Mobile Positioning Techniques in GSM Cellular Networks: A Comparative Performance Analysis

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Abstract: Locating the position of a mobile user with a high degree of accuracy is a research interest that holds the key to a breakthrough in many service challenges faced by operators in the wireless communication world. The benefits of a success in this field ranges from value added services and efficient advertising to crime detection and fighting. Many technologies have been developed which made use of different algorithms to provide answers to these challenges but with varying degrees of accuracy, operational challenges, varying ease of deployment and cost of installation. Mobile position estimation technologies use techniques such as Time Difference of Arrival (TDOA), Observed Time Difference of Arrival (OTD), Enhanced Observed Time Difference of Arrival (E-OTD), Angle of Arrival (AOA), Time of Arrival, Received Signal Strength (RSS) indication, GPS systems, and Cell ID. It is the focus of this paper to analyze the performance of these techniques using different performance indices and then relatively compare the results available from these indices.

Index Terms: Angle of Arrival (AOA), Enhanced Observed Time Difference of Arrival (E-OTD), Observed Time Difference of Arrival (OTD), Time Difference of Arrival (TDOA)

I. INTRODUCTION

Mobile location estimation simply talks about obtaining the location of a mobile unit or a mobile station (MS). This term is synonymous with radio location and radio navigation. MS location usually implies the coordinates of the MS that may be in two or three dimensions, and usually includes information such as the latitude and longitude of where the MS is located [1]. Such information is made possible by measuring some properties of the radio signals transmitted or received by the cellular phone.

Technologies that determine the location of a mobile station (MS) are increasingly gaining prominence in the wireless market. This is a direct result of intensified research efforts to improve the location information available in a wireless network as required by the FCC mandate.

The FCC mandate requires that a public safety answering point (PSAP) be able to locate mobile device to within 50m, for 67 percent of E-911 calls and 150m for 95 percent of the calls if a hand based geolocation technology is used and to within 100m (300m) for 67 percent (95 percent) of calls if network-based geolocation technology is employed [2].

Many companies exist today which apply various mobile location techniques to provide solutions to mobile location estimation and location-based services. The accuracies of their location estimates for a mobile station are limited by environmental factors and the degree of accuracy of the geolocation technique used, among other factors. These techniques either use the statistical or geometric algorithms to estimate the position of a mobile station to a certain degree of accuracy. In the geometric approach to location estimation the measurements are transformed into distance and angle measurements with respect to a group of reference points, such a base station. A location estimate is then derived using basic geometry.

Mobile location techniques are either based on the signal transmitted between satellites in the orbit and a mobile device on the earth, the most prominent of which is the Global Positioning System (GPS), or they are network-based in which case the signal transmitted between the cell phone and the network is used for the positioning, or handset-based in which case the handset gets all the parameters it needs from the network and uses it to determine its own position.[3] Satellite-based location systems, often called satellite navigation systems are used extensively in military and commercial applications, such as vehicle tracking, navigation, and clock synchronization. These so called network-based location systems are used in order to avoid the necessity to integrate GPS hardware or to serve as fall-back systems in locations where GPS is not available.
This paper makes a comparative and analytic study of the various techniques for mobile positioning and presents the limitations of each and the performance of each method based on some performance indices that will be used in the analysis.

II. PERFORMANCE INDICES FOR MOBILE LOCATION TECHNIQUES

The comparative analysis of the techniques will be done under the following matrices:

Reliability: simply put is the mean time between failures and the mean time to repair. Generally a uniform measurement for reliability is difficult to define due to the variations in technologies. In GPS systems, reliability is defined as a measure of how consistent a GPS horizontal error levels can be maintained below a specified reliability threshold. In mobile positioning methods, we can simply define reliability as the ratio of successful positioning attempts out of all attempts made. Systems used in personal positioning should uncompromisingly give extremely reliable performance especially in emergency cases since failure could be very detrimental. This is an important indicator of performance because a positioning device that frequently fails or gives false positions will not be seen as trustworthy by the users [4].

