A Novel Positioning Technique with Low Complexity in Wireless LAN: Hardware implementation

Monji ZAIDI, Ridha OUNI, Jamila Bhar and Rached TOURKI

***Abstract*—Nowadays, several positioning systems are available for outdoor localization, such as the global positioning system (GPS), assisted GPS (A-GPS), and other techniques working on cellular networks, for example, Time of Arrival (TOA), Angle of Arrival (AOA) and Time Difference of Arrival (TDOA).However, with the increasing use of mobile computing devices and an expansion of wireless local area networks (WLANs), there is a growing interest in indoor wireless positioning systems based on the WLAN infrastructure. Wireless positioning systems (WPS) based on this infrastructure can be used for outdoor / indoor localization to determine the position of mobile users. An important factor in achieving this is to minimize and simplify the instructions that the mobile station (MS) has to execute in the location determination process. Finding an effective location estimation technique to facilitate processing data is the main focuses in this paper. Therefore, in the wireless propagation environment the Received Signal Strength (RSS) information from three base stations (BSs) are recorded and processed and they can provide an overlapping coverage area of interest. Then an easy new geometric technique is applied in order to effectively calculate the location of the desired MS.**

Our new positioning method design was verified at the algorithmic level using Matlab tool, described in Very-high-speed integrated circuit Hardware Description Language (VHDL) at the register transfer level (RTL) and it has been synthesized using 7.1 version of FPGA Advantage for HDL Design that evaluates the circuit in terms of speed, area and power consumption.

***Index Terms*—Geometric technique, Position estimation, Wireless LAN, VHDL.**

I. INTRODUCTION

Recently, the subject of mobile positioning in wireless communication systems has drawn considerable attention. With accurate location estimation, a variety of new applications and services such as Enhanced-911, location sensitive billing, improved fraud detection, intelligent transport system (ITS) and improved traffic management will become feasible [1]. Mobile positioning using radiolocation techniques usually involves time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), signal strength (SS) measurements or some combination of these methods.

All of these methods are mainly based on trigonometric computation. Comparisons and survey of these methods are given in [2] and [3].

The TOA technique determines the MS position based on the intersection of three circles. Two range measurements provide an ambiguous fix, and three measurements determine a unique position.

Given the coordinates of BSj, (j = 1, 2, 3) as (Xj, Yj), and the distances dj between MS and BSj, the simplest geometrical algorithm for TOA positioning (Figure. 1(a)) is given in [2]. Coordinates of MS position (x,y) relative to BS1 can be calculated as:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \frac{1}{2}\begin{bmatrix} X_2 & Y_2 \\ X_3 & Y_3 \end{bmatrix}^{-1} + \begin{bmatrix} {X_2}^2 + {Y_2}^2 + {d_1}^2 - {d_2}^2 \\ {X_3}^2 + {Y_3}^2 + {d_1}^2 - {d_3}^2 \end{bmatrix}$$

The simplest geometrical algorithm for TDOA positioning (Figure. 1(b)) is given in [4]. There are two estimated TDOA-s dj, 1 between BS1 and the jth base station (j = 2, 3). Coordinates of MS position (x, y) relative to BS1 can be calculated in terms of d1 as:

$$\begin{bmatrix} x \\ y \end{bmatrix} = -\begin{bmatrix} X_2 & Y_2 \\ X_3 & Y_3 \end{bmatrix}^{-1} * \left\{ \begin{bmatrix} d_{2,1} \\ d_{3,1} \end{bmatrix} d_1 + \frac{1}{2}\begin{bmatrix} {d_{2,1}}^2 - K_2 + K_1 \\ {d_{3,1}}^2 - K_3 + K_1 \end{bmatrix} \right\}$$

Where:

$$K_1 = {X_1}^2 + {Y_1}^2$$

$$K_2 = {X_2}^2 + {Y_2}^2$$

$$K_3 = {X_3}^2 + {Y_3}^2$$

The AOA technique determines the MS position (x, y) based on triangulation, as shown in (Figure. 1(c)). The intersection of two directional lines of bearing with angles θ_1 and θ_2 defines a unique position, each formed by a radial from a BS to the MS. The simplest geometric

