Performance Evaluation of a Time-of-Arrival Based Indoor Localization System

Vladica Sark, Nebojsa Maletic, Jesús Gutiérrez and Eckhard Grass

Abstract – The appearance of global navigation satellite systems (GNSS) has boosted the development of many location based services and applications. Additionally, abundancy of WiFi access points has brought these services and applications indoors, where GNSSs are not available. In indoor environments, WiFi is mainly used for coarse localization, since no other, widely available, solution exists. In order to increase the localization precision in indoor environments, many time-of-flight (ToF) solutions are emerging. These solutions are mainly working in the 2.4/5 GHz or 60 GHz industrial-scientific-medical (ISM) band or they use impulse-radio (IR) ultra-wideband (UWB) technology. In this paper, we evaluate the performance of a time-of-arrival (ToA) based localization, which is using ToF. The performance of the ToA localization is evaluated for systems working in the 2.4/5 GHz ISM band. The channel bandwidths, which are evaluated, are typical for these bands. The performed simulations show that localization precision better than 1 meter can be achieved. Only line-of-sight (LOS) scenarios were considered.

Keywords – time-of-flight, time-of-arrival, localization, ISM, line-of-sight, location based services

I. Introduction

The appearance of global navigation satellite systems (GNSS) has opened huge possibilities for many location based applications and services. Initially, the GNSSs, or more specifically global positioning system (GPS), was reserved mainly for the military applications as well as marine navigation of civil vessels, mainly due to the absence of other high precision systems and the high price of the GPS equipment. With the newest advances in technology, GPS (also other GNSSs) receivers have become more affordable, smaller and power efficient. This has opened new possibilities for integrating them in car navigations units and, nowadays, in every smartphone. The GPS (and also other GNSSs) has an impressive advantage due to its global availability, previously not offered by other localization systems. Nevertheless, this global availability has a few disadvantages, which hardly would be resolved in the future. These disadvantages originate from the limited transmit power of the GPS transmitters as well as the huge distance between the transmitter, being a low Earth orbit satellite, and the receiver. The received power in an outdoor environment is about -130 dBm [1], which introduces a huge challenge for the GPS receivers. Additionally, this power goes down by additional 10-30 dB indoors [2] making it impossible for decoding even by the most sensitive GPS receivers. The latest advancements in GPS receiver design have shown that sensitivities down to -160 dBm can be achieved [2], making them usable in some indoor environments. Unfortunately, this is very limited and not possible in multi-story buildings, made of concrete and steel, where the additional attenuation is even higher than 30 dB. Therefore, many islands with no GPS coverage exist and severely limit many location-based services and applications. Additionally, in urban canyons (streets surrounded by tall buildings) only a limited visibility of GPS satellites is feasible. This strongly limits the positioning precision of the GPS system reducing its usability.

In order to solve the main coverage problem of the GPS (and GNSS) systems, many indoor localization systems start to appear [3]. Many of them develop proprietary hardware, while most of the solutions try to use the already available infrastructure, i.e. available WiFi access points, in order to benefit from cheap and easy deployment.

One of the first commercially available indoor and outdoor localization system is LOCATA [4]. This system is mainly used for outdoor applications, where the GNSS performance is poor or not available at all. It can be also used indoors for indoor navigation in factories etc.

One of the mostly used approach nowadays is localization using WiFi. Many different WiFi localization solutions are already available. Some of the approaches use a database with positions of the available WiFi access points. These methods can perform coarse localization, with precision not better than a few meters, but the main advantage is that they are straightforward to implement and available in almost all urban environments where WiFi is deployed. There are already a few databases with WiFi access points and their corresponding locations available [5].

In order to improve the precision of the WiFi localization, an approach called WiFi fingerprinting is extensively being investigated [6]. With this approach, a map of received signal strength (RSS) from different WiFi access points is constructed. This mapping is a painstaking process because many measurements must be performed. The maps are stored in a database. When a user demands to obtain its position with, for example, his smartphone, the RSS value for each visible WiFi access point is measured.

