Combination of GSM and GPS signals for Mobile Positioning and Location Service Using Kalman Filter

S. Hamani, M. Oussalah, P. Hall

University of Birmingham, Electronics, Electrical and Computer Engineering
Edgbaston, Birmingham B15 2TT

Abstract— **Location based services are becoming an emerging market due to technological advances achieved both at GSM phone operators and the multimedia nature of the mobile handsets. In this paper, a new methodology of mobile positioning integrating both GSM network using signal strengths and GPS readings in the light of an assisted GPS based approach. The methodology employs an extended Kalman filter approach in which the stochastic errors related to various measurements are appropriately characterized and modeled. The methodology uses Netmonitor software to retrieve network information including signal strength and cell-identities of various base transmitter stations (BTS). The distance from the mobile station (MS) to each BTS is therefore determined using Hata-Okumura radio propagation model. The different distances and the GPS readings are therefore combined in the framework of extended static Kalman filter. Once positioning is achieved, a .NET like application is implemented to access the Microsoft MapPoint Web Service, via the Internet (http protocol), which visualises the mobile's location on a map, finds nearby points of interest (POI) and computes routes between them. In order to demonstrate the feasibility of the proposal, experiment is carried out in Birmingham area and compared to the result yielded by the commercial software of MobileLocate Ltd. An accuracy of less than 70 meters has been achieved, which shows substantial improvement over standard Timing Advance related techniques and the commercial software.**

Index Terms— mobile positioning, Kalman filter, Netmonitor, MapPoint server.

I. INTRODUCTION

Since the emergence of mobile computing applications, the development of location based systems has grown drastically. This has been motivated and encouraged by the E911 standard. This mandate required mobile operators to provide the Public Safety Answering Point (the emergency call centre) with the geographic position of 911 wireless callers, which forces the mobile positioning within 400 ft of its actual location 67% of the time [4,13]. For this purpose, several positioning techniques have been developed and investigated. These range from techniques using only the available infrastructure without any changes to those actually requiring some changes. The former class of methods includes the Cell Identity (CID) in which positioning is performed by finding the cell (geographical coverage area of a base station) the mobile is currently in . Another approach uses the timing advance (TA), which is based on measuring the round-trip propagation delay of the signal transmitted from the base station to the handset and back to the BTS [2, 3, 5]. The latter allows the user, given the speed of radiowaves, to determine the distance between the BTS and the MS, thereby, when several BTS were used, the location of the MS is determined as the intersection of the underlying range circles. Other methods use signal strength as received by the MS from the base station, which using a propagation model [1, 7, 8, 10, 12, 14] is transformed into distance from MS to related BTS. On the other hand, in the class, which requires changes in cellular infrastructure, one distinguishes time difference of arrival (TDOA) and angle of arrival (AOA) [7].

In contrast to cellular based techniques, GPS based technology uses GPS satellites, which, through a GPS receiver, the position of the MS in terms of latitude and longitude coordinates is determined with an accuracy of less than 10 metres. However, usually, such estimation is only plausible if there is a clear line-of-sight to at least four GPS satellites. This reduces its capability in case of dense urban-like environment or indoor environment. In order to deal with such situations, the idea of Assisted-GPS (A-GPS) has been acknowledged as a promising technology for future location based systems. The basic idea in A-GPS is to enforce a fruitful combination between Cellular network technology and GPS signals where an assistant server, which can be made available via, for instance, a network, helps the GPS receiver to perform the tasks required to determine position estimate. The resulting AGPS system boosts performance beyond that of the same receiver in a stand-alone mode. One of the main purposes of A-GPS is to provide municipalities with location-based emergency phone service, such as *E911* service. Another is to provide mobile carriers with end-user, location-based services such as a turn-by-turn navigation aid

Finding the position fix using the network can in fact achieve reasonable accuracies of less than 50 metres, based on the results of our previous work in [9]. Therefore, such network-based can be useful when GPS is unavailable. This paper advocates a fruitful combination of GPS positioning and cellular network-based methodology through conversion of signal strength into distance measurement. Especially, Hata's

propagation model [1, 7] will be used to determine various BTS-MS distances. Next, a Kalman filter approach will be developed that combines the different BT-MS distances together with GPS readings from the GPS receiver. Once the positioning is determined, through a connection to Microsoft MapPoint server, mobile location services, including, map generation, itinerary search, identification of points of interests, among others, can be enabled. An experiment is carried out in Birmingham area to prove the feasibility of the approach and comparison result will be provided.