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solution can be derived using [5] with two AOA measurements θ_1 and θ_2:

$$x = \frac{Y_2 - Y_1 + X_1 \tan(\theta_1) - X_2 \tan(\theta_2)}{\tan(\theta_1) - \tan(\pi - \theta_2)}$$

$$y = Y_1 + (x - X_1)\tan(\theta_2)$$

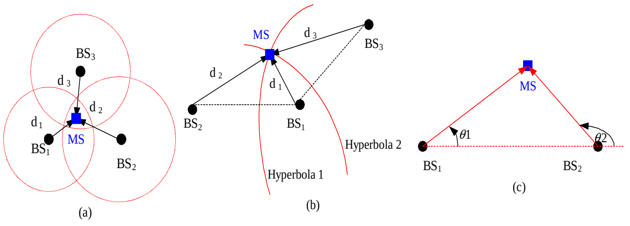

Fig. 1. Position determination techniques: (a) TOA; (b) TDOA; (c) AOA

Using any of the mentioned methods, the calculation can be done either at the BS [network-based schemes] or at the MS [mobile-based schemes]. Network-based schemes have high network cost and low accuracy [3]. Mobile-based location schemes are more interesting. However, since the MS has limited energy source, in the form of the battery pack, energy consumption should be minimized. An important factor in achieving this is to minimize and simplify the instructions that the MS has to execute in the location determination process. The conventional algorithms use complex computation methods that needed relatively long execution time.

In this paper, we propose a novel wireless positioning technique based on the WLAN infrastructure. The main motivation for our approach is twofold: to improve the accuracy of the location estimation and to minimize and simplify the instructions that the mobile station (MS) has to execute in the location determination process.

II. RELATED WORK

To improve the accuracy of the indoor positioning system, several techniques demonstrate the viability of this approach. Youssef et al. [6] show that the RADAR system can be improved using the perturbation technique (joint clustering technique) to handle the small-scale variations problem. This technique can improve theRADARsystem and provide location accuracy up to 3m.

The triangulation mapping interpolation system (CMU-TMI) [7] performs a location calculation on the current data, interpolates that data with the information in the database, and then returns a location estimate based on this interpolation. However, power consumption increases to measure the signal strength on the client side.

The Ekahau Positioning Engine 4.0 [8], released in October 2006, also uses an IEEE 802.11 network to provide location information. It achieves an average accuracy of 1m with at least three audible channels in each location. This system requires site calibration up to 1 h per 1,200m^2. While calibration-based efforts present good accuracy results, there is still room for performance enhancements. Due to the very dynamic nature of the RF signal, the assumption that the radio map built in the calibration phase remains consistent to the measurements performed in the real-time phase does not hold in practice; thus, at times, there is a need to rebuild the radio map. It seems more reasonable to design a fully-automatic system capable of acknowledging RSSI characteristics and variations in both spatial and time domains.

Hitachi [9] released location technology based on TDOA in March 2005. This system uses two types of access points: a Master AP and a Slave AP. Slave APs synchronize their clocks with that of a Master AP and measure the arrival time from a mobile terminal; the Master AP determines the location of the mobile terminal using the TDOA between the signal reception times at multiple Slave APs. While this technique has been found to achieve good results in indoor environments, it requires specialized hardware and fine-grain time synchronization, which increases the cost of this type of solution.

Kanaan proposed a closest-neighbor with TOA grid algorithm (CN-TOAG) [10]. This geolocation algorithm presents a TDOA-based position detection technique to improve location accuracy in the indoor environment by estimating the location of the user as the grid point. This technique is similar to the previous one [11], as it needs specialized hardware and fine grain time synchronization, which increase costs.

III. NEW GEOMETRIC LOCATION ALGORITHM BASED ON THREE BSs

In the general geometrical triangulation location researches, they assumed that the measured noise is additive and the NLOS error is a large positive bias which causes the measured ranges to be greater than the true ranges [12].

