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Mobile Positioning Using A PGWC-TDOA Hybrid Method

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Abstract

Finding the location of the mobile phone is one of the important features of the 3G mobile communication systems. In this paper, a simple, yet accurate, method to position mobiles in a cellular system is proposed. The suggested method depends on a hybrid combination of signal strength level and time difference of arrival. The proposed method is shown to meet the Federal Communication Committee (FCC) requirements and compare favorably to existing methods.

تحديد موقع الهاتف المتنقل بأستخدام طريقة هجينة

الخلاصة

ان ايجاد موقع الهاتف المتنقل يعتبر احدى المتطلبات المهمة للجيل الثالث من انظمة الأتصالات المتنقلة. في هذا البحث تم اقتراح طريقة بسيطة ، ولكنها دقيقة لتحديد موقع الهاتف المتنقل في انظمة الأتصالات الخلوية. تعتمد الطريقة المقترحة على الربط مابين مستوى الأشارة المستلمة و الفرق بين زمن وصول الأشارة من عدة محطات ارسال. اثبتت نتائج التمثيل بأستخدام الحاسبة على مدينة مفترضة دقة الطريقة المقترحة و تحقيقها للمتطلبات التي وضعتها منظمة FCC إضافة إلى تفوقها على الطرق الموجودة.

1. Introduction

Mobile positioning has received a considerable attention in the last years because of its different and important range of applications. Information regarding the position of a mobile can be used by operators to implement location-based call charges and to enhance radio resource management functions like handover and channel selection. It can be used for commercial purposes like navigation systems and location aware services. The driving force for mobile positioning is that, the FCC commission requires that all emergency calls from cellular phones must be located within (125 m) for 67% of the time and within (300 m) for 95% of the time.

The required accuracy of a location service is strongly dependent on the applications. For general information and advertising applications it is sufficient to determine only the cell of the mobile terminal and to send information related to this cell and then to the terminal. Other applications like emergency calls or navigation systems, require a very accurate determination of the position of the mobile terminal. In some applications, the relative position error between two mobile units is more interesting than the absolute error. The use of the satellite based Global Positioning System (GPS) in mobile terminals has several drawbacks and limitations. Additional equipment (GPS antenna, receiver circuitry etc.) is required in the mobile stations which increase the cost. A further disadvantage with GPS is that the received signal power is very low; line-of-sight (LOS) to at least three satellites is required in order to get a 2-D position. In urban areas, both outdoors and indoors, it is often impossible to get LOS paths to enough satellites, which leads to a low position accuracy.

Several methods for mobile positioning exist in the literature. The basis for these methods could be time measurements [1], signal-strength measurements [2] and angle-of-arrival detection [3]. The first and simplest method is the cell ID (CID) where the position

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estimate is simply the coordinate of the serving base station (BS) (usually the strongest one). In the second method [4], the mobile position is calculated as the centroid of the positions of all N-base station (BS) whose beacons the mobile station (MS) can decode. The third method uses circular trilateration of absolute propagation delays to find the position. This method is often known as time-of-arrival (TOA) [1]. Other common methods in the literature are hyperbolic multilateration of propagation delay differences (time-difference-of-arrival TDOA) and triangulation using direction information from antenna arrays or sector antennas (Angle-Of-Arrival AOA) [3].

2. Location Estimation Techniques

There are several methods that can be used to calculate an unknown mobile position from measurements based on signals from base stations of known position. These are summarized below.

2.1 *Signal strength analysis*

This technique is based on measuring the strength of signals from at least 3 BS's at the MS or on measuring the signal strength of the MS to at least 3 BS's. The signal strength measurements are related to the MS-BS separation distances. The MS location then can be calculated by the approximate intersection of 3 circles of known radius by using least squares to minimize the error (see Figure 1 (a)).

There are fundamental problems associated with signal strength measurements. Firstly the fading profile of received power requires that the mobile is not stationary and that some form of averaging is required. Secondly the signal strength measurements must be converted to distance measurements.

