Uplink Measurements Based Positioning of Mobiles in GSM Cellular Networks

Salem Balamash and Ivica Kostanic  
sbalamas@my.fit.edu, kostanic@fit.edu  
Florida Institute of Technology  
150 West University Boulevard, Melbourne, Fl 32901

ABSTRACT
In this paper a simple and inexpensive mobile locating method in a cellular network is proposed. The approach combines the Base Station (BS) information as well as parameters resulting from the uplink Mobile Assisted Handoff (MAHO) measurements to estimate the Mobile Station (MS) location. The approach is evaluated in two different scenarios. The first scenario is implemented completely within the Matlab simulation environment. The second scenario involves a comparison of the basic approach, against measured data collected on a live Global System for Mobile Communications (GSM). For each presented scenario, the accuracy of the location algorithm is determined and some avenues for its improvement are identified.

Keywords: Mobile Location, Cellular Systems, and Mobile Assisted Handoff.

1. INTRODUCTION

The explosive growth of mobile subscribers and full user mobility introduces the need for mobile locating technology. The mobile locating technology is capable of determining the geographical location (i.e. latitude and longitude) for any mobile subscriber connected to the network. There are a number of applications enabled by the mobile locating technology. Some of them are described as follows.

Location of emergency calls. The most important motivations for mobile locating technology are safety and emergency services. In the US, as of 1996, the Federal Communications Commission (FCC) mandates that the mobile phone operators be able to geo-locate mobile subscribers. The FCC's mandate requires that all wireless operators locate an emergency E-911 (Enhanced-911) caller within prescribed accuracy and within a given time. The accuracy requirements are provided in Table 1 [1]

<table>
<thead>
<tr>
<th>Solution</th>
<th>Accuracy (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network based</td>
<td>100</td>
</tr>
<tr>
<td>Handset based</td>
<td>50</td>
</tr>
</tbody>
</table>

Value-added services. Mobile locating technology can create many new services which are known as Location Based Services (LBS). LBS may be used to provide the mobile users with location-relevant information. Other possible services include monitoring important fleets, expensive cargos, and position dependent billing. It is expected that in the near future LBS will be benefiting both network operators and mobile users [2].

Network maintenance. Keeping the wireless network in a good working state and meeting the subscribers’ expectations requires network operators to collect information about the network performance. Mobile locating technology provides an inexpensive alternative to other data collection methods. At present, several methods have been proposed and standardized for MS location in the cellular environment [3] and [4]. The methods differ in the underlying location algorithm, achievable accuracy, implementation requirements, and costs associated with the deployment. For example, deploying the Angle of Arrival (AoA) method in the existing network (like GSM) requires adding a special antenna array at each BS which needs to be calibrated from time to time, whereas no modifications are required at the MS. On the other hand, deploying a basic method like CID (Cell Identity Method) requires no modification on either side. Figure 1 represents three different MS locating methods. The methods range from the simple ones like CID and CID+TA to more advanced approaches, such as AoA and Assisted Global Positioning System (A-GPS).
Mobile Assisted Handoff (MAHO)
Handoff is one of the most significant functions in the cellular communication systems. The most obvious cause for handoff is to maintain continuous communication as the mobile device traverses from the coverage area of one cell to the coverage area of the surrounding cells. There are three strategies for handoff decision: They are Mobile Controlled Handoff (MCHO), Network Control Handoff (NCHO), and Mobile Assisted Handoff (MAHO) [5]. MAHO methodology is used in all modern digital cellular systems, like GSM, cdma2000, UMTS, and LTE. In this handoff approach the MS assists the network decision making process by reporting some form of Received Signal Level (RSL) measurements of the neighboring sites. Based on these measurements, the network makes decisions on how to execute the handoff. Even though MAHO exists in all cellular technologies, the focus of this paper is on GSM. For other cellular systems, equivalent approaches may be used.