Latency:
Latency measure is basically the time from power-up to the instant when the first location measurement is obtained. In GPS, this is known as the time-to-first-fix (TTFF). The high demand for low or short latency is not only realized in the emergency cases but also from the LBS point of view. Example, the QoS and usability of guidance and tracking applications decreases if one cannot guarantee a real-time operation. Short latency also saves power. It is measured in seconds. Latency is further broken down into three main components by defining the call set-up delay, network delay and the processing delay. Briefly, call set-up delay is the time elapsed between call initiation at the MS and receiving the first response from the network. Network delay is defined as the time needed to transmit all messages excluding call set-up delay. Processing delay as the name implies is the time needed by the positioning device to measure and calculate the position [5].

Applicability:
Basically applicability measures the physical limitations and requirements associated with the implementation and use of certain technology in terms of technical and financial issues. The key issues affecting the applicability of mobile positioning methods are power consumption, hardware size, software size, processing load, supported positioning modes, network dependency, signal load, cost and standardization. [6].

Accuracy and Precision: Location accuracy of a geolocation method is defined to be the distance between the estimated location and the true location of the mobile station. It defines how close the location measurements are to the actual location of the mobile station being located. Accuracy is expressed in meters. A location system should report locations accurately and consistently from measurement to measurement. In evaluating the accuracy of a positioning device, one has to consider how many location measurements are made, how location measurements are scored and in what form the results are presented. There are a number of performance metrics for location accuracy in the literature. Root Mean Square Error (RMSE), Mean Squared Error (MSE), Circular Error Probability (CEP), and Cramer-Rao Lower Bound (CRLB). A widely used score function in accuracy evaluation of multiple location measurements is the square root of the mean of squared errors (RMSE), where RMSE is given by:

\[ RMSE = \sqrt{\frac{\sum d_i^2}{n}} \]

And

\[ d = \sqrt{(X_{est} - X_{true})^2 + (Y_{est} - Y_{true})^2} \]

Where \((X_{est}, Y_{est})\) is the estimated coordinates, and \((X_{true}, Y_{true})\) is the true location coordinates of the mobile station. Where \(d_i\) are distance errors and \(n\) denotes the number of location estimates. RMSE is the most applicable location accuracy performance metric in the literature. It is the most used and a simple metric.

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Margin of error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Greater than 150m</td>
</tr>
<tr>
<td>Medium</td>
<td>50 to 150m</td>
</tr>
<tr>
<td>High</td>
<td>Less than 50m</td>
</tr>
</tbody>
</table>

Cost: We can assess the cost of a location-sensing system in several ways. Time costs include factors such as the installation process's length and the system administration needs. Space costs involve the amount of installed infrastructure and the hardware's size and form factor.

Limitations: Some systems will not function in certain environments. This limitation has implications for the kind of applications we can build.

Coverage: coverage in telecommunications systems is related to the service area where, at a bare minimum, access to the wireless network is possible. For the mobile location techniques under consideration in this paper, coverage corresponds to the availability of a sufficient number of measurements to perform a location computation.
III. PERFORMANCE ANALYSIS OF TECHNIQUES

There are numerous techniques that can be considered for use in wireless position location systems. However, we will discuss only those techniques that can be practically incorporated in the GSM cellular-type systems. Such techniques can be broadly classified into two categories. Either the position location system will require a modification in the existing handsets or the system can be designed in such a way that all the modifications take place at the base stations or the switching centre with no modifications in the existing handsets.

From a physical localization point of view, all the techniques discussed in this paper will be examined and distinguished under the following principal techniques.

1. Signal strength and network parameters
2. Triangulation/Trilateration
3. Proximity
4. GSM fingerprint/database correlation method.