2.2 Angle of Arrival (AOA)

The AOA technique is based on calculating the relative angles of arrival at an MS of three BS's or the absolute angle of arrival of the MS at two or three BS's. This technique relies on the technology of antenna arrays which provide the direction finding capability to the receiver. The angles can be calculated by measuring phase differences across the array (phase interferometry) or by measuring the power spectral density across the array (beam forming) . Once the measurements have been made the location can be calculated by simple triangulation (see Figure 1 (b)).

It may be impractical to have an antenna array at the MS due to size, allignment and array separation problems. Antenna arrays at the BS are planned for UMTS mobile networks, for example, to provide directional transmission to improve network capacity . Field trials in London by [5] suggest that the angle error at the 67% percentile is 30^{o} for the uplink direction detection, which would make AOA unviable for urban location estimation.

2.3 Time of Arrival (TOA)

This method uses the measured propagation time between a mobile terminal and three base stations for positioning. The measured time-of arrival can be used to generate circles whose intersections provide the estimate of the MS position, see Fig. 1(a). Using this approach, with some modifications by using geometrical interpretation, [6] proved that FCC requirements can be met but it is highly sensitive to measurements error.

With the introduction of wide bandwidth digital systems, timing information becomes relatively easy to obtain by correlation of a known pilot sequence at the receiver. The maximum time resolution depends on the sampling rate at the receiver. Prefiltering the signal to band pass the frequencies with maximum SNR can further reduce the probability of timing errors.

2.4 Time Difference of Arrival (TDOA)

Positioning by this method is performed by measuring the relative arrival time at the MS of signals transmitted from 3 BS's at the same time (or known offset). Likewise the relative arrival times at three BS's of one MS can be measured. Again the maximum timing resolution depends on the sampling rate at the receiver. Precise synchronization of BS's will be required for this method. The estimate can be made from the intersection of 2 hperboloids depending on the measured time difference of arrival, see Fig.1(c). In UK, Cursor Systems [7] have developed a GSM compatible method based on TDOA of signals from both the BS's at the MS and additional sensors (of known location). This system also claims to meet the FCC requirements.

2.5 Hybrid techniques

Hybrid techniques using more than one of the above have been suggested, such as AOA and TOA or signal strength hybrid which has an advantage in that communication with only one BS is required (see Figure 1 (d)). Yost et al., [8] suggest that TDOA-TOA hybrid would improve location estimate accuracy, while [9] suggests a (signal level + TOA) hybrid method. An understanding of the relationship of the accuracy of each technique to different environments will help to combine the measurement types optimally.

