Mobile Positioning Technologies in Cellular Networks: An Evaluation of their Performance Metrics

Isaac K Adusei, K. Kyamakya, Klaus Jobmann

University of Hannover
Institute of Communications Engineering
Hannover – Germany.

Abstract

Effective evaluation of positioning methods in order to give fair results when comparing different positioning technologies, requires performance measurements applicable to all the positioning technologies for mobile positioning. In this paper, we outline and compare five major performance measures namely, accuracy, reliability, availability, latency, and applicability, and how they apply to positioning technologies.

Keywords: *Accuracy, Reliability, Availability, Latency, Applicability, Positioning Technology, Positioning Methods, Cellular Networks, and Performance Measure.*

1.0 Introduction

Mobile positioning has become a newsworthy technology simply because of its commercial potential. Looming commercial possibilities in Location-Based Services (LBS) and governmental regulations like E911 and E112 where mobile positioning is applied are the key reasons for the tremendous research interest in personal positioning technologies in cellular networks.
Another motivating factor is the benefits like home zone calls, traffic locating and network planning as well as assistance in handover that the network operators would get from this technology.

There are various means of mobile positioning, which can widely be divided into two major categories - network based and handset based positioning methods.

It is essential to note the word mobile positioning since the terms mobile positioning and mobile location are sometimes used interchangeably in conversation, but they are really two different things. Mobile positioning refers to determining the position of the mobile device. Mobile location refers to the location estimate derived from the mobile positioning operation.

1.1 Network-based Mobile Positioning Technology:

This category is referred to as "network based" because the mobile network, in conjunction with network-based position determination equipment is used to position the mobile device. They are basically the Multilateral (multiple BSs measuring simultaneously), unilateral (MS measures multiple BSs) and examples are the Angle of Arrival (AOA) and Time of Arrival (TOA) / Time Difference of Arrival (TDOA) approaches. The Bilateral (only one MS or BS) methods is typical of Cell ID, Cell ID + Round Trip Delay (RTD), and Location Fingerprinting (LF). It is worth noting here that, in GSM RTD is called Timing Advance (TA) and in 3G systems it is called Round Trip Time (RTT) [2].

Also LF, which is not quite known, is briefly explained by [2, 3] as: “the LF 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 know fingerprints, the caller’s geographical location is identified to one of the surveyed areas”

1.2 Handset-based Mobile Positioning Technology:

This category is referred to as "handset based" because the handset itself is the primary means of positioning the user, although the network can be used to provide assistance in acquiring the mobile device and/or making position estimate determinations based on measurement data and handset based position determination algorithms.

Here the MS has an active part in position measurement (unilateral), but position calculation is in the network end. In GSM this unilateral method is called Enhanced Observed Time Difference (EOTD), in the US CDMA, it is referred to as Advanced Forward Link Trilateration (AFLT), and in the upcoming 3G systems, this same approach is called Idle Period Downlink-Observed Time Difference of Arrival (IPDL-OTDOA). To implement a full handset-based approach has been quite unsuccessful due the small memory size of the LCS client (lesser memory implies more delay) and the little lifetime of the battery.

Category 1 / Category 2	Handset-Based	Network-Based	
	MS-Based Network assisted	MS-Assisted Network Based	Pure Network Based
Multilateral	None	None	AoA ToA or TDoA
Unilateral	EOTD, AFLT, IPDL-OTDOA, Rx-Level	EOTD, AFLT, IPDL-OTDOA, Rx-Level	Rx-Level
Bilateral	Cell Coverage, CI+RTD	None	LF, cell coverage, CI+RTD

Table 1: *Classification of Cellular Network Positioning Methods.*

It should be noted here that some methods could belong to both categories depending on the implementation approach. Example the EOTD where the receiver makes the TDOA measurements and either sends them back to the network for position calculation (MS-assisted) or calculates the position itself (MS-based).

2.0 The Performance Measures

This is basically a benchmark or a yardstick to impartially evaluate a positioning method with respect to other existing ones. In this section, we would define and consider in detail each of the criteria for evaluating and comparing of these positioning technologies and methods mentioned above.

