TDoA Positioning in Wi-Fi based Systems

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***Abstract*—In recent years, Wi-Fi-based positioning has become more attractive, as Wi-Fi-capable devices are readily available. Additionally, some positioning methods can be easily integrated using the currently available Wi-Fi devices. In this paper, we investigate a time difference of arrival (TDoA) approach for Wi-Fi positioning. The proposed approach works by receiving the Wi-Fi frames from Wi-Fi user equipment (UE) using a few, localization only, access points (AP), which are precisely synchronized. The TDoAs of the Wi-Fi frame at the different localization APs is used to estimate the position of the UE. Since the Wi-Fi can support bandwidths of up to 160 MHz, high precision positioning is expected. This paper presents the system architecture and signal processing approach for the proposed Wi-Fi positioning scenario.**

***Index Terms*—TDoA, positioning, Wi-Fi, Software Defined Radio.**

I. Introduction

The recent advancements in location-based services have increased the demand for more precise indoor positioning technologies. As the use of the global positioning system (GPS) is limited to outdoor environments, recent research focuses on alternative solutions for indoor positioning. One of the most attractive are Wi-Fi-based positioning solutions [1], due to high availability of Wi-Fi devices. Received signal strength indicator (RSSI) of the Wi-Fi access points (APs) or user equipment (UE) can be used to estimate the position of the UEs. However, high noise and multipath propagation adversely affects this approach, resulting in low precision [2]. The accuracy can be further improved by using Wi-Fi fingerprinting methods. Nevertheless, these methods are time-consuming and not robust in terms of environmental changes introduced later in a given scenario [3].

Unlike RSSI-based methods, Time of Arrival (ToA) or TDoA methods use the finite traveling velocity of radio waves and estimate the propagation time of the radio waves in order to obtain the distance or position. The traveling time of a frame transmitted from an UE and arriving at multiple APs would be different and proportional to the corresponding distances traveled. This can be used for position estimation of the UE if the time difference is known. This method is called time difference of arrival (TDoA), it is more robust and offers better precision proportional to the bandwidth of the transmitted signal.

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Over the years various indoor positioning systems have been investigated. Radio frequency Identification (RFID) technology uses active or passive tags attached to an object. When an object with an RFID tag approaches to a RFID reader it is recognizes and its location can be estimated [4], [5]. Due to their simplicity and cost effectiveness, RFID technology is widely used in indoor navigation systems [5], [6]. However RFID based positioning systems have a limited precision and require a dense deployment of RFID readers in order to be able to offer a satisfactory precision.

Bluetooth technology based positioning is another prominent indoor positioning solution with better accuracy compared to that of RFID based positioning. In these systems, user position is estimated with the help of Bluetooth beacon frames. By estimating the RSSI value of the received beacon frames, proximity (i.e. range) can be estimated. Use of different fingerprinting methods can additionally improve the positioning precision [5] [7]. Although Bluetooth technology based positioning systems are limited by short range, they provide high security and consume less power. Additionally, Bluetooth low energy (BLE) technology is optimized for power consumption and enables long operation on battery operated devices.

Infrared (IR) based positioning technology is also attractive, especially for industrial environments. In this systems, the user is equipped with an infrared tag and positions are estimated by a network of interconnected receivers for detecting the active tag. Due to the short range and disruption in presence of sunlight this technology is not widely spread [4].

Visible Light Communication (VLC) [8] technology is lately attracting a lot of attention since it offers a secure way for wireless data communication and, at the same time, it can offer positioning services. This positioning technology works by estimating the received light intensity from a luminary used for data communication. The main disadvantage of this approach is the limited precision, as in all RSSI based positioning systems.

Ultra wide band (UWB) technology is one of the most attractive radio frequency (RF) based indoor positioning technology and is based on time of flight (ToF) methods for position estimation. It offers many benefits over the other technologies such as centimeter level accuracy, little interference with other systems, low throughput data communication capability as well as low power consumption [5]. However, these systems require dedicated infrastructure which increases the costs [4].