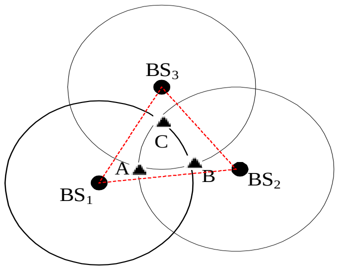

Fig. 2. Measured range circles and the associated intersected area

Under the assumption, the MS location will guarantee to lie in the overlapped region (enclosed by points A, B and C) of the range circles as shown in Figure. 2. Thus the MS is necessarily located in the region formed by the points BS_1, BS_2 and BS_3. But, it is noted that the intersection of three circles may not be overlapped with the real measurement results. Therefore, with the above assumption we have to judge whether the three circles intersect or not in our location algorithm.

If circles intersect as depicted in Figure. 3, then three triangles can be drawn as: BS_1MSBS_2, BS_2MSBS_3 and BS_3MSBS_1.

Assumptions:

- Different BSs are placed (two to two) at an equal distance
- The coordinates of BSs are known by the MS
- The MS can inquire only on the received power coming from the BSs (i.e. the distance which separates it from each BS).
- $\mathrm{d}_1 + \mathrm{d}_2 > D; \mathrm{d}_2 + \mathrm{d}_3 > D \; and \; \mathrm{d}_3 + \mathrm{d}_1 > D$

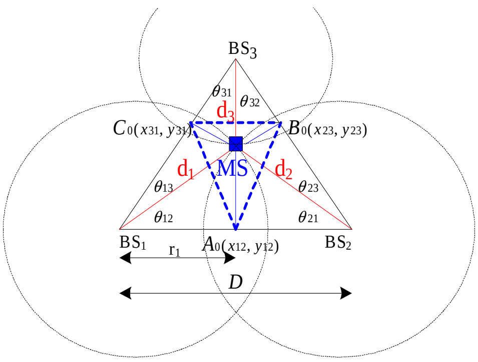

Fig. 3. The associated triangles of the standard intersection of three circles.

Note by:

- D: The distance between tow BSs.
- A_0, B_0 and C_0 are the orthogonal projections of the MS on (BS_1 BS_2), (BS_2, BS_3) and (BS_3 BS_1) respectively.
- d1, d2 and d3 are the distances that separate the MS from BS1, BS2 and BS3 respectively.
- θ_{12}: is the geometrical angle between the MS-BS1 and BS1-BS2. (Same things for the other angles).

We focus firstly on the triangle BS_1MSBS_2.

Based on the above assumptions and figure 2, we can write.

$$\mathrm{r}_1 = \mathrm{d}_1 \cos\theta_{12}$$

We can also write

$$\mathrm{d}_2{}^2 = (\mathrm{D} - \mathrm{r}_1)^2 + (\mathrm{d}_1{}^2 - \mathrm{r}_1{}^2) \Rightarrow$$

$$\mathrm{d}_2{}^2 = (\mathrm{D} - \mathrm{d}_1\cos\theta_{12})^2 + (\mathrm{d}_1{}^2 - \mathrm{d}_1\cos\theta_{12}{}^2) \Rightarrow$$

$$\mathrm{d}_2{}^2 = \mathrm{D}^2 + \mathrm{d}_1{}^2 - 2\mathrm{D}\mathrm{d}_1\cos\theta_{12} = \mathrm{D}^2 + \mathrm{d}_1{}^2 - 2\mathrm{D}\mathrm{r}_1 \Rightarrow$$

$$\mathrm{r}_1 = \frac{\mathrm{D}^2 + \mathrm{d}_1{}^2 - \mathrm{d}_2{}^2}{2\mathrm{D}}$$

We define here the first factor $\mathrm{q}_1$by

$$\mathrm{q}_1 = \frac{\mathrm{r}_1}{\mathrm{D}} = \frac{\mathrm{D}^2 + \mathrm{d}_1{}^2 - \mathrm{d}_2{}^2}{2\mathrm{D}^2}$$

Coordinates $(\mathrm{x}_{12}, \mathrm{y}_{12})$ of the point A_0 are given in [13] by

$$\mathrm{x}_{12} = \mathrm{q}_1\mathrm{X}_2 + (1 - \mathrm{q}_1)\mathrm{X}_1$$

$$\mathrm{y}_{12} = \mathrm{q}_1\mathrm{Y}_2 + (1 - \mathrm{q}_1)\mathrm{Y}_1$$

Where:

$(\mathrm{X}_1, \mathrm{Y}_1)$ and $(\mathrm{X}_2, \mathrm{Y}_2)$ are the coordinates of BS_1 and BS_2, respectively.