2.1 Accuracy

Accuracy of a geolocation technology is a measure that defines how close the location measurements are to the actual location of the mobile station being located [3]. Basically, the closer the measured location is to the true location the more accurate the measurement is. According to [2], 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. A widely used score function in accuracy evaluation of multiple location measurements is the square root of the mean of squared errors (RMSE) [4], where RMSE is given by:

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left[x_{mesured}(k) - x_{true}\right]^2}$$

Where N the number of measurements in the set and k is the index of the measurement. The set may contain either all the attempted location measurements or only the successful ones, and in each case, the kind of set used in the accuracy evaluation should always be mentioned. If only the successful location are used, the ratio of successful location measurements out of all attempted location measurements can be reported separately (the ratio is called reliability and is consider in the next section).

The value of the score function used is evaluated for two main dimensions namely the three-dimensional accuracy or two-dimensional accuracy. The two-dimensional accuracy (where altitude is ignored) is mainly used in mobile positioning. It is generally referred to a horizontal accuracy stated as 2drms if RMSE score is used. A one-dimensional accuracy is either a vertical measuring deviation in altitude or a radial accuracy, which is a measuring deviation in distance from the true location to the measured location.

Another common way to represent accuracy is based on classical probability calculus [2]. Here, the probability of multiple location measurements being inside a certain radius or sphere is reported to illustrate a vague distribution of the location measurements. Since in general cases, there is no knowledge of the statistical properties of the location measurements, we simply use Circular Error Probability (CERP) for 2-dimensional cases and Spherical Error Probability (SERP) for 3-dimensional cases. CERP is the most widely used unit. Example, *95% CERP within 50 meters* means that 95% of the location measurements are within 50m from the true location. Error probability can also be used to set limits for maximum inaccuracy allowed. Example is the FCC requirements concerning emergency calls within positioning accuracy of 67% and 95% CERPs [5], table below.

Method	67% CERP [m]	95% CERP [m]	Notes
Handset-based	50	150	e.g. GPS
Network-based	100	300	e.g. TOA, no positioning capability in the handset,
Network Software Solution (NSS)[1]	1000[2]	none	[1)] e.g. CI + TA, [2)] radial accuracy
EOTD[1] EOTD[2]	100 50	300 150	[1)] by October 2001. [2)] on and after October 1, 2003.

Table 2: *The FCC-E911 Requirements on Accuracy.*

Generally accuracy levels for location aware applications may be classified as follows:

Accuracy Level	Margin of Error
Low	Greater than 150m
Medium	50 to 150m
High	Less than 50m

Table 3: *Accuracy levels in Location-Based Services.*

2.2 Reliability

Generally a uniform measurement for reliability is difficult to define due to the variations in technologies. In GPS systems, reliability according to [4] 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 defined by [3], which states that: Reliability is 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. From the usability point of view, positioning devices that frequently fail or give false positions will not be trustworthy. Therefore, along with accuracy, it is equally important to know how reliable a technology is.
Here also, reliability levels for various location aware applications can be categorized as in table 2 above.

2.3 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. In [3], 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.

2.4 Availability

In most literatures availability can more be seen as a user-specific than system-related attribute. But availability as a performance measure in mobile positioning technologies should be considered more of a system-related characteristic than a user-specific attribute because of the two points given below. Ref. [4] defines availability to include the concept of coverage and capacity, the later is also mentioned in [3]. Actually, availability has to be a measure of its own since it measures very different aspects of positioning than accuracy and reliability [2]. An example to illustrate this is:

1. If a handset equipped with a standalone GPS is taken deep underground, GPS signals cannot penetrate thick walls and thus the signals become blocked. Naturally, GPS-based positioning cannot be carried at this point. Here, the fact that signals are blocked does not imply that GPS is not good in terms of accuracy and reliability, but it simply implies that GPS signals are not available for use in the underground.

2. Consider a cellular network-based methods, good positioning availability is due to careful network planning than a consequence of random phenomena affecting location measuring devices and signal propagation paths. If base stations or in this case measurements sites are effectively deployed, availability can be extremely good locally.

This makes it difficult to formalize a general measurement for availability. In cellular network-based methods, factors like channel capacity, cell coverage, base station geometry, and signal propagation environment affect positioning availability. Whereas for standalone GPS-based positioning, network channel capacity and network coverage are not issues.

