Performance of a time-of-arrival technique for positioning WLAN terminals

Fernán Izquierdo, Marc Ciurana, Francisco Barceló and Josep Paradells
Department of Telematic Engineering
Technical University of Catalonia (UPC)
Barcelona, Spain
{fernani, mciurana, barcelo, teljpa}@entel.upc.edu

Abstract— **Nowadays, several systems are available for outdoor location (i.e GPS, cellular networks based…). However, there is no proper location system for indoor scenarios. The technique presented in this paper proposes the use of the existing wireless LAN infrastructure with minor changes to provide an accurate estimation of the location of mobile devices in indoor environments. This technique is based on round-trip time (RTT) measurements, which are used to estimate TOA and distances between the device to be located and WLAN access points. To avoid the cumbersome modification of the physical layer, each RTT is estimated between the transmission of an IEEE 802.11 link layer data frame and the reception of the associated acknowledgement (ACK). By applying trilateration algorithms, an accurate estimation of the mobile position is calculated.**

Index Terms— **IEEE 802.11, link layer, positioning, ranging, round-trip time, time of arrival, triangulation, WLAN.**

I. INTRODUCTION: PREVIOUS RESEARCH AND GOALS

Currently available WLAN location approaches mainly correspond to radio-map based techniques [1], which ,despite of being able to provide good positioning accuracy, entail a complex offline training phase to construct the radio-map and present high variability to environmental (i.e. furniture) changes. In [2], a new approach is proposed to ranging in IEEE 802.11, without the requirement of initial synchronization between transmitters and receivers. Ranging is achieved by using a high precision timer in order to measure TDOA from two GRP (Geolocation Reference Point). The authors also propose to take advantage of the IEEE 802.11 data link frames for measuring TOA (time-of-arrival), but they do not give more insight to this matter. In [3], a system which can estimate TOA using IEEE 802.11 link layer frames is proposed, but the RTS (Request-to-Send)/CTS (Clear-to-Send) mechanism is required. Their ranging technique relies on internal delay calibration both at transmitter and receiver in order to correct the round-trip time (*RTT*). To mitigate multipath impact, the authors propose to use different carrier frequencies and to discriminate between strong and weak multipath (i.e. greater than three chips from the direct path) in order to apply different curve-fitting algorithms and obtain 1m or 3m accuracy. In [4], a method to estimate TOA between WLAN nodes without using extra hardware is presented, but the achieved accuracy (error of 8 meters) is not enough for some safety applications.

This paper presents a new indoor WLAN location technique based on distance measurements provided by TOA estimations—which are in turn based on *RTT* measurements at IEEE 802.11 link layer—between the mobile terminal (MT) to be located and WLAN access points (APs). An important feature of this system is its simplicity (e.g. in comparison with [3]), as only minor changes to the existing WLAN devices are required to provide accurate estimates (position error less than 2 m). The system is divided into the ranging and the positioning subsystem. The former estimates the distances between the MT and the APs, and the latter calculates the MT position using the distances and the APs' known positions. One challenge corresponds to achieving accurate estimations from *RTT* measurements performed using a standard IEEE 802.11b card clock at 44 MHz, which shall lead theoretically to errors of 7 m.

II. RANGING SYSTEM

A. *RTT estimation*

1) *Approach*

Round-trip time is the time a signal takes to travel from a transmitter to a receiver and back again, in our case from a MT to a fixed AP. We estimate the *RTT* by measuring the time elapsed between two consecutive frames under the IEEE 802.11 standard: a frame sent by the transmitter and an answer frame from the receiver. The link layer data frame and the link layer acknowledgement (ACK) frame of the IEEE 802.11 standard are used, but in fact other link layer frames would be also suitable [3]. Therefore, the *RTT* is measured from the last segment of the data frame sent to the first segment of the ACK frame received (see Figure 1).

The MT is a laptop with an IEEE 802.11b PCMCIA card. As the overall (i.e. propagation plus processing) *RTT* is expected to be in the order of microseconds, measuring it with software as in [4] leads to a significant lack of accuracy. Therefore, we propose to measure the *RTT* through a simple hardware module that starts counting cycles of the built-in 44 Mhz clock from the WLAN card when it detects the end of transmission of a data frame, and it stops when the corresponding ACK frame arrives**.** Then it sends its value (i.e. slotted in 44 MHz periods) to the laptop PC.

