positioning and navigation services have become a significant necessity in our daily lives. Nowadays, using Global Navigation Satellite System (GNSS) technology for positioning and navigation has never been easier and more affordable for the outdoor environment. The GNNS services such as Global Positioning System (GPS) technology, which is included in smartphones, provides an accurate position of approximate 7-13 meters in an outdoor environment [1]. However, for indoor environments, GPS is unable to function properly due to obstacles that prevent GPS Radio Frequency (RF) signals to penetrate walls and objects inside the buildings. Hence, alternative technology is needed to act similar to the GPS in indoor environments with higher accuracy. This has led many academic and industrial researchers in the last decades to work out how to emulate GPS in an indoor setting. These efforts shaped what is called an Indoor Positioning System (IPS).

The Indoor Positioning System (IPS) is a system, which can determine the object's position inside a building or in a certain coordinate system [2]. Positioning determination calculates by different means depending on various used technologies. These technologies include RF, Optical, Magnetic, and Acoustic-based technologies [3, 4]. However, RF-based technology is commonly used in IPS because radio frequency can penetrate walls to give a wide coverage area compared to other technologies, furthermore, has lower cost hardware, as in most cases, it is an existing infrastructure for communication such as Wireless Local Area Network (WLAN). Inside indoor spaces, indoor positioning has multi-dimensions challenges such as signal problems, limited infrastructure, and lack of maps. However, signal problems are one of the core challenges for RF-based indoor positioning systems. The signal problems represented in the signal multipath and attenuation have a great deal to degrade the indoor positioning for RF-based systems [4].

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Wi-Fi technology is widespread hence no additional infrastructure cost is imposed, therefore; IPS researchers have focused on making Wi-Fi an enabler for IPS. Wi-Fi belongs to the IEEE 802.11 standard, this standard supports intensity measurement functionality for RF signals on Wi-Fi chips/card, and this can be represented as Received Signal Strength Indicator (RSSI) at terminal devices. Thus, users can use their devices such as mobile phones to locate themselves indoors by just using the Wi-Fi indoor positioning system. Therefore, this study is focusing on the efficient design of the RSSI-based method with fingerprinting technique for IPS. **Error! Reference source not found.** Illustrate the Wi-Fi RSSI-based fingerprinting system for IPS.

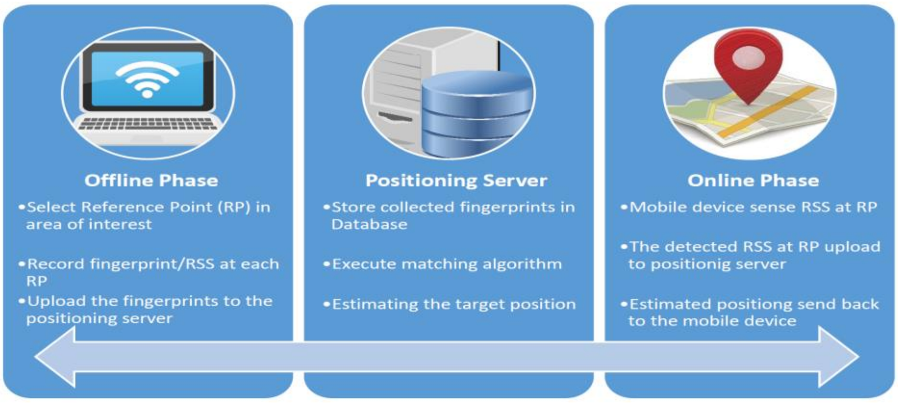

Figure 1: Wi-Fi Fingerprinting creation and operation.

1.1. Research Problem

Fingerprint positioning based on Wi-Fi, compared with other positioning systems, has the advantages of low-cost and high accuracy as described above. However, up-to-date Wi-Fi fingerprint-positioning technology needs high computation algorithms to estimate positioning, thus having a relatively long time consumption and high algorithmic complexity. Moreover, this method requires initial predefined position data along with efficient database management. In addition, to maintain the fingerprinting database each time the environment has changed, i.e. change of furniture or APs, etc. this requires fingerprinting update by manual calibration. Although many previous approaches attempted to make fingerprinting, an efficient way to meet IPS requirements with low cost and less complexity, to date there is no system has reached this goal. Most existing systems did not assume the quality of their system design and its integration with the used infrastructure, which is crucial for IPS performance. In our study, we assume that looking at the system as a whole in an explorative study aiming to prove the design of IPS Wi-Fi RSSI-based system could improve if design factors of IPS architecture along with positioning framework are considered. As these factors of IPS design have an impact on Wi-Fi RSSI-based positioning performance.

1.2. Research Motivation

Our research motivation is to find out the efficient design that makes IPS based on Wi-Fi fingerprinting more simple and scalable to enhance indoor positioning performance. Knowing that Cyber-Physical Systems (CPS) are evolving and gradually building an ecosystem of smart homes, smart cities and automated systems, IPS plays an essential part in providing location-based services to many demanded applications such as Robots, UAVs, Shopping Mall, Health Care and more. As a result, we will set system design parameters that can apply to Wi-Fi infrastructure in indoor settings trying to address the following:

- Improve positioning accuracy and reduce the complexity of Algorithm calculations.
- Improve system scalability and reduce database-fingerprinting complexity.