Let the distance between BS_2 and B_0 be r_2 and the distance between BS_3 and C_0 be r_3

As we described previously, we can get the coordinates of points B_0 and C_0 as:

$$\mathrm{x}_{23} = \mathrm{q}_2\mathrm{X}_3 + (1 - \mathrm{q}_2)\mathrm{X}_2$$

$$\mathrm{y}_{23} = \mathrm{q}_2\mathrm{Y}_3 + (1 - \mathrm{q}_2)\mathrm{Y}_2$$

$$\mathrm{x}_{31} = \mathrm{q}_3\mathrm{X}_1 + (1 - \mathrm{q}_3)\mathrm{X}_3$$

$$\mathrm{y}_{31} = \mathrm{q}_3\mathrm{Y}_1 + (1 - \mathrm{q}_3)\mathrm{Y}_3$$

Where:

$$\mathrm{q}_2 = \frac{\mathrm{r}_2}{\mathrm{D}} = \frac{\mathrm{D}^2 + \mathrm{d}_2{}^2 - \mathrm{d}_3{}^2}{2\mathrm{D}^2}$$

$$\mathrm{q}_3 = \frac{\mathrm{r}_3}{\mathrm{D}} = \frac{\mathrm{D}^2 + \mathrm{d}_3{}^2 - \mathrm{d}_1{}^2}{2\mathrm{D}^2}$$

MS is then located in a new triangle $A_0B_0C_0$, which is smaller in terms of area compared to the starting triangle $BS_1BS_2BS_3$. In the other word we have just created three new virtual BSs placed at A_0, B_0 and C_0.

It is very easy to calculate the distances between the MS and the new points A_0, B_0 and C_0 using the Pythagoras formula. Thus

$$\mathrm{d}(\mathrm{MS}, \mathrm{A}_0) = \sqrt{\mathrm{d}_1{}^2 - \mathrm{r}_1{}^2}$$

$$\mathrm{d}(\mathrm{MS}, \mathrm{B}_0) = \sqrt{\mathrm{d}_2{}^2 - \mathrm{r}_2{}^2}$$

$$\mathrm{d}(\mathrm{MS}, \mathrm{C}_0) = \sqrt{\mathrm{d}_3{}^2 - \mathrm{r}_3{}^2}$$

Now, with the three new virtual BSs, MS can repeat the same calculations as shown above. During this second iteration, the orthogonal projections of MS on (A_0B_0), (B_0C_0) and (C_0A_0) must be done to obtain new point A_1, B_1 and C_1 that their coordinates may be determined as previously. $A_1B_1C_1$'s area is smaller than the $A_0B_0C_0$ one. At the i^{th} iteration, the MS will be located in an $A_iB_iC_i$ triangle which is smaller than $A_{i-1}B_{i-1}C_{i-1}$ one. This $A_iB_iC_i$ triangle allows to designing the next triangle $A_{i+1}B_{i+1}C_{i+1}$.

After a small number of iterations, the coordinates of three vertices of the triangle (A, B and C) converge to the actual coordinates of the MS. At the limit, the triangle $A_{conv}B_{conv}C_{conv}$ with vertices A_{conv}, B_{conv} and C_{conv} will be considered as a point. So, it is possible to write:

$$x_{Aconv} \approx x_{Bconv} \approx x_{Cconv}$$

$$y_{Aconv} \approx y_{Bconv} \approx y_{Cconv}$$

We can then take the coordinates of the MS as:

$$x_{MS} = \frac{x_{Aconv} + x_{Bconv} + x_{Cconv}}{3}$$

$$y_{MS} = \frac{y_{Aconv} + y_{Bconv} + y_{Cconv}}{3}$$

The division by 3 implies that the MS is equivalent to the gravity center of the A_{conv}, B_{conv} C_{conv} triangle.

Figure 8 (section 5) shows the evolution and the convergence of the three vertices coordinates for different values of d_i (d_1, d_2 and d_3).

IV. VHDL MODEL

The operation destined to calculate the coordinates of a mobile terminal is known as a Location Process. Original design of this process, has just considered.

Figure 4 shows the main elements involved in our new mechanism: the MS, Three BSs, and the distribution system (DS) or Ethernet.