From published tests, reports and simulations, the limitations of methods in terms of coverage, geometry and signal environment were studied [2], and using these materials, availability can therefore be evaluated in terms of verbal granularity instead of numerical figures of merit.

Table 3 gives how availability could be characterized.

Class	Examples
Remote	Open sea, desert, polar regions, and no cell coverage areas.
Rural	Countryside, residential houses, highways.
Suburban	Residential houses (brick or wooden), bungalows, parks, malls, shopping plazas, dense foliage.
Urban	High buildings and constructions, urban canyons
Indoor	Metal roofed, wooden or concrete walls, office buildings.
Underground	Concrete element constructions, parking garages.

Table 4: *Availability Classifications.*

2.5 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 [2]. 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]. Briefly, I will outline this sub-topic.

1. *Power Consumption*: This becomes a limiting factor if a positioning method is using resources inside a handset solely for the need of positioning or if dedicated hardware has to run to perform measurements or position calculations. Here, estimates on power consumption can be made on the basis of data sheet and specifications.

2. *Hardware Size*: If additional hardware components are needed to enable positioning, the physical size required to house and/or integrate these components inside a handset become a critical issue. Although there are increasing number of new and multimedia applications on handheld devices but user still expect the sizes of their devices to become smaller [7], so increased size of handheld devices because of positioning capability will not go well with users.

3. *Software Size*: Some positioning methods require additional software to perform measurements and/or position calculations or to support positioning. If additional software is required, practical limitations might be encountered concerning the size of the software due to a limited memory or other resources available.

4. *Processing Load*: This is closely related to the previous factor. For real-time applications, the availability of sufficient processing power is imperative, but the need for extra processor becomes a problem in this ever-reducing size of handheld devices.

5. *Supported Positioning Modes*: Location measurements can be a point-solution or a continuous or filtered solution. In point-solution just one set of measurement is needed to do the job, example during emergence calls. On the contrary, in filtered solution, such as navigation or guidance application requires continuous positioning. Supported modes therefore have a great impact on applicability, that is, depending on the positioning technology, one or both modes is supported.

6. *Network Dependent and Signaling Load*: If a positioning method is solely dependent on a network for measurements assistance and position determination, its general usability in applications favoring autonomous positioning is reduced.
Signal Load rather becomes a limiting factor if a positioning method requires intensive two-way communication between a network element and the mobile station or a large amount of assistance data with very short notice. Hence the average and maximum expected signaling load should be estimated if the positioning method is dependent on the network.

7. *Cost*: Despite good merits in performance, a position method may be inapplicable if its deployment and operational cost are very high compared with some other methods, although it might not have the same level of performance and technology. With respect to cell phones, handset cost is minimized if a positioning method is directly applicable to all phones including legacy phone (phones in use).

8. *Standardization*: Finally, common standard is a vital issue in applicability. It has an important role in development and deployment of positioning technologies. Standardized interface to enable roaming and interoperability between terminal and networks from different vendors is underway. This co-operation initiated by Nokia, Ericsson and Motorola (Location Interoperability Forum - LIF) is under seeing to this.

As seen from the above eight sub topics, it is difficult to find a general measurement for applicability. However, applications and chosen positioning technologies greatly dictate what is expected and required from the network and handset. We can again classify applicability as been low, medium or high.

2.6 Comparison of the Positioning Methods

A summary of the various methods with their accuracy and availability measures are summarized in the figure below. The figure gives a comparison of most of the positioning methods I mentioned in the introduction.