**Signal strength and network parameters based techniques.**

(a) The Cell ID:

This is a network-Based method of locating which uses the Cell ID of the serving base station of the MS. This technique makes no explicit attempt to resolve the position of the mobile device beyond indicating the cell with which the mobile device is (or has been) registered. When applied to 802.11 systems, this technique tracks the cell to which a mobile device associates. The Cell-ID is then converted to a geographic position using knowledge of the operator’s network, such as coverage database at the serving mobile location centre (SMLC). It has a Low cost of implementation. It is the most primitive method of locating a wireless user and does not require enhancements to be made to the network infrastructure or to the individual handset. It is, however, the least accurate of all location-identification technologies and does not meet the requirements of Phase II of the E911 Act.

Accuracy is based on coverage radius of serving cell, and therefore is much better in urban environments and ranges from 300 m to 20km. In this method, accuracy level is dependent on factors such as cell size, cell type (Omni-directional or sectored), among other factor. However, there is no way to determine whether the user is, say 15 kilometres north, east, south or west of the serving base station. In areas where towers are close together, users can be located more precisely, as the range of each tower is smaller. In rural areas, however, where there are fewer towers and the range of each tower is greater, the degree of accuracy is much less.

Its main advantage is that it supports legacy handsets and roaming subscribers. The larger the number of antenna’s providing the sector information in the sectored type, the more accurate the location of the device will be. Here the handset’s location is calculated using mathematical algorithms.

(b) Timing Advance and Round Trip Time:

Another primitive location estimation method is the Timing Advance (TA) in GSM and Round Trip Time in 3G systems. The TA is a measure of the handset range from a BTS (Base Transceiver Station), and has a resolution of 550m. It improves accuracy level in larger (Omni-directional and sectored) cells, as in GSM 900. With TA, the handset registers with at least three base stations which send out a timing signal, for which the handset sends back a result to the network for a position calculation.

The Round Trip Time (RTT) of the signal between the mobile and the serving base station can be used to get a radial distance measurement. The intersection of the circle with radius equal to half the RTT and the hyperbolic curve indicates the position of the mobile.

(c) Received Signal Strength Indication (RSSI):

Received Signal Strength (RSS) is used to calculate the distance between transmitter and receiver based on known transmitter power and transmitter location, and an appropriate path loss model. More realistic mobile communications channel model such as Okumura-Hata Model, can be used to convert the signal strength measurements into distance.

In this method, Radial distance from reference points is used to construct intersecting circles.

**Triangulation/Trilateration:**

In trigonometry and elementary geometry, triangulation is the process of finding a distance to a point by calculating the length of one side of a triangle formed by that point and two other reference points, given measurements of sides and angles of the triangle. Such trigonometric methods used for position determination can be distinguished as:
- Distance-based (tri)-lateration (example: Global Positioning System, GPS). For distance-based lateration, the position of an object is computed by measuring its distance from multiple reference points.
- Angle or direction based (tri)-angulations (example: AOA, TDOA, EOTD)

(a) GPS

Fig. 2 A GPS satellite system

One of the most straightforward solutions to meet the position location requirements is to use the GPS [7]. Its accuracy under ideal conditions, with clear open sky is on the order of tens of meters (30m-80m). This technique when applied to cellular phones may involve installing a complete or a partial GPS receiver in the handset and then transmitting the received GPS data on the reverse link to the base station for further processing and position determination. However, number of factors has made this method undesirable. The total cost of building, staffing, maintaining and monitoring a satellite used for location identification purposes is extremely expensive. The satellites currently being used have life spans of 7–15 years, making periodic replacement inevitable. Apart from increasing the size and weight of the handsets, the GPS receiver would result in additional drain for the batteries in the mobile phones. This will result in reduced talk time which would be highly undesirable. Since GPS operates in L-Band (1575MHz) [8] which is different from either of the cellular or the PCS frequencies, the mobile antenna would need redesigning. All these factors would result in increased cost for the handset. Another factor weighing against this solution is the “warm-up” time of the GPS. After being turned on, a GPS receiver takes at least one to one and a half minutes or even longer depending on the design, to start giving readings and, hence, this would be highly undesirable for an emergency 911 situation. To find the geographical location, the GPS receiver needs to have at least four satellites visible at all times, which is difficult in heavily shadowed and covered urban environments and impossible for indoor and underground calls. All of these factors make it extremely unlikely that a GPS-based solution will be used to solve the position location challenge in cellular-type systems. However, in vehicle based mobile phones, GPS is a more realistic option as it can be permanently installed in the car and may be used whenever the phone is being used from the car.