Uplink measurements in locating mobiles
In the GSM, the MS listens periodically to control channels called Broadcast Control Channels (BCCH) and selects the strongest one as its server. Once the serving BCCH is selected, the mobile reads its configuration data and a list of radio frequency channel numbers (ARFCN) that are allocated to the BCCHs of neighbors for the serving site. From that point, the MS periodically measures the signal strength and the quality of the serving BS, and the RSL of the six strongest neighboring candidates. The MS forwards these measurements to the network and they are used for radio resource management. The measurement reports contain several types of measurements, such as Cell ID (CID), signal strengths, and Timing Advance (TA). All of this information is location specific and therefore may be used for location purposes.

3. THE METHOD

As a part of the regular call processing, a GSM mobile reports signal strength information of the serving cell along with several neighboring cells. The proposed approach is to estimate the location of the mobiles on the basis of the uplink MAHO measurements. The approach is illustrated with the help of Figure 2. Consider the MS located in the position (latitude, longitude) as shown in Figure 2. The mobile is served by the cell that has the cell ID of 25121. As a part of the MAHO measurements, the mobile reports back to the system the signal strength of the serving cell, and its neighbors. From the mobile signal strength reports and using some type of prediction model, the system may estimate the distance between the mobile and serving cell, as well as the distance between the mobile and neighboring cells. The estimates of these distances are inputs in the triangulation process which provide the final estimate of the mobile location.

Figure 2. Geographical area of the system used for testing the location algorithm

Sources of errors
All wireless positioning technologies suffer from a number of factors that introduce errors. Even though the approach presented here is quite simple, it needs to overcome several obstacles that could be sources of errors. The sources are listed as follows.

Unfavorable cell site layout - The proposed approach assumes that once the distances between the mobile station and surrounding cells are known, a triangulation method may be used to locate the mobile. In most cases this would be true; however, there are certain cases when the geometrical layout of the cells does not favor triangulation. For example, if the mobile is on the highway between population centers, the cells are placed along the "highway line" and triangulation becomes more difficult.

Multipath Propagation - The proposed approach relies on the macroscopic models for path loss estimation. These models assume direct (i.e. shortest distance) propagation between the transmitter and the receiver. Therefore, the direct component dominates the other components, which are produced by reflection and diffraction. In many RF environments, the existence of multipath propagation is very common. As a result, it may happen that the direct path is obstructed and that most of the signal reaches the mobile through the multi-path rays. In such cases, the distance estimation may become erroneous.

Inaccuracies in propagation modeling - In current engineering practice, various empirical propagation models are used to predict the path loss. Some examples of the most common models are Hata, Okumura, Two-ray, etc. However, even the most advanced propagation models exhibit limited prediction accuracy. This accuracy is usually characterized by the standard deviation of the measured versus prediction error. A typical value for this standard deviation may be as high as 8dBi.

Cell site database – The triangulation method requires that the database of the cell site information is up to date and reflects
the true values of the network’s parameters, such as BSs’ coordinates (latitude and longitude), transmitted power, and azimuth center. This source of error is one which can be managed through periodical audits of the database and its regular updates.

4. ANALYSIS OF THE RESULTS

This section discusses the achieved results. To evaluate the accuracy of the proposed method, two different scenarios are investigated. The first scenario is implemented completely within the Matlab simulation environment. The second scenario involves the comparison of the basic approach against measured data collected on a live cellular network of a major US provider.

Scenario 1: Matlab simulations

A Matlab based simulation environment has been developed. The environment simulates the proposed approach on a simple system consisting of randomly placed cellular sites. The assumptions of the simulations are listed as follows.

- Network covers an area of 8 by 8 kilometers.
- The network consists of six randomly placed omnidirectional base stations. Each base station has the Effective Radiated Power (ERP) of 50dBm.
- The propagation follows log normal path loss model with a slope of 38.4 dB/decade and one Kilometer reference path loss of 107 dB [6]. These are nominal parameter values for suburban propagation environment at 850MHz.
- The standard deviation of the log normal shadowing varies between 1 and 12 dB.
- The network implements the GSM standard.