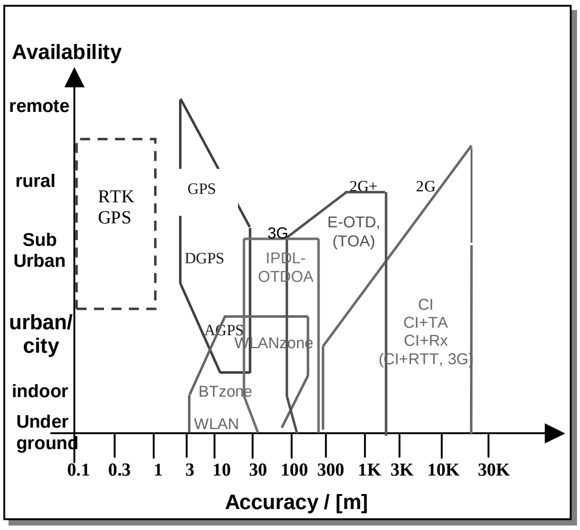

Figure 1: *Comparison of the various Positioning Techniques*

From the figure 1, we consider a positioning method like E-OTD used in second generation (2G+) mobile phone. When ones availability is underground, the best accuracy is a little above 100m and in the worse case, above 2km but far less than 3km. The accuracy improves steadily to below 100m when you move from the underground to indoors. The accuracy will not have any significant improvement than this value when you move from indoors to urban and suburban area, but it rather deteriorates when you approach rural areas.

Positioning Method	Reliability	Latency	Applicability
GPS			
Standalone	high	< 35s	high
AGPS	medium	1-10s (outdoors)	medium
Cellular Networks			
AOA	medium	~10s	low
RSSI	high	< 5s	high
LF	low	< 10s	low
CI+TA	high	< 5s	high
TOA/TDOA	medium	< 10s	low
EOTD or OTDOA-IPDL	medium	< 10s	medium

Table 5: *comparison of positioning method in terms of reliability, latency, and applicability [2].*

It deteriorates from around the 100m range to somewhere around the 500m range and the worse case still stays between the 2 to 3km range. It can also be seen that AGPS has the widest availability, except in some indoor and underground areas. In terms of accuracy, AGPS is superior compared with the other [2].

For the other measurements, the table below from ref. [2] rates the positioning methods in terms of their reliability, latency and applicability.

3. 0 Conclusion

Various positioning methods have been mentioned and in order to evaluate these methods, we mainly outlined the five major measurements of performance applicable to all of them. With these measures it would be possible to produce impartial results for comparison purposes. It was also seen that despite the viability of these measures, hardly would one be suitable for all the positioning technologies.

However there are combinations and hybrid solutions to these methods to improve their performeance measures. The hybrid methods are aimed at complementing the downside of one method with the other method to provide better performance measures. Further work is ongoing but below are a list of some forseeable secenarios.

1. *Cellular – Cellular Combination*: while with AOA + TOA, there will only be the need for one BS to reduce signaling load, EOTD + Cell ID+RTT, will greatly improve availability.

2. *GPS – Cellular:* (WA)GPS + EOTD (+ Cell ID+RTT) will have good overall availability and good outdoor accuracy. In addition, the same network elements can be used to assist both technologies.

3. *GPS-Inertial Sensors*: key example is the well talked about Enhanced GPS (EGPS), with accuracy of within 1 and 30m in urban and suburban areas.

4. *GPS-Cellular- Inertial Sensors*: A very high complexity, but superior availability and good accuracy could be wireless assisted GPS + EOTD + low-cost low-power inertia navigation system (INS).

4.0 References

[1] ETSI GSM TS 101 723 v7.2.0 (2000-02), “Digital Cellular Telecommunications System (phase 2+); Location Services (LCS); Service Description, stage, (GSM 02.71 version 7.2.0 Release 1998)”

[2] J. Syrjärinne, “Studies of Modern Techniques for Personal Positioning” Doctor of Technology thesis work, Tampere University of Technology, March 2001.

[3] CDG 2000, “CDG Test Plan Document for Location Determination Technologies Evaluation (Baseline version)”, 2000

[4] GPS 1995, “GPS Standard Positioning Service Signal Specification”, 2nd Edition, June 1995.

[5] E. D. Kaplan, Understanding GPS: Principles and Applications”, Artech House Inc. 1996.

[6] L. Lopes, E. Viller, B. Ludden, “GSM standards activity on location”, IEE Colloquium on novel methods of location and tracking of cellular mobiles and their systems Applications. 1999.

[7] I. K. Adusei, A. I. Mitzeva, N. Saeed, ”User Interaction Paradigms on Portable Devices.”, Intelligent Multimedia 9th semester project work, Aalborg University – Denmark, 2001.