(b) Angle of Arrival (AoA):

Fig. 3 AOA technique

AOA methods are sometimes also referred to as Direction of Arrival (DOA) methods. AOA methods utilize multi-array antennas and try to estimate the direction of arrival of the signal of interest. Thus a single AOA measurement restricts the source location along a line in the estimated AOA. If at least two such AOA estimates are available from two antennas at two different locations as shown in fig 3 above, the position of the signal source can be located at the intersection of the lines of bearings from the two antennas. To estimate the AOA, algorithms are used that exploit the phase differences or other signal characteristics between closely spaced antenna elements of an antenna array and employ phase-alignment methods for beam/null steering. AOA works well in situations with direct line of sight with low likelihood of interference such as sparsely populated areas, but suffers from decreased accuracy and precision when confronted with signal reflections from surrounding objects. In dense urban areas, AOA becomes barely usable because line of sight to two or more base stations is seldom present. The accuracy of signals using AOA, however, is limited by various forms of signal interference. For example, city skyscrapers may cause the signal to bounce. If the signal bounces, it is less likely to reach the target, resulting in a weak signal or none at all.
Another factor is the considerable cost of installing antenna arrays considering that these antennas are at needed at the base station. Although adaptive antennas hold considerable promise for improving the capacity of cellular systems, they would only be needed in the areas where capacity enhancement will be required. Hence, for rural and suburban areas which are sparsely populated, this would be a costly solution to meet the E-911 requirements. Even if antenna arrays are in place at some base stations, the position location system may need regular calibration since a minute change in the physical arrangement of the array because of winds or storms, may result in considerable position location error as the absolute angular position of the array is used as a reference for the AOA estimates.

(a) Time of Arrival (TOA)

Time of arrival systems are based on the precise measurement of the arrival time of a signal transmitted from a mobile device to several receiving sensors. Because signals travel with a known velocity (approximately the speed of light \(c\) or approximately 300 meters per microsecond), the distance between the mobile device and each receiving sensor can be determined from the elapsed propagation time of the signal travelling between them. The TOA technique requires very precise knowledge of the transmission start time(s), and must ensure that all receiving sensors as well as the mobile device are accurately synchronized with a precise time source.

From the knowledge of both propagation speed and measured time, it is possible to calculate the distance \(D\) between the mobile device and the receiving station.

\[ D = c(t) \]

Where: \(D\) = distance (meters)
\(c\) = propagation speed of approx. 300 meters /microsecond
\(t\) = time in microseconds

With distance used as a radius, a circular representation of the area around the receiving sensor can be constructed for which location of mobile device is highly probable.

(b) TDOA.

It is obvious that even small errors in the click at the transmitting or the receiving end causes a major error in the distance estimate. Usually the mobile unit cannot be synchronized accurately enough to directly obtain the time used by the signal to travel between a mobile unit and a base station. One solution to get around the synchronization problem is to use differences in the time delays of multiple base stations instead of absolute times.

The Time-Difference-Of-Arrival (TDOA) is measured between multiple pairs of reference points with known locations. Each TDOA measurement yields a hyperbolic curve on which the mobile may reside. The intersection of multiple curves produces the location estimate.

