A REVIEW OF TECHNIQUES FOR POSITIONING IN WLAN WITH LIMITED DATA

Vitaly Romanov and Giancarlo Succi

Innopolis University, Innopolis, Republic of Tatarstan, Russia

ABSTRACT

Traditionally, positioning in WLAN was associated with some issues. The presence of the multipath forced researchers to resort to fingerprinting based positioning techniques that inherently require extensive site surveying and the abundance of reference signals. However, if we consider WiFi data for the task of crowd analysis, the data should be collected on the side of the network provider and, in this case, it is usually scarce. Thus, methods that require fewer reference signals for positioning are needed. This paper provides the comparison of WLAN based positioning methods that can operate with a single AP.

KEYWORDS

Localization, Wireless, WiFi, Mobility Tracking, Mobile Users.

1. INTRODUCTION

One of the applications of positioning systems is crowd mobility analysis that can be used to detect common patterns in crowd movement, irregular commotions in the area, etc. This task largely relies on the ability to estimate the locations of people in the crowd. Several technologies are currently available to provide reliable location information. The most widely known - Global Positioning System (GPS) - is successful in doing this outdoors. However, it is reported that positioning precision suffers a lot in city landscapes, and requires additional reference signals or calibration [1]. A local area positioning system can provide one of the solutions for this problem.

One of the requirements of a successful and efficient positioning system is the ease of creating the infrastructure. The popularity of GPS is caused by its availability worldwide, and this trait is hard to achieve for other positioning systems by design. Ideally, a local positioning system would be very cheap to set up and sustain. For this reason, there are attempts to adopt cellular or wireless local area networks (WLAN) as the basis for a positioning system that would enable localization indoors or in dense urban environments [13]. Cellular data is ideal for the task of crowd mobility tracking (in term of coverage), but it provides very rough granularity. WLAN data does not suffer from this issue.

Dhinaharan Nagamalai et al. (Eds) : ITCSE, WiMo, ICAIT, ICDIPV, CRYPIS - 2018
pp. 23–33, 2018. © CS & IT-CSCP 2018 DOI : 10.5121/csit.2018.80703

The major problem for crowd analysis task is that the data should be collected on the side of the network provider and, in this case, it is usually scarce. The most popular method for positioning with fingerprints requires several reference signal to achieve reasonable precision. Such abundance of information is often unavailable on the network service provider side. Thus, methods that require fewer reference signals for positioning are needed.

Many of classical positioning approaches that use cellular networks or WLAN are based on triangulation and trilateration techniques, which are not applicable when less than three measurements from different base stations are provided. Another class of methods, based on the distribution of received signal strength (RSS), made its appearance in the last decades due to the availability of vast computational resources. Although more computationally intensive, these new methods allow achieving reasonable positioning accuracy in environments subject to multipath propagation.

RSS based techniques proliferated in the area of WLAN-based positioning where the measure of received signal strength is provided by Received Signal Strength Indicator (RSSI). WiFi networks are most common for indoor spaces, which simplifies the application of RSSI positioning techniques that are usually referred to as fingerprinting methods. Indeed, the indoor area is constrained by the borders of the premises, and the rest of the surrounding environment lies outside the consideration. When applied to a larger scale positioning, namely for cellular networks, the computational diffculty of signal strength based methods explodes due to an inherently large size of fingerprint database, and the need for site surveying.

Indoor WLAN-based positioning with RSSI is usually performed with measurements from multiple access points (APs). However, there are situations when the area is covered only by a single AP, or information from only a single AP can be utilized appropriately (i.e., the case of network-side data collection). In these scenarios, techniques like triangulation and trilateration are hardly applicable. The contribution of this paper is in providing the comparison of WLAN based positioning methods that requires can operate with a single active AP.

The rest of the paper is organized as follows. In section 2 we overview related work. In section 3 we formulate the problem of positioning in WiFi networks and discuss signals used for positioning and limitations that emerge when positioning with a single AP. In section 5 we classify existing techniques for positioning with one AP. Section 6 concludes the paper.