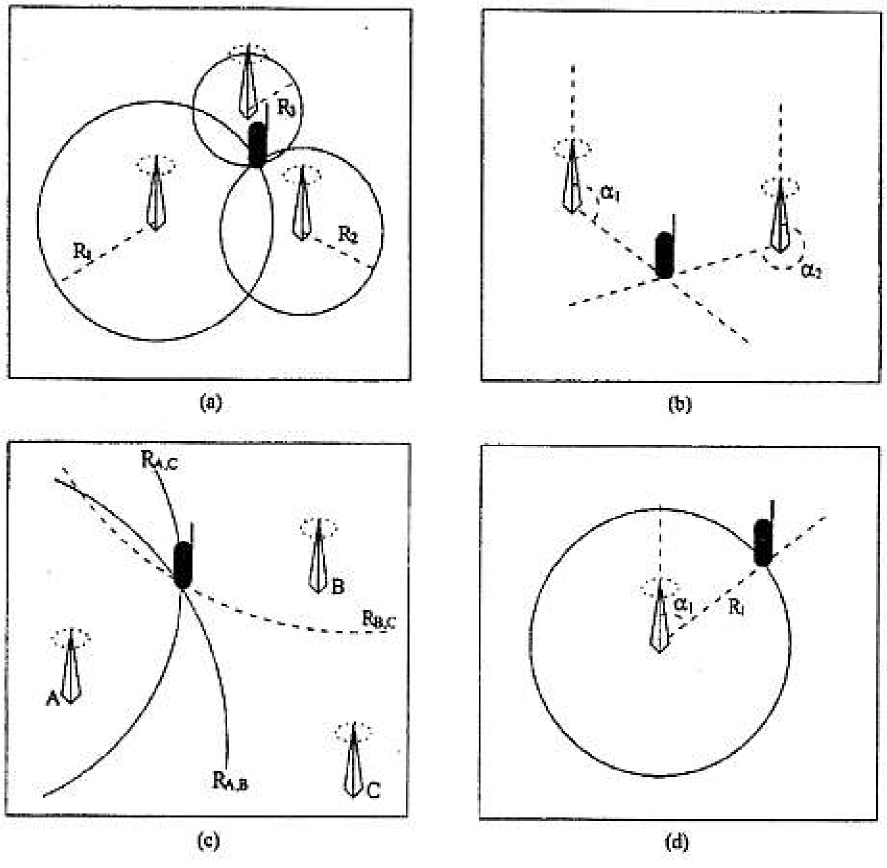

Fig. 1: Position estimation for the (a) TOA and signal strength techniques, where R_1, R_2 and R_3 are the estimated distances from MS to BS_1, BS_2 and BS_3 respectively (b) AOA technique where $\square_1$: AOA from BS_1 to MS $\square_2$: AOA from BS_2 to MS (c) TDOA technique where $R_{A,B}$,$R_{A,C}$ and $R_{B,C}$ are the estimated distance of MS from Base Stations A&B,A&C and B&C respectively (d) AOA-TOA/signal strength hybrid technique.

3. Main Obstacles to Location Estimation

There are several key obstacles associated with location estimation which will have to be overcome. The most important obstacles are discussed here.

3.1 Multipath conditions

Multipath propagation is the primary reason for inaccuracies observed in the AOA and signal strength measurement systems as well as the time-based positioning systems. Because of multipath, the received signal will be made of several different copies of the same transmitted signal at different time delays, magnitude and phase. The occurrence of multipath makes the information of timing, signal strength and AOA inaccurate. Typical effect of multipath on AOA measurements, for example, appears as a large angle spread that may be observed at the receiver. Measured values are 360° for indoor, 20° for urban and 1° for rural environments [10].

3.2 Non Line Of Sight (NLOS) conditions

With NLOS propagation, the signal arriving at the BS from the MS is reflected or diffracted and takes a longer path than the direct ray. Timing, signal strength, and especially AOA information will be inaccurate. Typical error introduced by NLOS propagation which has been measured, indicate change in propagation distances of 400-700 m for an MS experiencing NLOS conditions [11]. In TDOA, timing errors may cancel out to a certain degree assuming similar NLOS properties to each BS. It seems feasible that the NLOS propagation effects may be cancelled using spatial filtering as proposed by [12].

4. Location Estimation Enhancement Techniques

Several methods have been proposed to improve the location estimation techniques. [13] presented a database correlation method, which is based on results of the propagation models during the planning process. These results are used to define a look-up table. By evaluating the measured path losses between the mobile terminal and the base stations and by correlating these losses with the entries of the look-up table, the mobile positioning is performed.

Some methods proposed the use of weights proportional to the confidence in a set of data. For instance the effect of data on the location estimate from far away BS's could be reduced. Another method proposed for TOA is to restrict the error range to a positive sign (TOA methods cannot underestimate the time delay). Morley et al., [14] show that adding this further constraint to the least squares solution can significantly reduce errors. It may be possible to extend this idea to TDOA if one postulates that a TDOA measurement between a close and a far BS will tend to be an overestimate as a far BS is more likely to suffer from NLOS.