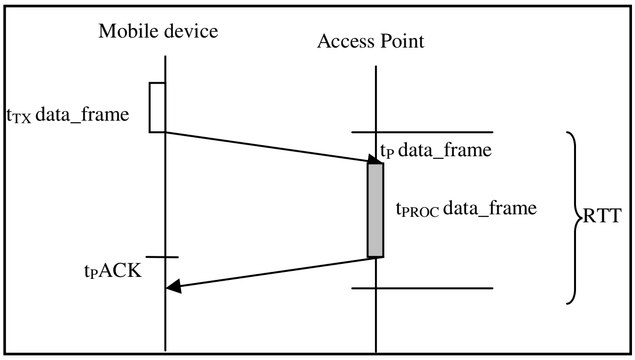

Figure 1. *RTT* measurement using IEEE 802.11 data/ACK frames

2) Mitigation of errors

It should be possible to estimate a distance by using only one *RTT* measurement. However, the *RTT* is time-variant due to constraints such as the variability of the radio channel multipath [5], the 44 MHz clock quantification errors [4], delays due to the electronics of the hardware module and the relative clock drift. If we only considered the quantification errors, a distance estimation error of 7 m should be present.. In order to mitigate these errors this paper proposes to perform several (*n*) *RTT* measurements and to use a proper *RTT* estimator based on the statistical set obtained.

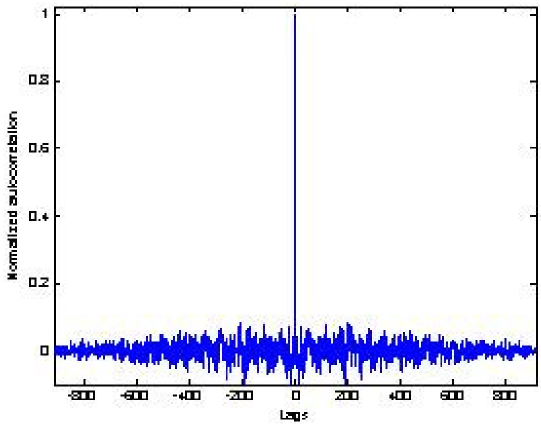

Figure 2. Autocorrelation function of a series of 1000 *RTT*

First, it should be verified that every obtained *RTT* was independent and not correlated with the rest of them. Hence, the autocorrelation function for several series of 1000 *RTT* samples -corresponding to different real distances between the MT and the AP- were obtained. All of them (see Figure 2 as an example) show that there correlation is negligible.

The chosen *RTT* estimator was the average *RTT* value (η, measured in number of clock cycles) obtained from all the measurements, since among all tested choices this value provides the best *RTT* estimation. Other choices, such as the half range *RTT*, the *RTT* mode, the average of *n* minimum *RTT* values and η- β times the standard deviation were also tested but they did not provide the best accuracy and are not reported in this paper.

3) Number of RTT measurements needed

It is important to know the number of *RTT* measurements needed to estimate the *RTT*. This number is relevant in order to find a reasonable trade-off between bandwidth used, time employed and accuracy obtained. Since *RTT* is a random variable and the average is used as estimator, the number of *RTT* samples can be set from a target confidence interval of the estimated average –around the population average- for a certain confidence level.

The formula of the confidence interval depends on the premises that can be assumed regarding the *RTT* distribution and a minimum number of samples needed that is accepted. In this case, since *RTT* distribution is not normal and 100 is accepted as the minimum number of samples, the formula is (for a confidence level of 95% of the time):

$$\eta \in (\overline{x} \pm z_{0.975} \cdot \sqrt{S^2 / n}), \quad (1)$$

where η is the estimated *RTT* average, $\overline{x}$ is the population average, *S* the estimated standard deviation from the population and $z_{0.975}$ the *z* function value for a confidence level of 95%. The units for this confidence interval are 44 MHz clock cycles. From Eq. (1), *n* can be deduced:

$$n = (2 \cdot z_{0.975} \cdot S / A)^2, \quad (2)$$

where *A* is the width of the confidence interval. The value of the *z* function for 0.975 is 1.96, the estimated standard deviation from the population (*S*) is 2. Taking into account that every 44 MHz rising clock implies a distance of 7 m., it was considered that only values of *A* under 0.5 (it is 0.25 rising clocks around the population average) had to be accepted. It was obtained *n* = 246; being aware that usually a small portion of the performed *RTT* measurements are not valid (due to errors of several types), *n* = 300 seemed to be a conservative figure to accurately estimate the *RTT*.