2. RELATED WORK

Positioning in WLAN is related to other forms of wireless positioning, more precisely, positioning with radio signals. Liu et al. (2007) provided a general review of methods for localization in wireless networks and performed their comparison concerning accuracy, precision, complexity, scalability, robustness, and cost [8].

Farid et al. (2013) considered only indoor positioning techniques [3]. They included recent work and performed the comparison of positioning methods using other criteria, such as coverage provided by the system, power consumption, and susceptibility to multipath.

Quoc Duy Vo and Pradipta De (2016) compared existing wireless positioning techniques for outdoors concerning accuracy and power consumption [13].

Until recently, there were two types of information that a client or an AP could measure during communicating in WLAN. The first is the RSSI and the second is temporal delay. With the introduction of MIMO (Multiple Input Multiple Output) in IEEE 802.11 standard, it became much simpler to obtain the information about the direction of the incoming signal.

The initial attempt to create indoor positioning system with WiFi could be classified as time-based or signal strength-based. Although time-based methods often do not allow to use off-the-shelf hardware, Makki et al. (2015) explored the opportunity of positioning using time measurements in WiFi and discussed existing ways to overcome the issues with resolution and the prospective opportunities of time-based positioning in WLAN [9].

Suining He and Gary Chan (2016) considered only fingerprinting methods for localization [4]. They noted the use of spatiotemporal patterns, collaborative localization, and motion assistance in recent papers. Additionally, they reviewed different techniques for reducing the site survey, calibrating the system for heterogeneous devices, and performed the comparison of many methods using various criteria.

Although RSSI-based methods deal with the problem of multipath, they require the knowledge of space configuration and the presence of signal strength map, which takes a lot of time and resources to collect. Mahtab Hossain and Wee-Seng Soh (2015) decided to look into calibration-free indoor positioning methods, which do not require extensive map collection or even the precise knowledge of the floor plan [5]. For comparing these calibration free methods, they considered map requirements, the necessity of the initial location fix, the amount of user participation, and the need for additional sensors, such as inertial sensors.

The difference of our review is that we consider only positioning techniques that require only a single active AP to localize the client. Intuitively, if a method achieves reasonable localization error with a single AP, it's results are likely to improve when scaled to several APs. Papers covered in this review were not considered in previous surveys. Our contribution is in aggregating the information about this subtype of positioning methods and providing their comparison.

3. PROBLEM FORMULATION

3.1 Positioning Procedure

The goal of positioning is to identify the location of a user relative to a set of base stations (BS). In the case of WLAN-based positioning, the user is a network client, and APs serve as BS. Conventionally, two types of positioning approaches are distinguished: deterministic and probabilistic [4]. Deterministic algorithms use some similarity or distance metric to compare observed signals with a prerecorded database. In this case, the positioning procedure becomes an optimization problem

$$\hat{l} = \mathrm{argmin}_l SIM\left(\mathrm{s}, \mathrm{s}_l\right)^b$$

where *SIM* is a similarity function, and b = 1 when *SIM* (s,s') increases as s' → s and b = -1 if otherwise. Here, *l* denotes the location, and s_l - the signal associated with the location.

On the other hand, the probabilistic approach employs maximum likelihood (ML) technique where a probability distribution ties together the signal space and locations on the map and the goal is to maximize the conditional probability

$$\hat{l} = \mathrm{argmax}_l \mathbf{P}(l|\mathrm{s})$$

These two approaches constitute the basis for building positioning algorithms and the papers considered further use either of them.

Besides choosing the location estimation method, it is essential to select an appropriate set of signals. In the next section, we will discuss the types of measurements that are used for positioning in WLAN.

3.2 Signals for positioning in WLAN

Measures that are used for positioning in WLAN include RSSI, time or phase, the angle of arrival (AoA), and channel state information (CSI). In this paper, we refer to those as location signals, and their properties are described below.