5. The Proposed Method for Mobile Positioning

5.1 Path – Gain Weighted Centroid (PGWC)

The method proposed in this paper is an extension to the unweighted centroid method described in [4], where the mobile unit position is calculated as the centroid of the position of all N-base stations whose beacons the mobile unit can decode;

$$\left. \begin{aligned} x &= \frac{\sum_{i=1}^{N} X_i}{N} \\ y &= \frac{\sum_{i=1}^{N} Y_i}{N} \end{aligned} \right\} \qquad \dots (1)$$

where (X_i, Y_i) is position of the i-base station, (x,y) is the estimated position of the mobile unit. The improvement made on this method, by [9] is by using a weighting factor (ω_i) for each base station. This method is called path-gain weighted centroid (PGWC) since the weights are a function of the path gain between BS and MS. For PGWC, the MS position estimate is given as:

$$\left.\begin{aligned} x &= \frac{\sum_{i=1}^{N} \omega_i X_i}{\sum_{i=1}^{N} \omega_i} \\ y &= \frac{\sum_{i=1}^{N} \omega_i Y_i}{\sum_{i=1}^{N} \omega_i} \end{aligned}\right\} \quad \dots (2)$$

Where $\omega_i = g_i^{1/n}$, and g_i is the path gain from BSi to MS, n is taken to be (2).

The modification that is to be carried out on the above method, is to try different values of (n) and find the optimum value which gives the highest possible accuracy. Simulations in an urban area have been performed to study this situation and the results are explained in section 7.

5.2 Time Difference of Arrival (TDOA) method

The requirement for the TDOA to work is that the mobile must detect at least three pilots in a tightly synchronized network. The relative arrival times of the signals from the visible base stations are then used to form hyperboloids, the intersection of which gives us the location estimates. As in Fig.2, assume that the coordinates of the three base stations are known. Without any loss of generality, one can assume that the coordinates of the three base stations and the mobile station are as follows [15]:

BS1: (0,0) , BS2: $(0,y_2)$, BS3: (x_3,y_3) , MS: (xo, yo)

Assuming that t_1, t_2 and t_3 are the time it takes for the pilots to travel from BS1, BS2 and BS3 to the MS, respectively and c is the speed of light, then the TDOA algorithm draws two hyperboloids using;

$$c_1 = d_2 - d_1 = c.(t_2 - t_1) = \sqrt{x^2 + (y - y_2)^2} - \sqrt{x^2 + y^2} \quad \dots (3)$$

$$c_2 = d_3 - d_1 = c.(t_3 - t_1) = \sqrt{(x - x_3)^2 + (y - y_3)^2} - \sqrt{x^2 + y^2} \quad \dots (4)$$