Wi-Fi fingerprinting approach has become more attractive in the recent past. Using this method, the location of the user is estimated by characterization of the radio signal environment using a dataset obtained in extensive measurement campaign. The UE compares the RSSI values collected from different APs with this dataset. This approach is attractive because the necessary architecture, Wi-Fi APs and UEs, are already widely available. The main disadvantage, which extensively limits this approach, is the need for creating a large fingerprinting dataset. This is a painstaking process which needs to be repeated when the indoor environment changes.

Additionally, a few readily available proprietary solutions for indoor positioning, operating in the 2.4/5 GHz ISM bands [9] already exist [2]. These systems have limited accuracy due to small channel bandwidths available.

In this work, we propose a ToF based approach for Wi-Fi UE localization. The proposed approach uses TDoA to perform position estimates for Wi-Fi-enabled UEs. The proposed approach for localization is being intended for implementation on software defined radios (SDR) since the commercially available Wi-Fi APs are not offering the possibility of introducing changes in their hardware. Nevertheless, it is also possible to implement the proposed approach on hardware in future WiFi implementations.

This paper is organized into five sections. At first, the TDoA positioning approach is described. Further system architecture is presented. In Section IV the implementation details are given. Section V discusses the obtained results and the conclusion and future work are given in section VI.

II. TDoA positioning approach

The fundamental TDoA based positioning approach is shown in Figure 1. The system is consisted of multiple APs (AP1, AP2, ...) with a fixed and known position and a UE (or more UEs), which position should be estimated. The UEs are transmitting known RF signal (e.g. WiFi frame) which is received by the anchor nodes. The anchor nodes are synchronized and estimate the time of arrival of the RF signal.

In order to perform position estimation of the UE, the UE transmits an RF signal at time t_0. The transmitted signal would travel a distance of r_i to each of the APs, AP_i, where $i = 1, 2, 3, 4$. The time of arrival at each AP would therefore be:

$$t_{oai} = \frac{r_i}{c} + t_0 \quad (1)$$

where t_{oai} is the time of arrival at AP_i and c is the speed of light. The distances r_i can be calculated as

$$r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad (2)$$

By substituting Eq. (1) in (2) and multiplying by c the following system of equations would be obtained

$$\left\{ \rho_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} + b_i \right|_{i=1,2,\ldots} \quad (3)$$

where $\rho_i = t_{oai} * c$ are pseudo distances, x and y coordinates of the UE and x_i and y_i coordinates of the APs.

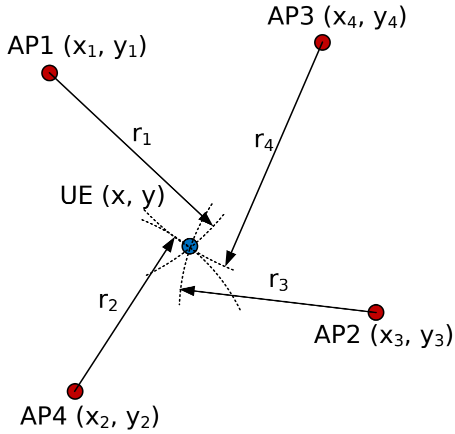

Fig. 1: TDoA based positioning approach

This system of equations can be solved since each of the equation in the system of equations describes a circle and these circles intersect in a single point, i.e. the UE position. In 2-dimensional case, intersection of a total of 3 circles around 3 APs would unambiguously intersect in a single point. Nevertheless, since the time of transmission t_0 is not known at the APs, the parametar b_i would also not be known and, therefore, one more equation would be needed in the system of equations. This means that there would be a total of 4 equations, i.e. 4 APs needed in 2-dimensional case. In 3-dimensional case, additional coordinate would be present, i.e. z, meaning that one more equation in the system of equations would be needed. This means that the system of equations would need a minimum of 5 equations, corresponding to 5 APs.

In a real scenario, the time of arrival of the RF signal would be estimated with an error included in the estimation. This means that the circles around each of the APs would not intersect into a single point. Therefore, the system of equations would not have a solution. The common approach in this case is to use a least squares (LS) method to obtain an approximate solution. Since the system of equations in this case is nonlinear, a non-linear least squares (NLLS) method should be used. A few different methods, like Gauss-Newton or Levenberg–Marquardt algorithm can be used for finding the NLLS solution of this system of equations.