Vladica Sark, Nebojsa Maletic and Jesús Gutiérrez are with the IHP – Leibniz-Institut für innovative Mikroelektronik, Frankfurt (Oder), Germany
Eckhard Grass is with the IHP – Leibniz-Institut für innovative Mikroelektronik, Frankfurt (Oder), Germany and Humboldt-University of Berlin, Berlin, Germany
E-mail: {sark, maletic, teran, grass}@ihp-microelectronics.com

The obtained RSS values are queried in the database and the position with the highest likelihood is found. This process can be quite complex and computationally intensive. Nevertheless, with this approach, already available hardware is used and no infrastructure deployment is necessary. Localization precision of less than 1 meter can be achieved [3]. Main disadvantages include creating the fingerprint database, which can be a long process, as well as the complexity of the position estimation algorithm, which in some cases must be performed on a high performance server computer, i.e. in the cloud.

Another group of localization systems uses proprietary hardware in order to perform localization. The simplest approach is the RSS based ranging which is used to estimate the distance between two wireless nodes. Knowing the distance between the anchor nodes, i.e. nodes with known positions, and the mobile node, i.e. with unknown position, one can perform trilateration and find its position. This is a very simple approach, since almost every radio receiver can estimate the RSS value. The main disadvantage is that due to the multipath propagation, the free space path loss formula is not valid anymore, since the path loss exponent is lower or larger than 2 [7]. It is hard to estimate this coefficient correctly since it depends on the environment. Despite the fact that this approach leads to extremely imprecise location estimates, it is still being attractive due to its simplicity. It can be used in very simple systems, like for example wireless sensor nodes, which usually have very limited hardware and radio resources available.

In order to achieve better precision and accuracy, usually methods based on ToF of the radio signal are used. These methods are used to estimate the propagation time of a RF signal between two wireless nodes. Having the propagation time and multiplying it with the speed of light, the distance between the nodes can be estimated. A few different approaches for measuring the ToF are possible. One of the simplest is to perform a so-called two way ranging (TWR) [8]. With this approach, the ToF, i.e. distance, between two wireless nodes is estimated and later used to estimate node's position, using trilateration. The main advantage is that no precise synchronization between the nodes is required. The main issue is the large number of wireless transmissions needed for location estimation in a wireless network where large number of nodes demand position estimation. In order to avoid large number of transmission, a so-called time of arrival (ToA) based approach is usually used. In this approach, multiple anchor nodes are synchronized and transmit timestamped frames. Nodes that require estimation of their position receive these frames and estimate its own position. The receiving nodes must not transmit any frames back to the anchor nodes in order to estimate their own position. The main complexity of this approach is in the synchronization of the anchor nodes. Nevertheless, it allows unlimited number of users to estimate their positions. However, in all of the ToF based localization methods, it is important for the RF signals to travel the line-of-sight (LOS) path. Otherwise, a positive bias would be added to the range, or position, estimate if the non-line-of-sight (NLOS) paths are used for distance estimation, since these are the reflected paths and are longer than the LOS paths.

In this paper, we evaluate the position estimation error of a ToA based indoor positioning system. We use a simulation approach, since finding a closed form expression for the error is significantly complex.

In addition, worth mentioning is that large number of non-RF based localization approaches are being investigated. Some of them used cameras, other use inertial navigation, some use ultrasound etc. They would not be addressed in this paper.

The rest of the paper is organized as following: in Section II we describe the method for position estimation in indoor environment, in Section III the simulation scenario is presented, Section IV gives the obtained results and Section V is concluding this paper.

II. ToA LOCALIZATION

A. Position estimation using ideal range measurements

In a ToA based localization, multiple synchronized anchor nodes are transmitting timestamped frames in a previously defined sequence. A scenario with four anchor nodes and a single mobile node is shown in Fig 1.

The anchor nodes are synchronized and share a common time base. The synchronization can be performed using wireless or wired IEEE 1588 [9] protocol or other synchronization method. It can be assumed that the nodes transmit sequentially starting at t_{TX1} for the anchor node 1, t_{TX2} for anchor node 2 and t_{TXi} for anchor node i. The transmitted frames are received at the wireless node with the unknown position (ST) at times t_{RX1}, t_{RX2} and t_{RXi} correspondingly. The distances from the anchor nodes to the mobile node can be calculated as

$$r_i = c \cdot (t_{RXi} - t_{TXi} + t_{OS}) \qquad (1)$$

where r_i is the distance between the anchor node and the mobile node, t_{TXi} and t_{RXi} are the transmission and reception times and t_{OS} is the offset of the real time clocks between the mobile node and the anchor nodes. It is worth mentioning that the anchor nodes and the mobile node have different time base, since they are not synchronized, and the time difference between them is exactly t_{OS}.