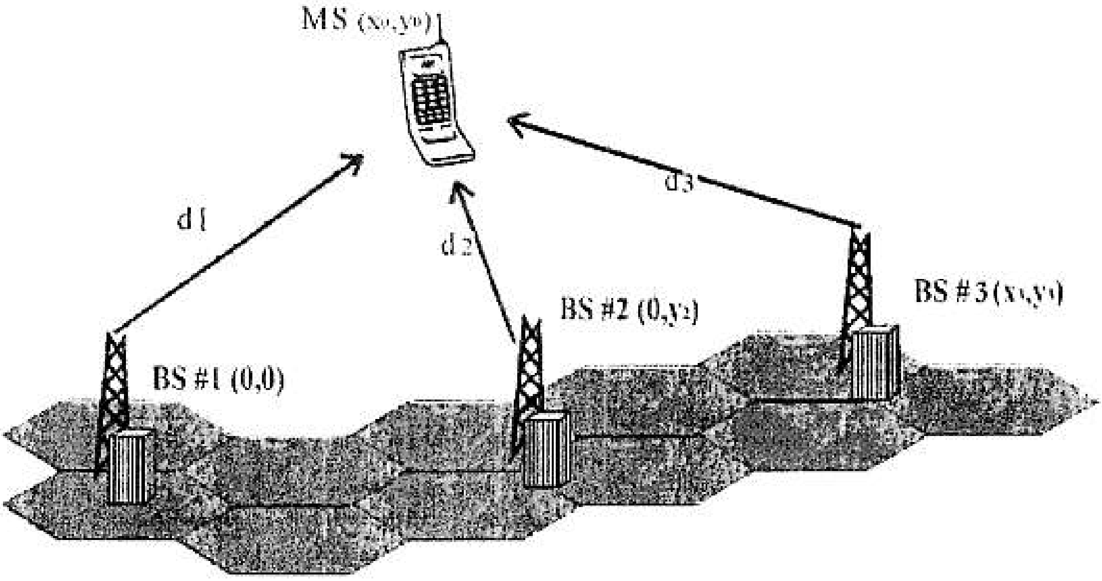

Fig. 2: Configuration of the three Base Stations (BS) and the Mobile Station (MS) to be located.

The above two equations have two unknown, x and y. Values of y_2, x_3 and y_3 are known from the base station coordinates and (t_2-t_1) as well as (t_3-t_1)is measured and thus c_1 and c_2 are known as well. The two equations in (3&4) can be solved in many different ways. They can be solved iteratively using the Steepest Descent Method, or using Talyor series expansion. In this paper, Fang's method [16] is used.

5.3 The hybrid method

To increase accuracy of position estimation even more, the hybrid estimation method (PGWC +TDOA) is used. As the PGWC method has the lowest accuracy in the border region [9], then the following algorithm is used, so that in the border region, TDOA method is applied;

(i) Calculate the path loss from the BS's to MS.

(ii)If two (or more) of the paths with lowest path loss BS's are near the border, then the MS is expected to be at or near the border, so the TDOA method is used, else the PGWC method is used.

6. Models Used In The Simulations

The urban area used in this paper is based on a Manhattan Scenario, See Fig.3. This scenario is proposed by ETSI (European Telecommunications Standards Institute) for UMTS radio transmission technology selection [17]. The block size is (200m) by (200m) and the street width is (30m) giving (230m) between street corners. The simulation area is finite (about 8 km²), i.e. no wraparound is used. This assumption permits to take effect of the border on the results and that will be the case in real systems.

For the outdoor propagation model, path loss in (dB) is given by [18]:

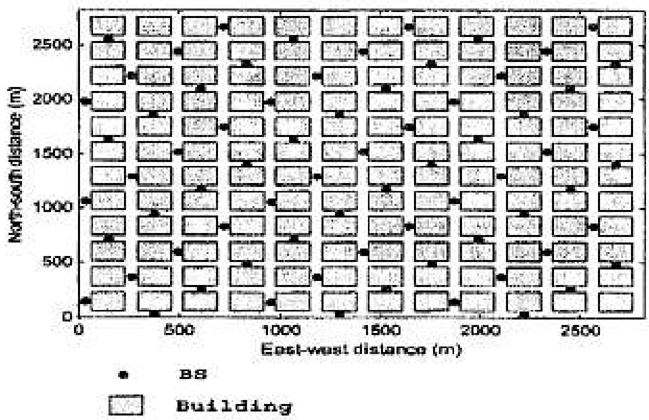

Fig. 3: A Manhattan scenario, 12 by 12 blocks with 72 base stations.

$$L_s = 20\log\left[\frac{4\pi d_m}{\lambda} \times D\left(\sum_{j=1}^{m} S_{j-1}\right)\right] \quad \dots (5)$$