The simulation process is conducted using the Monte-Carlo approach in the following manner. The proposed area is divided into small sub-areas (called bins) of size 50m × 50m. Each bin is defined by its x and y coordinates.

1. The received signal strength (or predicted signal strength) for each bin is calculated using the log distance propagation model as

\[
RSLP[dBm] = RSLP(d_x) - 10 \log_{10}(d) \quad (1)
\]

Where \( RSLP(d_x) \) equals -57dBm, \( m \) equals 38.4dB/decade and \( d \) is the distance between receiver and transmitter expressed in km.

2. Random mobile locations are generated; 2300 mobile locations for different values of log normal shadowing.

3. Measured RSL (RSLM) for each mobile location is simulated by taking into account the variation of received power at a certain distance due to the propagation environment (better known as shadowing component), \( X_σ \) [dB] [7]. \( X_σ \) is a random variable that has Gaussian distribution with zero mean and standard deviation \( \sigma \). Taking \( X_σ \) into account, the measured RSL at the mobile location is estimated as

\[
RSLM[dBm] = RSLP(d_x) - 10 \log_{10}(d) + X_σ \quad (2)
\]

4. A vector of differences between RSLM and RSLP for all sites is formed at each of the bins. That is

\[
E = [RSLM_1 - RSLP_1, \cdots, RSLM_n - RSLP_n] \quad (3)
\]

5. The bin with the smallest value of \( |E| \) is assumed to be the one where the mobile is located.

6. Steps 2-5 are repeated for each of the different mobile locations and \( \sigma \) values.

To enhance the accuracy of the prediction, it is assumed that along with the values of the measured RSL, the mobile reports the time advancement information. In this case, the simulation algorithm is described as follows.

1. The proposed area is divided into 50 meter bins. Each bin is defined by its x and y coordinates.
2. The received signal strength for each bin is calculated using Eq. (1).
3. Random mobile locations are generated; 2300 mobile locations for each different environment.
4. For each of the mobile locations, the serving cell site is determined on the basis of the signal strength.
5. TA value for each MS location and each bin is calculated as

\[
TA = d / 0.55
\]

Where, \( d \) is the distance between receiver and transmitter (e.g. receiver is mobile station and transmitter is the serving base station).

6. All the bins where the TA is different from the one reported by the mobile are eliminated.

7. A vector of differences between RSLM and RSLP for all sites is formed at each of the bins with the proper TA value. That is

\[
E = [RSLM_1 - RSLP_1, \cdots, RSLM_n - RSLP_n] \quad (5)
\]

8. The bin with the smallest value of \( |E| \) is assumed to be the one where the mobile is located.

9. Steps 3-8 are repeated for each of the different mobile locations and \( \sigma \) values.

The results obtained from the two simulation approaches are presented in Table 2 and Figure 3. As seen, use of time advancement information (TA) improves the location accuracy. Furthermore, one readily notices that these improvements become more significant as the uncertainties in the propagation environment become larger (i.e. the \( \sigma \) becomes larger). Table 2 reports the accuracy values for 67% and 95%. This allows direct comparison with the FCC accuracy requirements.
Table 2. The first scenario accuracy results

<table>
<thead>
<tr>
<th>St. Dev. (dB)</th>
<th>Percentage [m]</th>
<th>RSLP</th>
<th>RSLP+TA</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ =1</td>
<td>67%</td>
<td>164</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>360</td>
<td>352</td>
</tr>
<tr>
<td>σ =3</td>
<td>67%</td>
<td>468</td>
<td>425</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>1051</td>
<td>981</td>
</tr>
<tr>
<td>σ =6</td>
<td>67%</td>
<td>927</td>
<td>772</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>2354</td>
<td>2109</td>
</tr>
<tr>
<td>σ =8</td>
<td>67%</td>
<td>1244</td>
<td>965</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>3224</td>
<td>2596</td>
</tr>
<tr>
<td>σ =10</td>
<td>67%</td>
<td>1633</td>
<td>1240</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>4389</td>
<td>3353</td>
</tr>
<tr>
<td>σ =12</td>
<td>67%</td>
<td>1875</td>
<td>1420</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>5369</td>
<td>3888</td>
</tr>
</tbody>
</table>