It can mentioned that different BSs are placed (Two to two) at an equal distance, and the MS can inquire only on the position and the received time coming from the BSs (i.e. the distance which separates it from each BS)

The equations for the x and y position of the mobile was modeled using VHDL. The numeric_std package was used to construct the VHDL model that was readily synthesized into a low power digital circuit. The input signal of the model are the x, y positions of the three BSs, i,j,k in meters, and the signals TOA from the individual BS to the mobile in nanoseconds. The input signal assignments are x_i, y_i, TOA_i, x_j, y_j, TOA_j, x_k, y_k, TOA_k

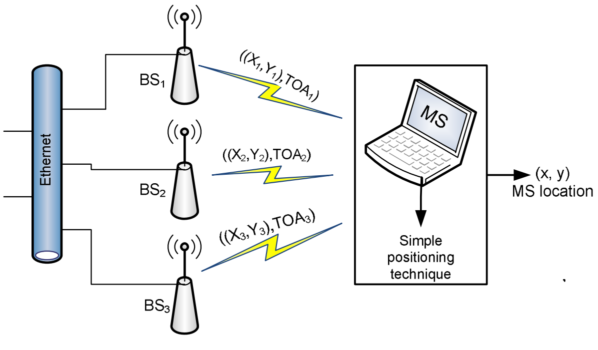

Fig. 4. Involved elements in the Positioning process

Now, we describe the hardware implementation of the location process. Figure 5 illustrates the system architecture; we try to divide location process to 4 parts: a process location algorithm, the square root component, divider block and buffers to store data. The following notations are used to describe the signal type: I: input signal; O: output signal

TABLE I

PROCESS LOCATION PART INTERFACE SIGNALS

Name	Type	Description
CK	I:bit	Operation clock.
RST	I:bit	RESET system
TOA_1	I:std_logic_vector	Input from the BS_1, it gives the time of arrival value to travel the d1distance
X_1	I:std_logic_vector	BS_1 abscissa
Y_1	I:std_logic_vector	BS_1ordinate
TOA_2	I:std_logic_vector	Input from the BS_2, it gives the time of arrival value to travel the d_2 distance.
X_2	I:std_logic_vector	BS_2 abscissa
Y_2	I:std_logic_vector	BS_2abscissa
TOA_2	I:std_logic_vector	Input from the BS_3, it gives the time of arrival value to travel the d_3 distance.
X_3	I:std_logic_vector	BS_3 abscissa
Y_3	I:std_logic_vector	BS_3 abscissa
X_{estim}	O: std_logic_vector	Estimated abscissa of MS
Y_{estim}	O: std_logic_vector	Estimated ordinate of MS

First, the main program (process location) receives data from the external environment. Then, it calculates the parameters r_1, q_1, r_2, q_2, r_3, and q_3 as it was presented in Section 3. During this stage the divider component is called by the main program to perform the operations division. Meanwhile the virtual coordinates $(x_{12}, y_{12}), (x_{23}, y_{23})$ and (x_{31}, y_{31}) of points A_0, B_0 and C_0 respectively, are determined.

Secondly, the distances $d(MS, A_0)$, $d(MS, B_0)$ and $d(MS, C_0)$ are calculated using the square root operators

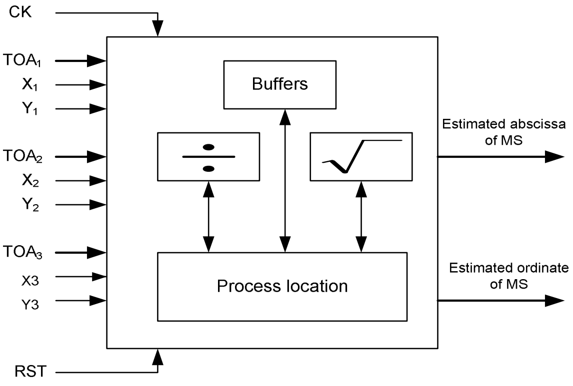

Fig. 5. Top level structure of the Location circuit

The implemented square root algorithm uses unsigned integers, which have several advantages over floating-point numbers in FPGA arithmetic. Operations on unsigned integers are often simpler to implement, and they require less chip area and resources. The square root operator assumes that its input argument has already been converted into an unsigned integer, which must be taken care of if an application uses signed integers.