III. System Architecture

The main components of the proposed localization system are at least four SDRs for 2-dimensional localization, performing the role of localization APs and a Wi-Fi capable UE as shown in Fig. 2. The APs are tightly synchronized. In the best case the the clock and the time of the APs should be synchronized, but, usually, having a good timing synchronization is essential. The affordable timing synchronization error depends on the required positioning precision. The higher the positioning precision required, the lower the synchronization error should be.

In order to perform UE localization, Wi-Fi frames are sent from the UE and are received by the different APs and

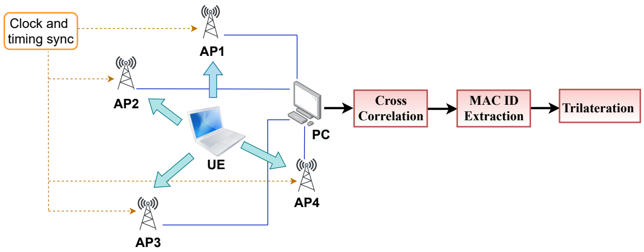

Fig. 2: System model for TDoA estimation.

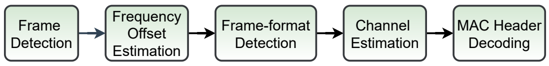

Fig. 3: Wi-Fi frame decoding and MAC ID extraction.

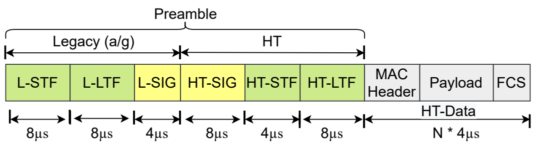

Fig. 4: IEEE 802.11n HT-Mixed frame format.

are saved for further processing. These WiFi frames are also timestamped using the SDR time, which is synchronized across all the APs. Later, the signals from the different localization APs, containing the received WiFi frame are cross-correlated to find the time differences between the frame received at different APs.

The received Wi-Fi frames are also partially decoded in order to find the MAC ID of the UE, to uniquely identify the UEs. This process is complex and involves several processing steps.

A. MAC ID extraction from Wi-Fi frames

The MAC ID extraction process is performed using the following steps: packet detection, automatic gain control, frequency-offset correction, detection of modulation scheme, and channel estimation, as shown in Fig. 2. These pieces of information are extracted from IEEE 802.11 n/ac standard frame preamble, in this case. The format of 802.11n high throughput (HT) standard mixed-mode frames is shown in Fig. 4. The 802.11n standard is enhanced in high throughput (HT) mode to support data rates up to 600 Mbps and operate at radio frequency (RF) bands of 2.4 and 5 GHz [10], [11]. Once the channel is estimated, the MAC address from the decoded header of the frame is obtained.

B. TDoA estimation

In the process of MAC address extraction, a coarse estimation of the start of the Wi-Fi frame is estimated. This coarse estimate is not sufficient for precise position estimation and, therefore, additional processing must be performed to obtain precise TDoA.

At first, the frames arrived at different APs are extracted and further correlated. The correlation between the frames would produce a signal as the one shown in Fig. 6. The peak, marked with red line in Fig. 6, is the cross-correlation peak, and its position actually corresponds to the TDoA of the same Wi-Fi frame in two different APs. The cross-correlation is performed between the frames received at the different APs.

The TDoA estimation is performed by finding the largest sample in the obtained cross-correlation function. Nevertheless, since the signals are sampled with a finite sampling rate, only a discrete values for the TDoA can be obtained. This would introduce a time quantization error in the TDoA estimate, which would further be translated into a positioning error. In order to mitigate this problem, a common approach is to utilize an interpolation in the cross-correlation function for obtaining a sub-sample TDoA estimate. A few different approaches can be used in order to perform interpolation. In this case, a quadratic interpolation around the correlation peak is chosen, since it is quite simple and compared to other interpolation methods, it offers a similar performance.