Figure 3. Accuracy results obtained from Matlab simulation

One sees that using the proposed approach in an “out of the box” manner falls short of satisfying the FCC requirements. However, there are many avenues for improvements that may be used to improve the accuracy to a level that would be acceptable for commercial use.

Scenario 2: Real network measurements

To further investigate the performance of the proposed algorithm, a series of tests on a live cellular network are performed. The network is a GSM network of a major cellular provider in the US. The network is located in Palm Bay, Florida. The layout of the network along with the test route used for data collection is presented in Figure 4. The evaluation process is conducted as follows.

1. Using drive test equipment, the measurements are performed along the test route indicated in Figure 4. The drive test data are collected with SAGEM mobile test phone. The phone provides measurements of the signal strength from the surrounding sites along with the GPS coordinates where the measurements are taken.

2. The measurements taken by the phone are used to determine the location of the mobile. Since the same measurements are reported by the phone to the network, this process simulates the process of the real-time location of the mobile by the network itself. For estimation of the distance between the phone and the cell sites, two cases are considered. In the first case the nominal propagation model is used, while in the second case the algorithm uses the optimized propagation model.

3. For each propagation model, two cases are considered. In the first case, the cells are assumed omnidirectional, while in the second case the sectorization information and TA measurements are used as well.

The results of the analyses are presented in Table 3 and Figure 5. From Table 3 and Figure 5, it is evident that the error remains relatively large in comparison with the FCC requirements. However, one notes that there are several very important issues that are not considered. The propagation model used for the RSL prediction seems to be inadequate for the task at hand. The use of nominal values of the propagation model parameters results in large location errors. Even the least amount of optimization put into the propagation model produced large accuracy improvements (c.f. Table 3). Therefore, one of the most important avenues that need to be pursued is the improvement of the propagation modeling. Such improvement would include modeling of the antenna patterns, surrounding clutter, cell site tower height, and other factors that affect propagation. Additionally, one notes that all of the predictions of the mobile location are performed in a “single shot,” without any attempt to perform spatial averaging and filtering. Use for spatial filtering has been reported to improve the accuracy of predictions and further research should take this into account [8].
Table 3. The second scenario accuracy results

<table>
<thead>
<tr>
<th>Method</th>
<th>67%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CID + TA (Omni-directional)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal propagation model</td>
<td>2903</td>
<td>4565</td>
</tr>
<tr>
<td>Optimized propagation model</td>
<td>1650</td>
<td>3803</td>
</tr>
<tr>
<td>CID + TA (Directed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal propagation model</td>
<td>1597</td>
<td>3452</td>
</tr>
<tr>
<td>Optimized propagation model</td>
<td>1133</td>
<td>2471</td>
</tr>
</tbody>
</table>

Figure 5. Comparison between nominal and optimized propagation model

5. OBSERVATIONS AND CONCLUSION

This paper presents a MAHO based approach for estimation of the MS location coordinates. The approach is cost effective and easy to implement. It is software based and it does not require any changes to the existing network infrastructure or to the MS. However, it is observed that the method does not meet FCC’s mandate from the accuracy standpoint. The principle reason for location estimation inaccuracies is found in propagation modeling errors. In this study, even small effort in improving the propagation modeling resulted in significant location accuracy improvements. Therefore, the approach becomes viable only in cases when accurate propagation models are available. Additionally, as presented in this paper, the location estimation is based on the instantaneous set of MAHO measurements. It is expected that further location accuracy improvements may be achieved through the use of some form of spatial averaging or filtering.

REFERENCES