In this paper, without loss of generality, we are describing a 2-dimensional case, but the process is the same for a 3-dimensional case.

The distances between the anchor nodes and the mobile node can be calculated as

$$\begin{aligned} \sqrt{(x-x_i)^2+(y-y_i)^2} = r_i = \\ = c \cdot (t_{RXi} - t_{TXi} + +t_{OS}) \end{aligned} \qquad (2)$$

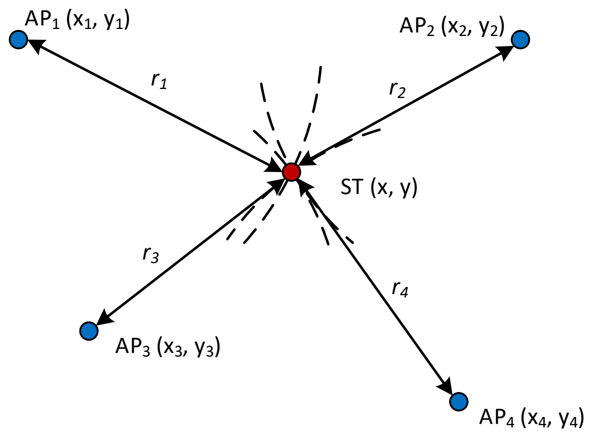

Fig. 1. Position estimation of a mobile node and four anchor nodes using trilateration

Eq. (2) is a quadratic equation valid for each anchor node. There are three unknowns in a 2-dimensional space. The unknowns are the position coordinates x and y and the time offset t_{OS}. In order to find the position coordinates and eventually the time offset, the system of equations consisted of Eq. (2) for each anchor node should be solved. Therefore, for a single solution of the system of equations, four equations are needed. Nevertheless, even when a fully determined system of equations is available, its solution can be challenging, if it is not linear, as in this case. In order to solve this system, the nonlinear equations can be linearized and the system can be solved [1].

B. Position estimation using noisy range measurements

The approach discussed is the ideal case. In real systems, additional noise would be present and the circles described by the radii r_1, r_2, r_3, and r_4 in Fig. 1, would not intersect in a single point. Therefore, we need to find a position that minimizes the sum of squared differences i.e.

$$(\hat{x}, \hat{y}) = \underset{(x,y)}{\operatorname{argmin}} \sum_{i=1}^{n} [r_i^2 - (x - x_i)^2 - (y - y_i)^2]^2 \quad (3)$$

where the $(\hat{x}, \hat{y})$ is the estimated position. This is a minimization problem, which can be solved using different approaches as Gauss-Newton or Levenberg–Marquardt algorithms [10]. With this approach, even more than the minimum necessary anchor points can be used in order to improve the precision of the noisy position estimate. Anyway, if less than four access points are available for two-dimensional case, additional constraints for the possible positions can be introduced in order to have a fully determined system. Otherwise, the algorithms would not be able to converge.

C. ToA estimation

As shown in Eq. (2), time of arrival of the transmitted frames, t_{RXi}, should be estimated for each frame arriving from the access points. The precise estimate of the ToA would lead to precise position estimate. Just as an example, if the receiver has a sample rate of 200 Msps, each 2 successive samples would be spaced 5 ns apart. If the ToA is estimated with a resolution of 5 ns, this would lead to a distance estimation resolution of 1.5 m, because the speed of light is c = 300 000 *km/s*. Therefore, additional measures must be taken in order to improve the ToA estimation resolution.

The ToA at the receiver can be estimated using a few different approaches. The simplest one is to detect the increase in the received power over a given threshold and to use this time as a ToA. This method is rather simple, but sensitive to noise in low SNR scenarios.

The second approach is to transmit a pseudo-noise (PN) sequence with a strong autocorrelation peak. When this sequence is received at the receiver, it is correlated with the same sequence, locally generated. This would generate a peak, which position corresponds to the ToA. Nevertheless, this would only solve the issue with the noise in low SNR scenarios, but would not improve the ToA estimation resolution. Therefore, additional interpolation over the cross-correlation peak is performed. A quadratic interpolation is usually sufficient.