If only two base stations are available, then only one hyperbolic curve is produced based on the TDOA. TDOA measurements do not require precisely synchronized clocks at the fixed location receivers \[9\]. This corresponds to the timing standards already provided at cellular base station sites, making TDOA more realistic than requiring each mobile unit to have an accurate clock.
Atomic clocks, such as a Cesium time source or a GPS receiver clock, are typically used for timing at base stations. Hence, it is concluded that the TDOA technique appears to be the most feasible option for the wireless E-911 solution.

Furthermore, this method offers many advantages over other competing techniques. Since all the processing takes place at the infrastructure level; no modifications are needed in the existing handsets. In this respect, this solution would be more cost effective than a GPS-based solution. It also does not require knowledge of the absolute time of the transmission from the handset like a modified handset TOA method needs. Since this technique does not require any special type of antennas, it is cheaper to put in place than the DOA finding methods. It can also provide some immunity against timing errors if the source of major signal reflections is near the mobile. If a major reflector affects the signal components going to all the receivers, the timing error may get cancelled or reduced in the time difference operation. Hence, TDOA methods may work accurately in some situations where there is no LOS signal component. In this respect, it is superior to the DOA method or the TOA method.

The required changes to incorporate the TDOA method are only to be in the software of the system.

(a) Enhanced Observed Time Difference of Arrival E-OTD.

Cambridge Positioning Systems, a proponent of the E-OTD system, offers a product with positioning accuracy within 50 meters. This time-based technique requires location receivers in the network infrastructure called a Location Measurement Unit (LMU), and operates using time measurements of signal travelling distances between the MS and the LMU as in the TDOA technique. Every 30 seconds, each base station broadcasts a signal in an asynchronous manner.

When signals from at least three base stations are received by the handset and LMU, the time differences of arrivals of the signal from each base station at the handset and the LMU are calculated. The differences in time stamps are combined to produce intersecting hyperbolic lines and finally the location estimate of the MS is determined by the intersection of the hyperbolas.

The LMUs help to determine the clock offsets between base stations. One LMU is needed for every 3 to 5 base stations. However, the cell towers initiate the transmission to the handset and LMU, not vice versa. The Location Measurement Units (LMUs) are essentially modified mobile devices, optionally with a GPS receiver, placed in a fixed geographical position, with the capability to perform E-OTD measurements and return them to the SMLC. E-OTD accuracy is dependent on cell density, cell plan, multi-path, interference, noise, LMU performance, and cell site position accuracy. In this technique the accuracy does not degrade much indoors, and it performs well in high base stations density areas. Conversely, E-OTD performance is degraded in areas with low base stations density. It is an Expensive solution for operators with accuracy ranging from 50m to 500m and latency around 5s.

Proximity:

In this technique, Mobile position location is determined by assigning the coordinates of a known location that is “close” to the mobile. This known location could be a Base station serving cell or the closest WiFi access point. It can also use the intersection of multiple overlapping areas to improve accuracy.