1.3. *Research Contribution*

In this study, we are aiming to identify system design considerations based on Wi-Fi fingerprinting for indoor positioning systems that can be simple and perform well compared to state-of-the-art systems, with acceptable positioning services. We expect this work to make three contributions as follows:

1. To simplify the Wi-Fi fingerprinting technique for indoor positioning.
2. To identify Key Performance Indicators (KPI) for efficient design of IPS.
3. To propose an optimal IPS Wi-Fi system with acceptable accuracy and scalability.

2. Research Proposed Plan

Choosing Wi-Fi as a main indoor positioning technology, defined our environment and applications. The environment is any place that has existing WLAN, which is the indoor buildings that are provided with local hotspots such as offices, markets, etc. The application is to locate people who are using their mobile devices, providing that their smartphones or laptops are equipped with Wi-Fi chips. Our experiment will be a software-based simulation using MATLAB to simulate IPS using a publicly available dataset called UJIIndoorLoc, available from the online repository IndoorLoc. To test and evaluate our proposed system, focusing on getting better performance and scalable system compared to the state-of-the-art IPS systems.

3. Research Progress

In our experiments, we started working on basic algorithms such as K-Nearest Neighbors (KNN), Weighted K-Nearest Neighbors (KNN) and Support Vector Machine (SVM). These algorithms are used for position estimation in the calculation between real location and estimated location. Although we focused more on KNN because of its simplicity compared to other algorithms, which fit very well in simplifying our positioning estimation system design. Hence, the KNN and its variants such as WKNN are more applicable for general use in IPS. Our experiments investigated the first part: improving the positioning accuracy of Wi-Fi RSSI-based systems. This includes looking at Positioning Algorithm KNN including K-value, distance function, distance weight, and RSSI data representation.

3.1. Achieved Results

MATLAB experiments conducted using the UJIIndoorLoc database with a KNN algorithm were deployed. The UJIIndoorLoc has a training dataset and validation dataset. In these experiments, we considered one k-value for both Longitude and Latitude, when calculating the mean positioning error. This experiment concludes that the correlation distance function is among the best algorithms in the UJIIndoorLoc dataset, especially when it combines with exponential data representation. In addition, introducing the distance weight i.e. WKNN has provided the lowest positioning error to the whole dataset at 7.39 (m) compared to KNN. However, the success rate does not improve and remains the same in both KNN and WKNN. In terms of distance weight, the inverse is the best for the whole dataset and it varies on the individual building between inverse and squared inverse. In WKNN, the best tuning is Correlation distance in conjunction with exponential data representation, inverse weight, and k=26.

3.2. Next Work

A large database will be created during fingerprinting process over time. Managing the positioning values and calculating the estimated position are challenges. These challenges can be addressed through an efficient design using the lowest cost and available hardware. In this second part, we will work on designing elements for Cloud-based IPS. Cloud infrastructure provides lower cost and efficient deployment. The design considers the deployment efficiency of fingerprinting database and Cloud management, and accordingly set the system requirements for optimal performance.

4. Related Work

With the proliferation of Wi-Fi hotspots, many Wi-Fi positioning systems have been proposed, according to surveys [3, 5-9] reported early systems that use Wi-Fi based fingerprinting, some of these well-known systems such as RADAR, Horus, in 2000 and 2005 respectively. However, the design element, in general, for IPS has been overlooked in the literature and there is a lack of studies that look at design considerations of scalable IPS. Few research studies dealt with the design of IPS as a tool to optimize location services. An early study by Kaemarungsi in 2005 [10] presented the results of a systematic study to improve the design of indoor positioning systems based on location fingerprinting techniques. Further Kaemarungsi suggests using proposed a modelling framework, which can be used as a tool to efficiently design such systems; this study quantifies accuracy and precision improvement resulting from adjusting system parameters. In 2010 You et al. [11] states that there is a lack of good analytical models that can be used as a framework for designing and deploying positioning systems.

Therefore, in their study, they proposed an innovative approach where WLAN planning and positioning error reduction are modelled as an optimized solution. This is to solve indoor positioning problems during the WLAN planning process for IPS infrastructure. Their design optimization has demonstrated efficiency in simulation for indoor positioning problem optimization. However, this study does not look at algorithmic aspects of positioning determination, which has a great impact on both accuracy and scalability. Nevertheless, their study has pointed out the significance of considering the WLAN as means of communication and positioning service from the early stages of deployment. In 2014 Aomumpai et al. [12] looked at how the reference nodes (RNs) are installed, as these nodes will determine system performance. In their study, they proposed an optimization technique that can be used to optimize the placements of reference nodes and improve the location determination performance. The results show that using the optimal placement of the reference nodes in the indoor positioning systems can significantly improve accuracy and precision. Further study by Jin et al. 2018 [13] aimed to design and implement a scalable and easily deployable indoor localization system based on Wi-Fi fingerprinting techniques and utilised the particle filter. In [13] a map of the location is created by leveraging a particle filter and then an automatic updating of the Wi-Fi fingerprints to estimate the user's location. Further, the collected fingerprints are refined through the system iteratively to enhance the performance during the online localization phase, which is able to further improve the positioning accuracy. The experimental results in this study demonstrate the scalability and effectiveness of the proposed solution.