In Fig. 2 a cross-correlation peak of a received PN sequence is shown. The time at the peak maximum represents the ToA. The red points are the samples of the peak. Additional interpolation can lead to a subsample resolution of the ToA estimation.

III. Simulation Scenario and Localization Precision Evaluation

In order to evaluate the localization precision, a two dimensional indoor scenario was assumed. The simulation scenario uses a square area of 10 × 10 meters, with four anchor nodes positioned in the corners of the area at positions (0, 0), (0, 10), (10, 0) and (10, 10) meters.

The mobile node was positioned at positions (x_i, y_i) where x_i = 1, 2, .. 9 and y_i = 1, 2, .. 9 meters. Dipole antennas with an antenna gain of 1.76 dB were assumed. It was assumed that the propagation loss is equal to the free space path loss (FSPL), since for some indoor environments the propagation loss can be lower or higher compared to the FSPL, due to constructive and/or destructive combining of the multipath propagation components. The noise figure (NF) of the low noise amplifier for the 2.4/5 GHz can go down to 1.2 dB, which is used in this simulation. A channel bandwidth of 20 MHz was used and a transmit power of 10 dBm. The maximal transmit power in these ISM bands is limited to 20 dBm.

For each position of the mobile node, a location estimation was performed multiple times and the location error was calculated.

As can be seen in Fig. 3, the red dots represent the true positions of the nodes and the blue dots represent the estimated positions. The black dots are the anchor nodes.

The estimated positions are concentrated around the true positions.

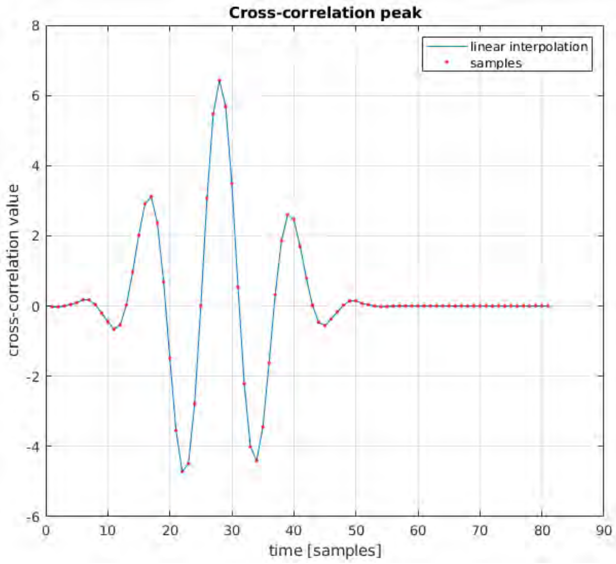

Fig. 2 – Cross-correlation peak of a received PN sequence

The positioning error empirical cumulative distribution function (CDF) was also calculated using the simulation data. It is shown in Fig. 4. As can be noticed, 90 percent of the positioning errors are under 1 meter. The root-mean-square (RMS) error for this use case was calculated to be 0.8 meters.

This error is comparable or even better to the systems reported in [3]. Nevertheless, these systems were tested in realistic scenarios where LOS and NLOS conditions are expected as well as strong multipath propagation. Having a narrow bandwidth, would cause significant issues when multipath propagation components should be resolved.