A symbol of the top-level VHDL design entity of the square root operator with parameterizable input argument width is presented in Figure 6.

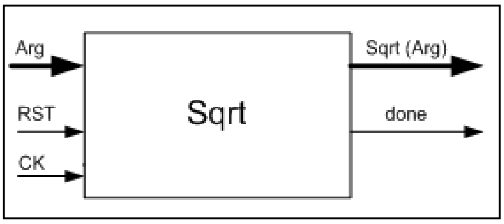

Fig. 6. Top level diagram of the square root operator

Figure 7 shows the simulation of a fast Location processing model. Optimal process latency is improved by reducing the iterations number needed for convergence. So, after a small number of iterations, the coordinates of three vertices of the triangle (A, B and C) converge to the actual coordinates of the MS. at this time, the triangle $A_{conv}Bc_{onv}C_{conv}$ with vertices A_{conv}, B_{conv} and C_{conv} will be considered as a point and we can write:

$$x_{Aconv} = x_{Bconv} = x_{Cconv}$$
$$y_{Aconv} = y_{Bconv} = y_{Cconv}$$

We can then take the coordinates of the MS as:

$$(x_{MS} = \frac{x_{Aconv}+x_{Bconv}+x_{Cconv}}{3},\ y_{MS} = \frac{y_{Aconv}+y_{Bconv}+y_{Cconv}}{3})$$

The division by 3 implies that the MS is equivalent to the gravity center of the $A_{conv}B_{conv}C_{conv}$ triangle.

The (x_{MS}, y_{MS}) Geolocalisation information, obtained with a minimal cost has a very important role in several applications. We are trying to take advantage of this important information to develop a fast handover in an environment with time constraints

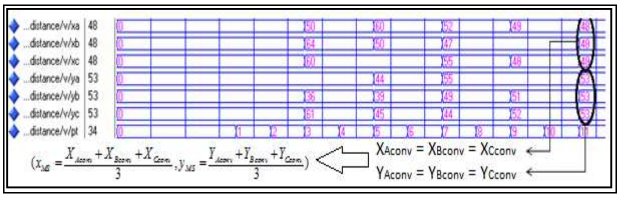

Fig. 7. Simulation results of the hardware positioning process

Now, it is necessary, as in any positioning method, to evaluate the error or deviation (in m) between actual (measured) and simulated values obtained by our method. For this two cases have to be considered:

A. *Line-of-sight (LOS) condition*

This case occurs in open areas or in very specific spots in city centers, in places such as crossroads or large squares with a good visibility of BS. Sometimes, there might not be a direct LOS signal but a strong specular reflection off a smooth surface such as that of a large building will give rise to similar conditions. The received signal will be strong and with moderate fluctuations. Therefore, the extracted distance from the received signal is correctly calculated.

In the table 1 we give some actual locations of the MS (Actual x and y). Corresponding values of the true distances d_1, d_2 and d_3 which separate it from BS_1, BS_2 and BS_3 are calculated. Then the estimated position and position error can be determined using our geometric method.

A. *Non Line-of-sight (NLOS) condition*

This case will typically be found in Indoor environments. This is a worst-case scenario since the direct signal is completely blocked out and the overall received signal is only due to multipath, thus being weaker and subjected to marked variations. Under these conditions the geometric method can be applied. However, the position error increases significantly.

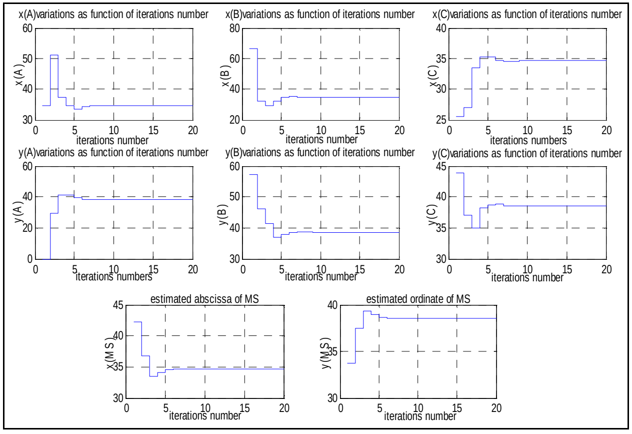

Fig. 8. Algorithm convergence with (d_1, d_2, d_3) = (52 m, 76 m, 50 m)

The oboe simulation was done with the following BSs coordinates.