However, in a highly dynamic and large-scale indoor environment, it is challenging to acquire accuracy and system reliability for positioning services in a cost-effective way. Therefore, several studies have focused on fingerprinting without an offline method with a combination of adaptive techniques and scalable enhancement for indoor positioning. Again Jin et al recently 2020 [14] worked on designing and implementing an adaptive and scalable indoor tracking system. This study proposes a zero site-survey overhead algorithm to enhance the system scalability, by constructing the fingerprint database without an extra site-survey overhead by a designing mechanism to update fingerprints continuously. The experiment results conclusively demonstrate the system scalability and effectiveness of the proposed algorithms. However, in their study, they have covered many aspects of the system including the framework, algorithm enhancement and auto-fingerprinting constructing techniques. In addition, they studied the impact of user device placement, but the system architecture and APs deployment are not investigated. Moreover, in their report, no accuracy figures were reported apart from claiming to get better results and system improvement. Because of this, our study approach to building IPS design is considering all involved elements that contribute to making the system work efficiently and effectively.

Another recent study in 2020 by Zhao et al. [15] proposed a positioning system which utilises crowdsourced Wi-Fi RSSI data. In this method, a geometrical algorithm was developed to convert the RSSI data into pairwise distances. Then fingerprints are constructed based on these pairwise distances, to compute the fingerprint's positions a multidimensional scaling (MDS) is then applied. This study proposes techniques for handling a large RSSI data set in a shorter runtime and an effective calibration-based method for crowdsourcing RSSI from IoT device deployments. The RSSI data will potentially be larger than Wi-Fi APs data alone. Therefore, it is challenging to construct the associated radio map for a scalable Indoor Positioning System on a large scale and keep the accuracy steady in the long-term deployment.

In recent years, researchers have been working to improve IPS accuracy using machine-learning techniques. Despite the excellent results of implementing AI algorithms on the signal processing side of the IPS, there is still plenty of room for improvement in the system design using AI, i.e., finding straightforward AI algorithms that do not require high computation which results in long-time processing. Islam et al. in [16] have designed an intelligent positioning approach based on AI algorithms in an indoor environment for precise positioning and decision-making through adaptation and learning. The simulation result confirmed that the AI algorithm estimated the position accurately up to 99% accuracy.

The Wi-Fi fingerprinting-based system has been extensively researched. However, fewer of the existing studies, to the best of our knowledge, investigate the design element of a scalable IPS. Most of the previous research mainly focused on improving positioning accuracy by adopting various approaches. However, a good design of Wi-Fi fingerprinting with suitable algorithms can lead to performance and scalability enhancement. In addition, the IPSs in previous works were most likely tested in certain environments, scenarios and/or devices; therefore, there are no unified metrics outcomes that can be used as a reference system for comparison. However, Table 1 shows a comparison of the existing systems in the literature. From Table (1), previous research on the IPS focuses on obtaining as an accurate indoor position as possible by developing/purposing methods and techniques for location technology based on a single technology. This type of research looked at modifying the network access points and/or mobile nodes based on the device-level approach. Therefore, signal processing measurements and hardware modification were required to obtain such solutions.

Table 1

Comparison of the existing systems in the literature for Wi-Fi-based IPS.

System	Technique	Accuracy	Scalability	Complexity	Cost
RADAR [17]	RSSI	>2m	High	Low	Low
Horus [18]	RSSI	Avg. Error 0.6m	High	Low	Low
SpotFi [19]	AoA	<1m	High	High	High
Ashami et al.[20]	RSSI	Avg. error 1.2m up to 98%	High	High	Low
Chen et al.[21]	T/CFR	<1m	High	High	High
DeepNar [22]	RSSI/trilateration	<1m and avg. error <0.75m	Low	High	High
Jin et al. [13]	RSSI	80% in 1.9m	High	Low	Low

However, the IPS will be built in a wireless ecosystem environment, optimization of APs placement and AP-centered architecture along with a collaborative positioning scheme between APs are factors in IPS design that have the impact of Wi-Fi RSSI-based positioning performance on top of the positioning framework. Thus, the design considerations of IPS based on Wi-Fi fingerprinting, as a holistic system is our research direction, aiming to propose an IPS system that can meet all the objectives shown in Table 1. In this view, it is challenging to have a practical and simple Wi-Fi-based system perform efficiently. Therefore, system design must explore multi-objectives optimization of the system and exploit various available techniques to build an efficient IPS

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