B. Distance estimation

1) Method

First, a *RTT* estimation at zero distance between the MT and the AP is obtained (the propagation times t_p is zero), in order to calibrate the time the AP takes to process the query (i.e. the link layer processing time). The figure obtained is assumed to be the t_{proc} *data_frame* part in Figure 1 so that it can be used as an offset for measurements at a non-zero distance. Consequently, by applying the offset obtained, it is possible to find the ΔRTT :

$$\Delta RTT = RTT_a - RTT_0 . \quad (3)$$

Once the 300 ΔRTT are calculated -and being aware that a 44 MHz clock was used for the measurements- the distance *d* (in meters) between the transmitter and receiver can be obtained as

$$d = c \cdot t_p = c \cdot \left(\Delta RTT / 2 \cdot 44 \cdot 10^6 \right). \quad (4)$$

Taking into account that the *RTT* estimator is the average *RTT* value (η, measured in number of clock cycles), Equation (4) can be rewritten as:

$$d = ((\eta_a - \eta_0) \cdot 3 \cdot 10^8)/(2 \cdot 44 \cdot 10^6). \quad (5)$$

2) Empirical coefficient

During the development process, it was observed that all the distances estimated were longer than the actual distances; therefore, the estimated distance had to be divided by an empirical coefficient to correct the estimated value. The empirical coefficient is justified by the special characteristics of the multipath indoor radio propagation channel [6], the measurement quantification errors and the delays caused by the electronics of the hardware module, which can increase the theoretical *RTT* expected.

To estimate that coefficient, all *RTT* measurements were analyzed and gathered according to the specific distances they belong. Afterwards, linear regression lines were traced relating the estimated distance obtained following the method described above with the actual distance (i.e. straight lines and not exponential or logarithmic relationship appeared between both variables). Furthermore, this relation did not show any independent term. The result is shown in Figure 3, being k=0.694 the coefficient found.

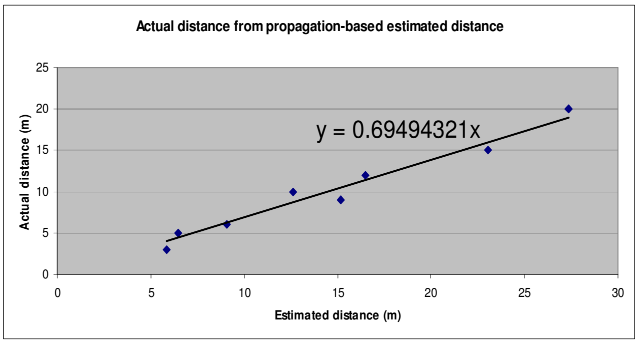

Figure 3. Estimation of the empirical coefficient

Therefore the corrected formula for calculating the distance is:

$$d = ((\eta_a - \eta_0) \cdot 3 \cdot 10^8 \cdot k)/(2 \cdot 44 \cdot 10^6). \quad (6)$$

Only one coefficient was used regardless of whether the system was working in an LOS or NLOS situation. In theory, NLOS cases would need a higher coefficient than LOS cases due to the increase in the delay spread, but real measurements showed that there is no real need for two different empirical coefficients, because the differences in distance estimation are so small that it is worthless to differentiate both situations. However, it has to be noticed that the considered NLOS situations are not likely to correspond to Undetectable Direct Path (UDP) radio channel profiles, but to Non Dominant Direct Path (NDDP) ones. A deeper study regarding this type of classification (see [7] for more information) would be interesting to present a proper assessment of the obstructed path problem between the MT and the AP.

C. Experimental Test Bed and Measurements

The experimental test bed consists of several distance estimations in the laboratory and its surroundings, under different conditions and with varying numbers of people in the rooms, at different times of the day, at various temperatures, and under different weather conditions. Therefore, all the measurements were taken in a real indoor working environment and without differentiating between LOS and NLOS situations. The accuracy of the ranging system was studied by performing several range estimations at different distances. Table I shows the absolute and relative errors obtained for every distance.