RSSI measurements are prone to high variance especially in indoor environments [2]. Although RSSI was initially adopted for positioning due to its indifference to multipath, latest work shows that it suffers from non-stationary variance [6]. Nevertheless, positioning with RSSI in WLAN is the most common technique to date.

Positioning in WLAN can be done using time or phase measurements. The simple idea is that these measurements can be converted into the distance that is further used to localize a user. Although less sensitive to noise, time intervals are harder to measure using off-the-shelf WLAN adapters due to internal clock resolution and the radio bandwidth of the received signal [9]. It was estimated that with the standard bandwidth of 40 MHz the inaccuracy of time measurements results in localization errors around 7 meters [11]. This number can be improved by applying special techniques.

CSI describes the state of the communication channel and provides rough information about channel impulse response. CSI is represented by phase and amplitude of the received signal in the frequency domain. The IFFT of CSI gives the notion of delays of different multipath components. Recent work treats it as a promising localization signal [2]. Currently, CSI is not available by default, and the driver for a wireless adapter should be modified to obtain the access to these measurements.

Methods for positioning described in this review use at least one of the signals above to infer user's location and some of them use their combination to improve the precision.

3.3 Positioning with a single active AP

In general, the level of confidence for estimated location is low when positioning with a limited number of APs. For an indoor environment, this problem can be addressed by considering the joint distribution of RSSI and the location on the map. The presence of obstacles on the way of WiFi signal propagation, like walls, create an irregular RSSI pattern across the area. Some patterns make it easier to infer the true location. The distribution of average RSSI across space is called coverage map. Techniques that utilize such coverage maps are usually called scene analysis techniques [8]. It is worth noting that the irregularity of a coverage map highly depends on the configuration of the environment, and in open spaces such maps do not provide significant benefits over other less memory intensive techniques such as statistical propagation models.

Another approach is related to the use of triangulation or trilateration. The position of a client can be identified when sets of distances and/or AoAs are known. With the introduction of MIMO in the current IEEE 802.11 standard, each compatible AP is equipped with multiple receiver inputs. This receiver antenna array can be used to infer the relative position of a user and the AP. For simplicity, we further refer to triangulation and trilateration techniques under a common term of triangulation.

We were able to discern three classes of positioning techniques with a single AP: (i) triangulation (ii) triangulation and dead-reckoning (DR) fusion (iii) scene analysis and dead-reckoning fusion.

The first class refers to techniques that rely on the one-time measurements, i.e. the location can be inferred from a single sample of all necessary parameters. The second one includes methods with similar positioning principles but relies on dead-reckoning for obtaining the final location estimate. The third - uses RSSI and coverage map together with dead-reckoning for localization.

4. COMPARISON CRITERIA

We choose to compare methods presented here using the following attributes. First, we distinguish the use of different positioning approaches, which define the set of used localization signals and processing techniques.

Often, the positioning system becomes harder to implement when there is a need for additional sensors. Therefore, we try to identify the extent to which a particular positioning procedure uses other measurements.

Some approaches must take advantage of low-level information from the physical layer of the communication protocol (PHY). This is often associated with particular modification and requires additional work during deployment.

The sampling rate (SR) is often crucial for positioning, especially when deadreckoning is used. High SR is associated with higher energy consumption and communication overhead.

The amount of user involvement in the positioning process differs for presented positioning methods. The necessity of additional computation on the side of the user requires both energy resources and specialized software, hindering seamless deployment of the positioning system.

One of the most critical factors for deployment is the necessity of extensive site survey. While it is nil for triangulation techniques, the presence of fingerprint database is the requirement for scene analysis methods.

Further, we are going to compare different techniques concerning these parameters. All information is taken from the reports produces by authors of corresponding methods, and we specify when we make our own notes and conclusions.