Where:

$$D(x) = \begin{cases} x / x_b & if\ x > x_b \\ 1 & otherwise \end{cases} \quad \dots (6)$$

and x_b is the breakpoint distance, which is taken to be (300m). Further, dm is the illusory distance, λ is the wavelength and m is the number of straight street segments (Sj) along the shortest path between BS and MS as shown in Fig.4. Notice that x in eq.6 is the summation of segments Sj , see eq.5. The illusory distance dm can be obtained by the recursive expressions;

$$\left.\begin{aligned} K_m &= K_{m-1} + d_{m-1} \times C_m \\ d_m &= d_{m-1} + K_m \times S_{m-1} \\ K_o &= 1 \\ d_o &= 1 \end{aligned}\right\} \quad \dots (7)$$

and (C_m) is a function of the absolute value of the angle (ϕ_m) between street segments (S_m) and (S_{m-1}):

$$C_m = 0.5^{\frac{|\phi_m|}{90}}, \ (\phi_m) \text{ in deg.} \qquad \dots (8)$$

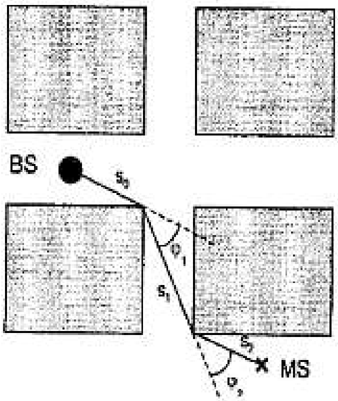

Fig.4: Propagation between BS and MS in Manhattan environment.

For the indoor users, an additional path loss equal to (10 dB) is added to take into account effect of wall penetration.

7. Discussion of the Results

In the following results and in order to take into account the real situation, it has been assumed that the path loss measurement suffers from a certain error. The error is assumed to follow a normal distribution and has a standard deviation of (10 dB). Also, the timing values, when using the hybrid method, are assumed to be accurate to within ±130ns and to have a uniform distribution [19].

Applying the PGWC method, with (n) varies in the range (1 to 4), to Manhattan model, the results shown in Fig. (5) are get. In these results, it is assumed that signals from up to six base stations can be received by the MS. Depending on the results of Fig. (5), Table (1) shows values of the position estimation error for different values of (n). It is clear that the best results are obtained at n =1 and n =1.5. The error in the position estimation is (169) m for (67%), while it is (588) m for (95%) of the total points when n =1. The error in the estimation is (144) m for (67%) and (714) m for (95%) of the total points when n =1.5.

Results of simulation using the hybrid method (PGWC + TDOA), and the PGWC method with n =1, are compared in Fig (6), while Fig (7) shows a comparison between these methods when using n =1.5. It is obvious that the hybrid method is superior to the PGWC method and meets the FCC requirements. Table (2) contains results of different methods from previous works as well as the results of this paper for a comparison. Some previous methods has been reapplied on Manhattan model so that the comparison with our results can be made. It is clear, from Table (2), that the proposed hybrid method compares favorably to existing methods.

8. Conclusions

Recently there has been much interest in the area of mobile positioning, only using information from received signals. In this paper, some of the different methods used in positioning are reviewed. The simplest positioning method, which does not need any modification on the existing systems, is the PGWC.

This paper concentrates on the use of PGWC method, a modification has been proposed on this method by trying different relations between the weight factor and the BS-MS path gain. Higher accuracy on the positioning estimation has been got, by carrying out simulations on Manhattan environment, at a certain relation between the weight factor and the path gain from the BS to the MS. The proposed modification gives even better performance and meets the FCC requirements when the hybrid method (PGWC+TDOA) is used.