Table I. RESULTS OF THE RANGING SYSTEM:ERROR

Distance	5 m	10 m	15 m	20 m
Average	0.51 m (10.2%)	0.51 m (5.1%)	1.38 m (9.2%)	0.47 m (2.3%)
Maximum	1.21 m (24.2%)	1.24 m (12.4%)	2.88 m (19.2%)	1.01 m (5.0%)

In a second set of measurements, the probability distribution of the distances estimated by the ranging system was obtained. One of the objectives of this statistical characterization is to feed the positioning subsystem simulations with actual distance measurements, as below discussed in Section III.B. This set of measurements consists of 450 distance estimations (450·300 *RTT* measurements), measured at a constant distance of 10 m, after the initial calibration at 0 m.

Ideally, all the distances measured should be 10 m; however, due to several error sources, the ranging system obtains distances from 8.80 m to 12.80 m. This empirical histogram was compared with known probability distributions. The best fit was found to be a Gaussian distribution, as can be seen in Figure 4.

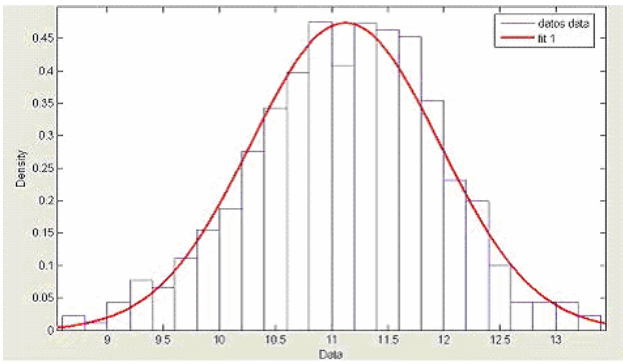

Figure 4. Histogram of distance measurements

III. POSITIONING SYSTEM

A. Introduction

The MT position is estimated once the distance estimations from a set of AP are known. This is done through triangulation on the distance measurements to at least three AP (for 2D positioning) at a known location. For details about the mathematics related with this topic see [8] and [9].

The algorithms that have been implemented and investigated are: Linear Least-Squares, Nonlinear Least-Squares (Newton) [8] and Independent time GPS Least-Squares. The first one is not very accurate, but provides an initial estimation of the position for other algorithms. The Independent time GPS Least-Squares is the basic algorithm included in the basis of GPS [9] system in order to solve the navigation equations if the Kalman filter is not used.

B. Experimental Test Bed: Simulations

Several simulations were performed, each carried out as follows:

- The positions of the three APs were introduced as well as the position of the MT that was going to be estimated.
- The simulation program calculated the exact distances from each AP to the MT.

  These distances were modified using the resulting probability distribution of the distance estimated, i.e. the exact distance from the MT to one AP was 10 m. Instead of using these 10 m distances, the simulation used the Gaussian probability distribution obtained from the true measurements of the ranging system for 10 m, as presented in Section II.C. Hence, the simulations were fed with actual data achieved in the measurements campaign. This probability distribution was divided into slots of 10 cm. Therefore, there was a probability associated with each possible distance the ranging system could measure. This is shown in Figure 5, in which there are three APs placed at 4, 12, and 17 m respectively, but these distances were replaced by their corresponding Gaussian bells. The same probability distribution was used for all distances because previous results show that there are no major variations when different distances are involved.