5. POSITIONING TECHNIQUES

5.1 Triangulation

The class of triangulation techniques includes methods that rely only on explicitly measured parameters and exclude the need for tracking. Thus, these techniques allow for positioning at any moment of time without the knowledge of previous locations. Also, they use only measurements for distance and angles.

CHRONOS The positioning system, named *Chronos*, designed by Vashisht et al. (2016), is based on commodity wireless adapters and allows localization with a decimeter level of precision [12]. It is claimed to be the first system that performs positioning with such accuracy without external sensors. The core idea of the method is to estimate distances between antennas of the AP and a client using absolute ToF.

Chronos uses commodity hardware Intel 5300 with a modified driver. The use of ToF is associated with a series of issues that were discussed in the section 3.2 but authors were able to find a way mitigate these limiting constraints.

Authors substantiate the claim that the phase of the zeroth sub-carrier in OFDM spectrum of WLAN transmission is equal to the true value of the phase, which allows eliminating additional phase shift due to packet detection delay. Thus,

ToF can be computed from the expression [12]:

$$\phi_{i,k} = -2\pi f_{i,k}\tau \mod 2\pi$$

where τ is the ToF, and $f_{i,k}$ is the frequency of the sub-carrier k in the frequency band i, and $\phi_{i,k}$ is measured by the receiver. Obviously, such an equation has an infinite number of solutions for τ.The unique solution can be found from a system of equations that uses frequencies for different channels. For this reason, the localization procedure involves channel sweep.

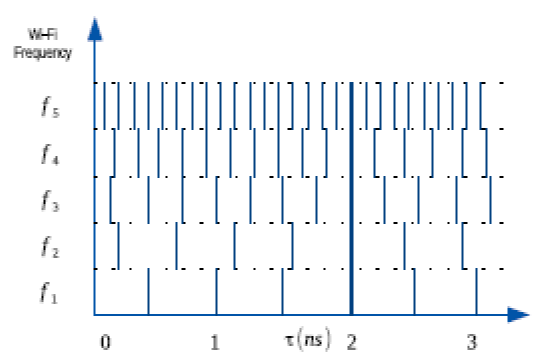

Fig. 1. Example demonstrates the process for solving the ToF based on measured phase. In each channel, there is a set of periodic solutions. The answer corresponds to the time when solutions for all the channels match [12].

The problem of multipath is dealt with using channel state information (CSI), which allows separating the component of the direct path from the rest. The final location of a user is found by solving a quadratic optimization problem. The goal of such optimization is to minimize the difference of distances between a user's assumed location and the AP, and distance estimations calculated from ToF measurements.

In the case of *Chronos*, the AP should have the modified driver installed. This driver provides access to physical layer information and enables the AP to drive frequency hopping procedure. The distance is estimated from the system of signal phase equations and does not require an onboard high-precision clock. In the case of LOS, 95% of ToF estimation error is contained within 1.96 ns, and the positioning error is under 2m in 90% of cases. One of the essential features of *Chronos* is its ability to produce confident location estimation after a single scan.

The success of Chronos arises the question of the impact of this positioning procedure on the network throughput. It was shown that single localization attempt that involves multiple channel sweeps reduces throughput of the network by approximately 5 MBits/s for the period of localization, which lasts about 84 ms.

Triangulation with passive sensors Another triangulation approach was proposed by Kraxberger et al. (2010) [7]. They developed a method that allows identifying the location without active collaboration from a user. In their scheme, there is a single active AP that communicates with the client, and several passive sensors. The job of sensors is to monitor the wireless channel and intercept packets transmitted by the client. The RSSI of intercepted packets carries the information about the distance to the client, which can be extracted using Two-Way-Ground propagation model. After distances between the client and three of the sensors are estimated, triangulation is applied.