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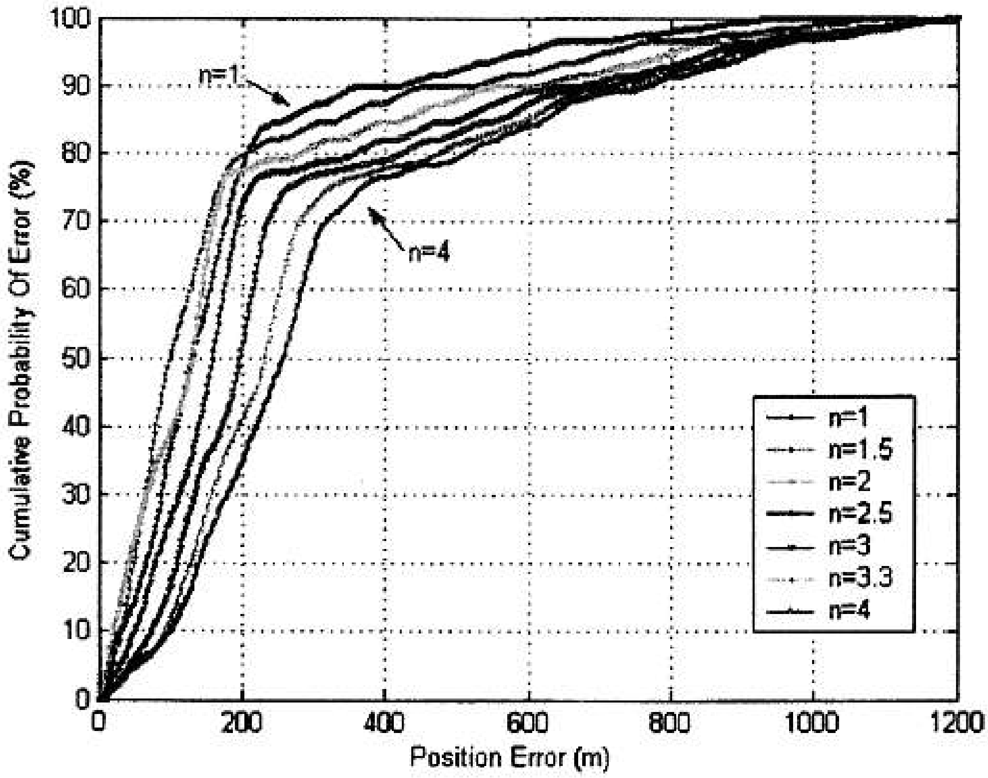

Fig. 5: Cumulative distribution of position error when using PGWC method with n varies from 1 to 4.

Table 1: Effect of the exponent (n) on accuracy of the PGWC method

Value of (n)	Position error for 67% of the points (m)	Position error for 95% of the points(m)
1	169	588
1.5	144	714
2	154	804
2.5	187	860
3	266	890
3.5	267	912
4	303	926