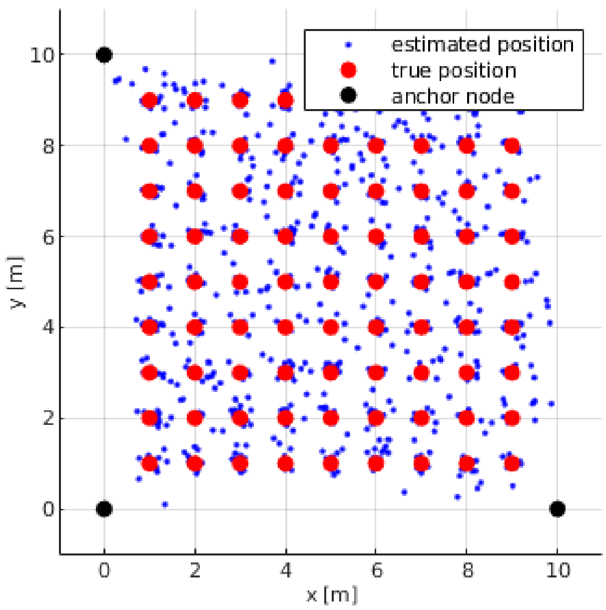

Fig. 3 – Estimated and true position of the mobile node

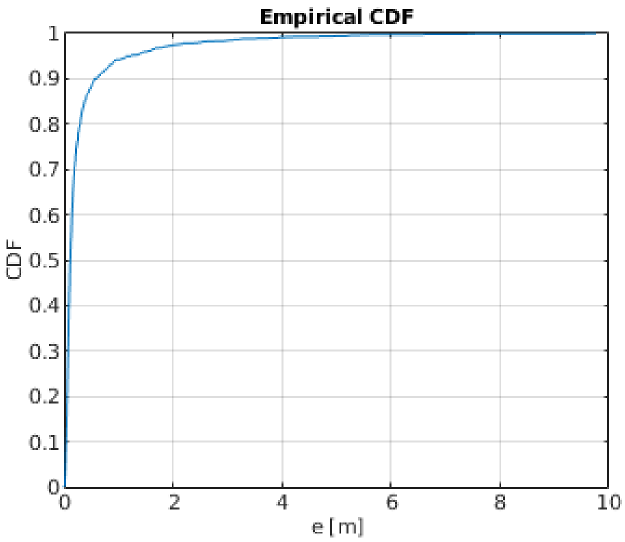

Fig. 4 – Empirical CDF of the positioning error

Therefore, the obtained results are expected to be slightly worse in realistic scenarios. In order to improve the precision longer PN sequences can be transmitted in order to obtain better coding gain and larger bandwidths can be used to improve the multipath resolution.

IV. Conclusion

In this paper, we evaluated the precision of a localization system which uses ToA approach. We use additive white Gaussian noise (AWGN) channel to evaluate the noise performance of this approach. The system was evaluated using simulation since obtaining a closed form solution is not straightforward due to the nonlinearity of the system of equations used. It was shown that with parameters typical for a WiFi, working in 2.4/5 GHz ISM band, positioning precision of better than 1 meter is possible.

Acknowledgement

This work has received funding from the European Union's Horizon 2020 research and innovation programme, WORTECS project, under grant agreement No 761329.

References

[1] Tsui, J. B.-Y., "Fundamentals of global positioning system receivers: a software approach", Vol. 173, *John Wiley & Sons*, 2005.

[2] Ozsoy, K., Bozkurt, A., Tekin, I., "Indoor positioning based on global positioning system signals", *Microwave and Optical Technology Letters*, May 2013.

[3] Lymberopoulos, D., Liu, J., et. al. "The microsoft indoor localization competition: Experiences and lessons learned", *IEEE Signal Processing Magazine,* Sep. 2017.

[4] Barnes, J., Rizos, C., Wang, J., Small, D., Voigt, G., Gambale, N., "Locata: the positioning technology of the

future", *InProceedings of the 6thInternational Symposium on Satellite Navigation Technology Including Mobile Positioning & Location Services*, Melbourne, Australia, July 2003.

[5] https://wigle.net/

[6] Basri, C., El Khadimi, A., "Survey on indoor localization system and recent advances of WIFI fingerprinting technique", *5th International Conference on Multimedia Computing and Systems (ICMCS)*, pp. 253-259, Sep., 2016

[7] Kaddouri, S., El Hajj, M., Zaharia, G., El Zein, G., "Indoor Path Loss Measurements and Modeling in an Open-Space Office at 2.4 GHz and 5.8 GHz in the Presence of People", *29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 1-7, Sep, 2018.

[8] Sark, V., Maletic, N., Ehrig, M., Gutiérrez, J., Grass, E., "Achieving Millimeter Precision Distance Estimation using Two-Way Ranging in the 60 GHz Band", *European Conference on Networks and Communications (EuCNC)*, pp. 310-314, Jun., 2019.

[9] Cooklev, T., Eidson, J.C., Pakdaman, A., "An implementation of IEEE 1588 over IEEE 802.11 b for synchronization of wireless local area network nodes", *IEEE Transactions on Instrumentation and Measurement*, Sep., 2007.

[10] Croeze, A., Pittman, L., Reynolds, W., "Nonlinear least-squares problems with the Gauss-Newton and Levenberg-Marquardt methods", *University of Mississippi*, Oxford, UK, Jun., 2012.