This technique does not require any modification of hardware or protocol logic and can be used with any off-the-shelf wireless adapter and AP. However, this method relies only on the statistical propagation model, which can be highly imprecise in certain environments. Thus, the effect of multipath is modeled only approximately. The authors do not evaluate the average accuracy of their method, making it difficult to perform the comparison with different techniques.

5.2 Scene analysis and dead-reckoning fusion

Zaruba et al. (2007) presented a method for indoor localization with a single access point that uses both scene analysis and dead-reckoning [14]. By combining these two approaches, they were able to achieve average positioning accuracy of 2m.

Before the positioning procedure can be used, one needs to calculate signal coverage map. To achieve this goal, the accurate floor plan is obtained, and then parametric ray-tracing is performed. By simulating the propagation of radio waves, one can predict the observed RSSI at a given point on the floor plan. To simplify and enhance the ray-tracing process, the passing and reflection coefficients are treated as unknown parameters. Their values obtained by numerically solving the minimization problem where the average squared difference between observed and estimated RSSI measurements serve as the cost function.

Positioning with fingerprints generated in such a way produces a set of possible locations that is too large in general. However, the use of dead-reckoning together with analytical movement model allows filtering the most unlikely positions of users. In this method, no additional sensors on the device are used, and analytical movement model is employed. The consecutive samples of this model follow Markov assumption. User's positions are processed with particle and Bayesian filters to increase the positioning accuracy.

This positioning technique handles the problem of the multipath well and requires no tampering with the WLAN communication protocol. However, the deployment is mostly hindered by the necessity of detailed floor plan. Moreover, the ray tracing procedure is merely an approximation of the real radio wave propagation process and inherently contributes to the final positioning error.

5.3 Triangulation and dead-reckoning fusion

In this class, the difference from the triangulation techniques is that some parameters are not estimated after single sampling is performed. Instead, necessary information is accumulated through the extent of time before the estimation can be produced.

CUPID Sen et al. (2013) designed a method that relies on measurements from client's device and a single AP and does not require extensive site surveying [11]. Their method uses distance estimated from a propagation model, and AoA obtained through dead-reckoning. The median localization error of the proposed technique is 5m. They successfully utilize information about multipath components, provided by CSI, and knowledge of user mobility to implement a system that works on commodity wireless cards.

In the presence of multipath, the value of RSSI can deviate from the expected value, and statistical propagation models are usually unable to reasonably describe this deviation, especially when the direct path component is not the strongest in the delay profile. On the other hand, when multipath components are filtered, the propagation model can be of greater use. Thus, Sen et al. use the energy of direct path (EDP) in conjunction with propagation model to estimate the distance between AP and the client. EDP is easily obtained once CSI is available**.**

The AoA is estimated with the facilitation of dead-reckoning. The true AoA cannot always be determined even when an AP with MIMO capabilities is used. In some scenarios, the strongest energy is contributed by a multipath component, drawing conventional methods for determining the direction of arrival of the strongest signal useless. A pseudo-spectrum is usually constructed outlining the dependence of RSSI from the AoA, and the angle that yields the peak energy value is chosen. If local maxima are considered, the procedure will result in the set of possible angles that needs further refinement. The possible solution is to use movement tracking with accelerometer and estimate traveled distance. As a result, a triangle can be constructed with two sides measured with propagation model, and the third - estimated through dead-reckoning, as shown in Fig. 2. Thus, angles from the set of possible solutions can be tried. After identifying the AoA and the distance, user's position is estimated.

This method introduces a calibration-free approach to local area positioning. It is claimed that the positioning procedure was designed with energy efficiency in mind and probing the client's location with a high rate is not required. On the other hand, the accuracy of DR highly depends on the sampling rate of the device's internal sensors. The method assumes the presence of direct path in the CSI. Authors assert that measurements of EDP lower than 12 dB are unreliable and should be discarded. This approach can be extended to use several AP with a successful decrease of localization error.