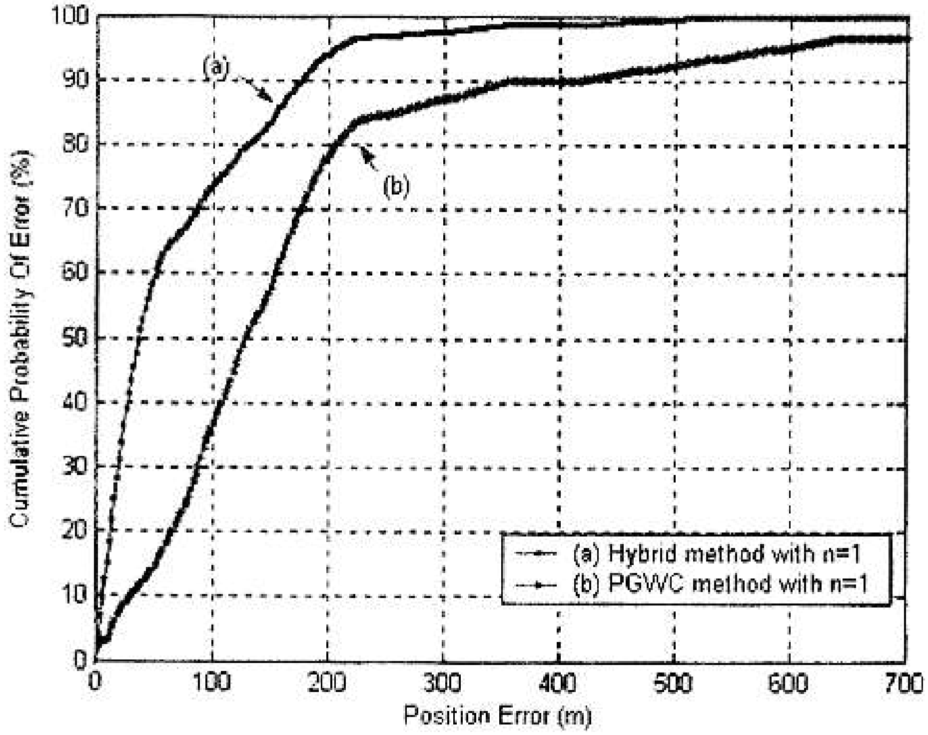

Fig. 6: Comparison between cumulative distribution of position error when using PGWC (with n =1) and the Hybrid method (PGWC + TDOA).

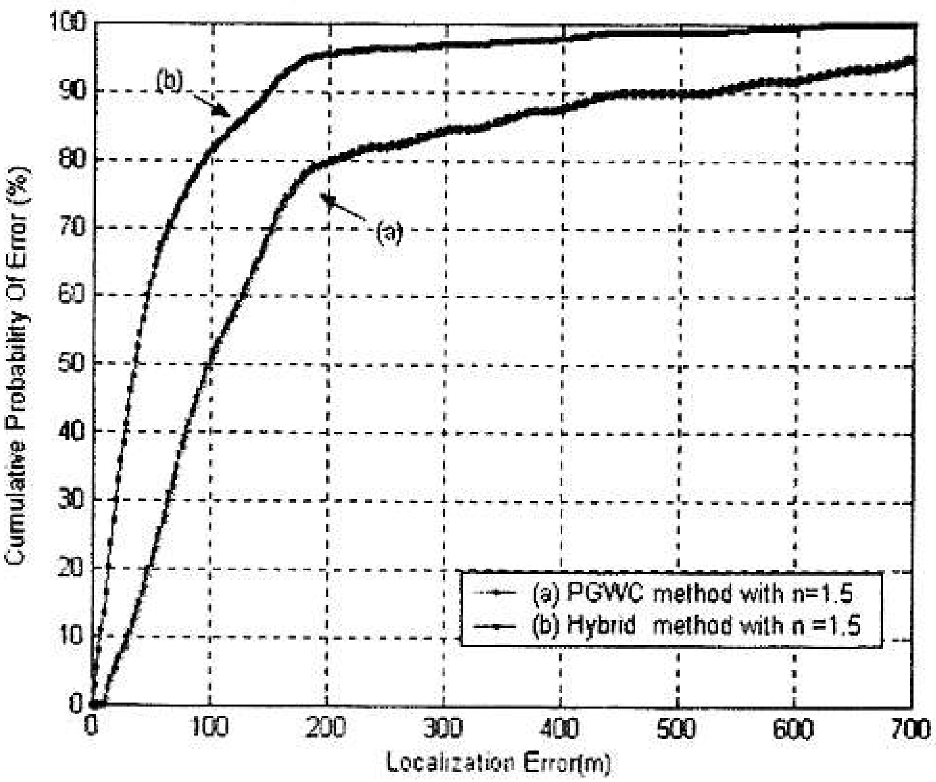

Fig. 7: Comparison between cumulative distribution of position error when using PGWC with (n=1.5) and the Hybrid method (PGWC +TDOA).

Table 2: Comparison between accuracy of proposed method and previous methods.

Method of positioning	Position error for 67% of the points (m)	Position error for 95% of the points (m)
UWC [4]	350	650
AOA [12]	<125	<300
TOA [9]	70	200
TDOA [7]	<100	<200
Enhanced [13]	65	150
PGWC [9]	165	500
PGWC+TOA[9]	98	410
PGWC(n=1)	169	588
PGWC (n=1.5)	144	714
Hybrid (n=1)	76	206
Hybrid (n=1.5)	56	184