BS_1 coordinates (in meters):$(X_1, Y_1) = (0,0)$
BS_2 coordinates (in meters):$(X_2, Y_2) = (100,0)$
BS_3 coordinates (in meters):$(X_3, Y_3) = (50,86)$

TABLE II
LOS MEASUREMENT AND POSITION DETERMINATION

x_{actua} (m)	y_{actua} (m)	d_1 (m)	d_2 (m)	d_3 (m)	x_{estima} (m)	y_{estima} (m)	C.t (i.n)	Error (m)
20	10	22.5	80.5	82.5	20.13	09.20	≤8	0.807
30	20	36	73	69.5	29.83	19.64	≤8	0.395
40	30	50.5	67	57.5	40.30	29.70	≤8	0.424
40	40	57	72	47.5	40.32	39.86	≤8	0.353
50	50	71	71	36	50.00	50.23	≤8	0.238
50	70	86.5	86.5	16	50.00	70.47	≤8	0.478
60	60	85.2	72	28.5	60.37	59.91	≤8	0.384
60	40	72	57	47.5	59.67	39.86	≤8	0.353
70	30	76.5	42.5	60.5	70.06	29.45	≤8	0.549
80	20	82.5	27.9	73	79.85	19.69	≤8	0.336
								M≈0.4

C.t: Convergence time
I.n = Iterations number
M: mean

TABLE III
NLOS MEASUREMENT AND POSITION DETERMINATION

x_{actual} (m)	y_{actual} (m)	$x_{estimated}$ (m)	$y_{estimated}$ (m)	Error (m)
20	10	18.9700	8.4826	1.8340
30	20	29.0950	19.2922	1.1489
40	30	39.0763	28.7347	1.5666
40	40	41.4850	40.8110	1.6920
50	50	50.0000	51.0523	1.0523
50	70	48.2600	70.9884	2.0011
60	60	58.7450	60.6642	1.4199
60	40	61.1350	40.4331	1.2148
70	30	70.2300	28.0174	1.9959
80	20	79.7000	17.5872	2.4314
				Mean≈1.6

B. *Synthesis results*

During the synthesis step, we have exploited FPGA Xilinx virtex 5 environment. This environment allows implementing communication systems on programmable circuits. The advantage of using FPGAs circuits is mainly the system re-scheduling. For our application, RTL synthesis is achieved using the ISE 10.1 of the Xilinx FPGA virtex 5 environment. A synthesis result, of the proposed process location, is shown in table 3. These results should be exploited in order to study their impact on the support of the technological parameters specified in IEEE 802.11. These results show that the circuit can operate with 142 MHz, which makes it more suitable for real time communications.

TABLE IV
SYNTHESIS RESULTS.

Number of Slices	Number of Flip Flops	Nb of 4 input LUTs	Nb of bonded IOBs	Frequency (MHz)
772	594	1371	30	142

V. CONCLUSION AND FUTUR WORKS

This paper presents new geometric oriented algorithm that is based on three distances measurements to determine the position of a mobile object. Provided that all operations in our proposed algorithm are additions, subtractions and multiplications based, the implementation is simplified which reduces complexity.

Our results show that for a very reduced number of iterations ($k \leq 8$), the proposed method converges and provides with a good accuracy the position of MS. Hence, the major advantages of our algorithm are: implementation simplicity, and low computation overhead.

We adopted the high level design for the implementation of this model. In fact, we have used VHDL as high level description language, ModelSim as a simulation tool to check the behavior of the model at the RTL level and ISE 10.1 of the FPGA xilinx environment for synthesis step.

We obtained the exact solution for the two-dimensional location of a mobile given the locations of three fixed base stations in a cell and the signal TOA (Time of Arrival) from each base station to the mobile device. Simulation results for two different situations predict location of the mobile is off by 0.4 m for best case and off by 1.6 m for worst case.

In our future work we are ready to integrate the position of the MS in the 4G Handover management.

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