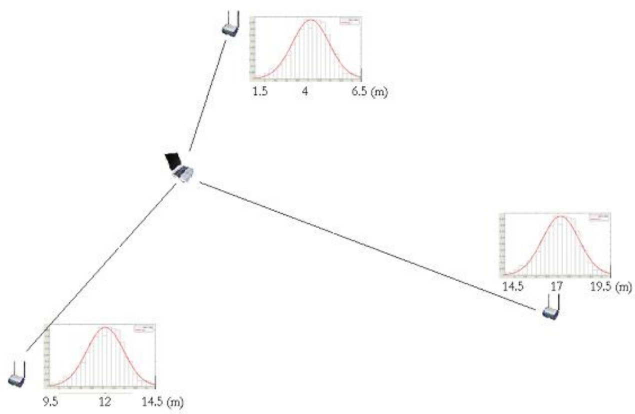

Figure 5. Simulation of the triangulation

- The simulation found the estimated position of the MT using the aforementioned algorithms for each of the possible distances estimated at each of the three APs. This means that each AP probability distribution was used at all possible points and that they were combined with the remaining APs to find all the possible position estimations and the probability associated with each of them. Once these estimations were known, they were subtracted from the MT's real position to find the position estimation error. Hence, this process made possible to obtain all the possible positioning errors for a specific scenario.
- Finally, the cumulative probability function of the position estimation error for every positioning algorithm was found.

The simulations considered several scenarios because the results depend on the relative geographical situation between the MT and the three APs. Since APs are assumed to be rationally deployed (non-colinearly, for instance), the geometric dilution of precision (GDOP) [10] in representative scenarios is expected to be good.

Figure 6 shows results (cumulative distribution function - CDF of the positioning error obtained) for a scenario in which the MT is located within the triangle formed by the three APs (i.e. best case). Accuracy is better than 1.4 with a 66 % probability. Figure 7 shows a case in which the MT is not within the triangle of APs but APs are properly deployed (i.e. GDOP is not bad, no alignment of APs). Accuracy is better than 1.8 m. with a 66 % probability. It can be also seen that the Nonlinear Least Squares (Newton) algorithm outperforms the GPS Least Squares algorithm in both cases.

IV. CONCLUSIONS

This paper presented a new TOA technique to locate WLAN terminals. Since TOA is estimated at the link layer, this proposal requires only minor changes on the hardware of the IEEE 802.11 b card: adding a counter (including triggers to start and stop) and interfacing the triggers and the result of the counter to the software. Estimating the TOA at the link layer involves more error sources than if the estimation is done at the physical layer; this paper proposes statistical methods to overcome the impact of such errors. The positioning system needs to use the WLAN transport resources to feed the MT with the information necessary to compute the location such as the calibration offset and the coordinates of the APs. First results show positioning accuracies lower than 2 m in most cases.

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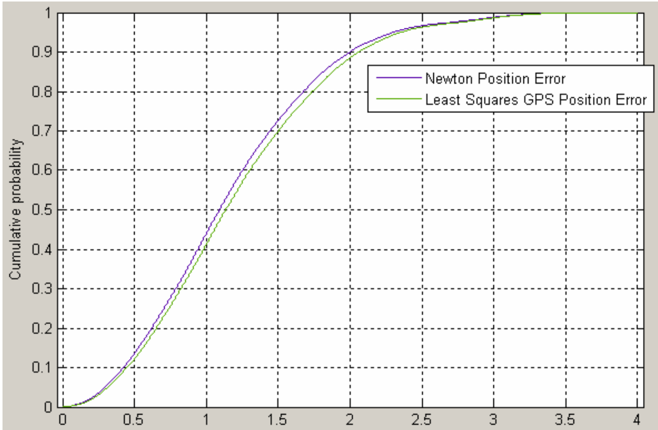

Figure 6. CDFs' positioning error (MT inside the triangle)

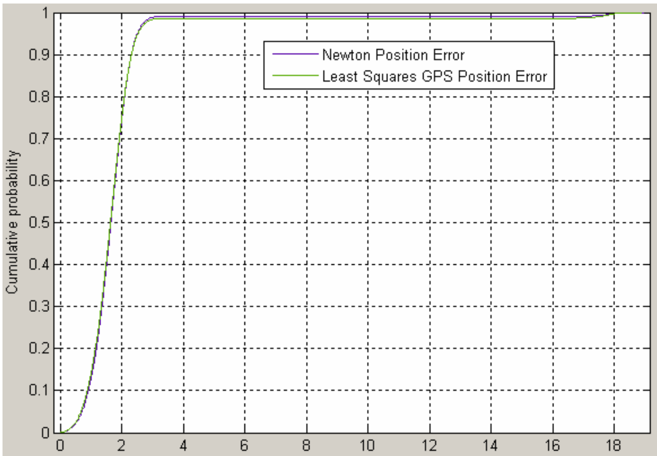

Figure 7. CDFs' positioning error (MT outside the triangle)

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