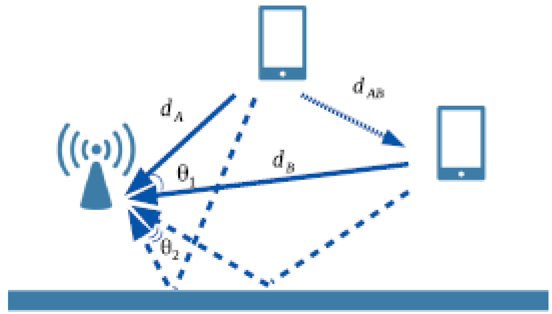

Fig. 2. Angle of direct path corresponds to the triangle with sides d_A, d_B and pAB. When signals from multipath components are tried, the angle does not fit this triangle [11].

SAIL The improvement of the previous approach was introduced by Mariakakis et al. (2014) [10]. The location is determined using distances measured through ToF and DR with the resulting median positioning error of 2.3m. They take advantage of CSI and user mobility to increase the performance of measurements, and device a heuristic for estimating absolute heading.

The ability of the AP to measure the delay between packet departure and ACK signal arrival lies in the foundation of this technique. The precision of time measurements limited by 40 MHz bandwidth is 25 ns. This precision can be enhanced by evaluating the relative time delay of signal arrival to different antennas. Additionally, the incorporation of human mobility and channel coherence property allows for the further decrease of positioning error.

Authors improved DR procedure by increasing the accuracy of the mobile device's inertial system. Driven by the goal to estimate the absolute heading, they develop a procedure to switch between readings from magnetometer and gyroscope depending on the current conditions. As a result, the average heading estimation error dropped from 27.4 to 5.9 degrees.

Eventually, the location was determined by constructing a triangle with two sides estimated using ToF, and the third - using DR. The number of possible triangle orientations was reduced by considering the absolute heading.

In this method, the accuracy of CSI measurements is increased by exploiting the channel coherency. Thus, the measurements are performed several times consecutively. This results in a small communication overhead.

6. CONCLUSION

We have reviewed methods for positioning in WLAN with a single AP. Conventionally, single AP provides only limited information that is not suitable for confident localization. Moreover, techniques for identifying both the distance and the direction to the user are constrained by the presence of multipath.

Table 1. Comparison of techniques for positioning with a single AP. FP - fingerprinting, SR -sampling rate, IMU - inertial measurement unit, PHY - physical layer.

Name	Pos. Method	Extra Sensors	PHY Info.	High SR	User Particip.	Comm. Overhead	Median Error
Chronos[12]	Trilat.	None	Yes	No	Modified driver required	Location fix in 84 ms	64 cm
Zaruba[14]	DR assisted FP	None	No	Yes	Measures RSSI	None	2 m
CUPID[11]	DR assisted trilat.	IMU	Yes	Not required, except for DR	Measures RSSI, performs DR	Low	5 m
SAIL[10]	DR assisted trilat.	IMU	Yes	Not required, except for DR	Measures RSSI, performs DR	0.20%	2.3 m
Kraxberger[7]	Tritat.	Packet sniffers	No	No	None	None	Unknown

The papers described here address the problem of multipath and propose methods that allow precise positioning in areas where it was not feasible before. We compared presented techniques according to the number of criteria that show the trade-off between the complexity of deployment and the complexity of positioning procedure.

Most of the introduced algorithms belong to the class of calibration-free techniques, which presents a significant advantage for deployment. All methods use commodity hardware, and some of them require the access to CSI provided by the driver.

The method presented by Zaruba et al. (2007) and Kraxberger can work with any hardware without limitations. Chronos, CUPID, and SAIL require WLAN standard 802.11n and above in conjunction with a modified driver. Although Chronos has the best positioning accuracy, it requires frequency hopping, that may pose more problems with additional drivers on the user-side and increase channel interference.

Overall, we see that positioning no longer requires the presence of multiple AP. This can enable new opportunities for WLAN based positioning systems and allows for improved accuracy in the case when more than one AP is present.

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