Finger printing/database correlation

This technique utilizes the distant RF patterns (multipath phase and amplitude characteristics) of the radio signals arriving at a receiver antenna from a single caller. The unique characteristics of the signal, including its multipath pattern are analyzed and a “fingerprint” is determined for a defined area. The fingerprint is then compared with a database of previously “fingerprinted” locations, and match is made. By matching the fingerprint of the caller’s signal with the database of known fingerprints, the caller’s geographical location is identified to one of the surveyed areas”. It has been shown that an accuracy of 44m is possible in GSM networks.
<table>
<thead>
<tr>
<th>Location technology</th>
<th>Observed information</th>
<th>Suitable environment</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOA</td>
<td>Propagation time of received signal</td>
<td>Urban and suburban</td>
<td>High accuracy is achievable where there is coherent detection</td>
<td>- Synchronization is required - it is expensive</td>
<td>Privacy is network controlled</td>
</tr>
<tr>
<td>TDOA</td>
<td>Time of arrival of signals emitted at the same time</td>
<td>Urban and suburban</td>
<td>-in the case where there is coherent detection, a high accuracy can be achieved -the receiver does not need the time of transmission -requires no modification to the handset. -requires no synchronization between MS and BS.</td>
<td>-It involves complex calculations. -expensive to implement</td>
<td>Privacy is network controlled</td>
</tr>
<tr>
<td>AOA</td>
<td>Angle of incidence of received signal</td>
<td>Rural areas and areas where direct LOS is available</td>
<td>-simple computation -independent of radio system -requires no synchronization with BS</td>
<td>-Offers low accuracy in large cells. -High cost of installing array antenna</td>
<td>Privacy is network controlled</td>
</tr>
<tr>
<td>RSS</td>
<td>Strength of the received signal</td>
<td>Urban and indoor</td>
<td>-involves simple calculations -low implementation cost -it is independent of radio systems -no synchronization for base Station is required -</td>
<td>Offers low accuracy in low cells</td>
<td>Privacy is user controlled.</td>
</tr>
<tr>
<td>GPS</td>
<td>Requires no change to network infrastructure,</td>
<td>Outdoors</td>
<td>-High battery usage, -lacks indoor coverage, and coverage in densely populated areas -long signal acquisition time</td>
<td>-subject to urban multipath problems -requires LMU in the network infrastructure</td>
<td>Privacy is user controlled.</td>
</tr>
<tr>
<td>E-OTD</td>
<td>Urban/suburban</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IV. CONCLUSION

A brief summary of the results of the analysis is presented in the table 4 below.

A major element is that the resolution of the location method typically depends on the size of the cells used. In and around the cities, the cell sizes tend to be small, so that the mobile station can be tracked with a reasonable accuracy. Unfortunately in a rural area where there is a small population and a low usage of the network, the type of cell to be used will be a large macro cell with a large coverage area, as there are no other cells within range to perform a handover, which gives information on neighbouring cell. Thus the location finding methods often give poor accuracies in the rural areas. A-GPS methods are obviously the best techniques for locating the mobile station, but it does suffer when there is poor radio reception, especially within buildings [10]. As has been seen, A-GPS suffers from poor coverage in urban environments and also within buildings.

Table 4: Summary of results

<table>
<thead>
<tr>
<th>Location Technology</th>
<th>Category</th>
<th>Accuracy</th>
<th>Cost</th>
<th>Latency</th>
<th>Coverage</th>
<th>Wireless standard</th>
<th>Reliability</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell ID</td>
<td>Network based</td>
<td>300m-200m</td>
<td>Low</td>
<td>Fast, &lt;5s</td>
<td>Moderate</td>
<td>GSM</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cell ID + SS</td>
<td>Network based</td>
<td>200m-11km</td>
<td>Moderate</td>
<td>Fast, &lt;5s</td>
<td>High</td>
<td>GSM</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>AOA</td>
<td>Network based</td>
<td>100m-200m, decreases with increasing distance between MS and BS</td>
<td>Moderate</td>
<td>Moderate, ≈10s</td>
<td>Good, (has multipath issues)</td>
<td>GSM</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>TOA</td>
<td>Network based</td>
<td>50m-200m</td>
<td>Low</td>
<td>Moderate, &lt;10s</td>
<td>Good, (has multipath issues)</td>
<td>GSM</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>E-OTD</td>
<td>Handset based</td>
<td>50m-125m</td>
<td>High</td>
<td>Moderate, &lt;10s</td>
<td>Good (has multipath issues)</td>
<td>GSM</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>GPS</td>
<td>Handset based</td>
<td>30m-80m</td>
<td>High</td>
<td>Slow, &lt;35s</td>
<td>Moderate in urban, high in rural/sub urban</td>
<td>All</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>RF fingerprinting</td>
<td>Network based</td>
<td>10m (indoor &amp; outdoor)</td>
<td>Moderate</td>
<td>Moderate, &lt;10s</td>
<td>Good</td>
<td>Multiple</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
References

   www.cwins.wpi.edu/publications/pown/chapter_14.pdf