IV. Implementation

For the initial experiments, Ettus research USRP N321 SDR platforms were used as APs and a personal computer (PC) with built-in Wi-Fi support as UE. The ISM band of 2.4 GHz offers channels with a limited channel bandwidth of maximum 40 MHz. Hence, for this experiment, we used the 5 GHz ISM band. In the setup, as shown in Fig. 5, four APs and one mobile node as UE are considered. The synchronization of the APs was performed using two different approaches. In the first approach, an OctoClock device was used [13]. This device supplies 10 MHz clock to each of the SDRs for frequency synchronization and additional 1 pulse per second (PPS) signal for timing synchronization. The setup, including the OctoClock is shown in Fig. 5. The main disadvantage of this solution is that the both signals are supplied using coaxial cables which introduces additional jitter to these signals, leading to increased TDoA and positioning errors. The second approach which was also tested is to use WhiteRabbit [14] synchronization which is supported by the USRP N321 SDRs. The WhiteRabbit synchronization implements both SyncE [15] and the PTP [16] protocols and enables sub-nanosecond timing synchronization. Additionally, this synchronization solution requires only a single simplex monomode fiber which additionally simplifies its installation. The supported lengths of the used fibers are in the order of tens of kilometers.

In order to test the system, Wi-Fi frames are transmitted by the UE's Wi-Fi and are received by the SDR APs. The received frames are then processed using the method described in Section III. The acquisition of the samples is performed in a custom C/C++ application developed for this purpose. The acquired data is saved into files and further processed in MATLAB.

These are only the initial experiments, and the TDoA between two APs are only estimated. In a real positioning scenario, a minimum of four APs will be needed for a 2D positioning scenario. Additionally, calibration of the system

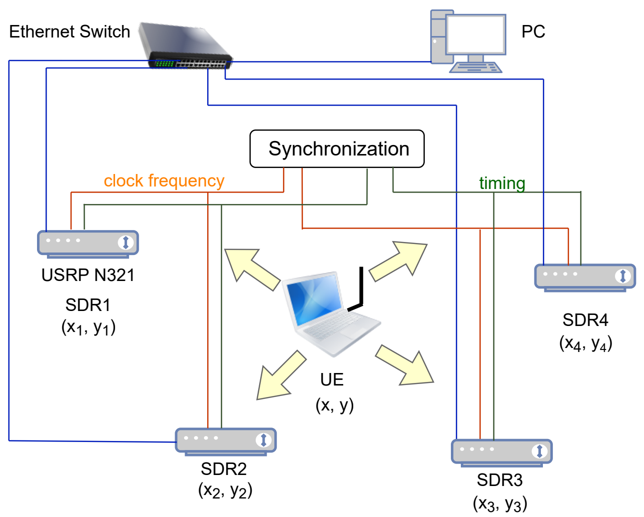

Fig. 5: Setup used for TDoA measurem ents.

should be performed before performing any localization experiments.

V. Results

In this paper a concept for Wi-Fi localization system was proposed. The proposed concept was partially implemented and initial tests were performed. The main functions that were implemented include synchronization of the APs, data acquisition using the SDRs, decoding of the received Wi-Fi frames and estimation of the TDoA before performing localization of the UEs. Our preliminary results show that we are able to estimate the TDoA using lags between the signals obtained using SDRs by performing cross-correlation.

VI. Conclusion and Future Works

In this work, we describe a method for Wi-Fi UE positioning. The proposed approach uses the existing Wi-Fi data frames, transmitted by the UEs for data exchange with the Wi-Fi APs. No additional frames are needed which means no additional use of the wireless medium for localization purposes. This enables the use of the system with a large number of UEs, since it does not introduce additional overhead in the wireless medium.

In order to test the proposed concept, it was implemented using SDRs. The used SDRs support the largest channel bandwidths that Wi-Fi supports, i.e. 160 MHz. This would enable high positioning precision.

The proposed approach can be easily implemented in the future Wi-Fi systems with minimal effort.

The future work would be focused on position estimation of UE by using the estimated TDoAs and trilateration.

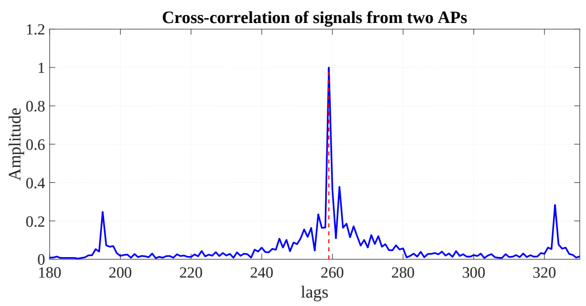

Fig. 6: Cross-correlation output indicating lag between signals.

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