Section 2 of this paper provides a general overview of the developed system. Section 3 details the Kalman filter approach. Section 4 details some experimental results carried out in Birmingham City area.

II. METHODOLOGY

The process of finding the location of the MS using the cellular network, and thereby enabling further services through MapPoint server, involves several stages.

A. Determination of Base Station locations

The determination of the location of the BTSs is accomplished using information available from the government website www.sitefinder.radio.gov.uk, which updates the location of GSM and UMTS base stations throughout the UK. It is therefore possible to measure the latitude/longitude positioning of all the surrounding base stations.

B. Signal strength calculation

Using NetMonitor software at the exact reference location, the strength of the signal received from the serving base station, as well as neighboring base stations, can be measured. Indeed, Netmonitor allows determination of the Cell Identity (CI) code of each BTS communicating with MS. By forcing the hand over in order to communicate directly with a specific CI (or BTS) using the channel number of such cell as pointed by the software, Netmonitor also allows us to display the received signal strength (Rx) transmitted by each of the surrounding BTS pointed out at previous test. See [9] for details of operation.

C. Distance calculation

The distance between each BTS and the handset can be determined using one of the empirical propagation models. We focused in this paper on Hata-Okumura propagation model [7], see [1, 9] for an exploration of alternative models. Basically, the model provides an expressing of the path loss of the signal transmitted by the BTS (Tx) (known through sitefinder) and received signal at the MS receiver (Rx), retrieved using Netmonitor, as a function of the distance between BTS and MS and the carrier frequency f, also determined using Netmonitor displayed parameters.

More formally, the Hata-Okumura model defines a parameter $a(h_M)$ to be the mobile height correction factor or gain (dB). As a result Hata subdivided the urban environment into large and small/medium cities.

For *urban areas* the path loss is expressed as follows:
$$Tx - Rx = 69.55 + 26.16\log(f) - 13.82\log(h_B) - a(h_M)$$
$$+ (44.9 - 6.55\log(h_B)).\log(d) \qquad (1)$$

For *suburban areas* the path loss is expressed as follows:

$$Tx - Rx = 69.55 + 26.16\log(f) - 13.82\log(h_B) - a(h_M)$$
$$+ (44.9 - 6.55\log(h_B)).\log(d) - 2(\log(f/28))^2 \qquad (2)$$

$a(h_M)$ refers to the small/medium gain factor and is given by:

$$a(h_m) = \begin{cases} 3.2(\log(11.75 h_M)^2) - 4.97, & \text{for large city} \\ 1.1\log(f - 0.7)h_m - 1.56\log(f) - 0.8, & \text{for small/medium city} \end{cases}$$

h_B stands for height of the base station (m).
h_M stands for height of the mobile phone (m).
d stands for BTS-MS distance

The carrier frequency f is determined by
$f = 1805 + 0.2 (CH-511),$

where *CH* stands for BTS carrier channel number as displayed by Netmonitor software.
Consequently, as all parameters are known, expressions (1) or (2), depending on type of environment, allows us to straightforwardly determine the distance d from the path loss (Tx-Rx) expression.

D. Mobile Positioning Location and Location Based Services

Once the different distances from the MS to the surrounding BTS are determined as in previous step, these distances are integrated together with the GPS information of the GPS receiver using an extended Kalman filter to determine the exact positioning of the MS in terms of the latitude/longitude coordinates. The detail of the Kalman filter is detailed at the next section. Thereby, once the location is known, a connexion with MapPoint web service SDK version 3.5 enables the access to mobile location services like map building, route tracer, nearest points of interest, among others.
The general scheme of this methodology is illustrated in the block diagram shown in Figure 1, which summarises the tasks that constitute the entire positioning methodology.
Basically, for each base station one retrieves its antenna characteristics in terms of height and Transmission power. On the other hand, using Netmonitor software, one retrieves the mobile station characteristics in terms received signal strength, channel number, cell identity code in the view of the underlying base station. Next, the use of path loss equation of

Hata-Okumura model allows us, by integrating the antenna characteristics and the retrieved mobile station characteristics, to determine the distance from the base station to the mobile station. The above process will be repeated for each base station. The obtained distances will therefore be integrated together with the GPS reading to yield an estimate of the mobile station in terms of latitude and longitude coordinates, which enables further location based services functionalities through connection to Microsoft MapPoint server.
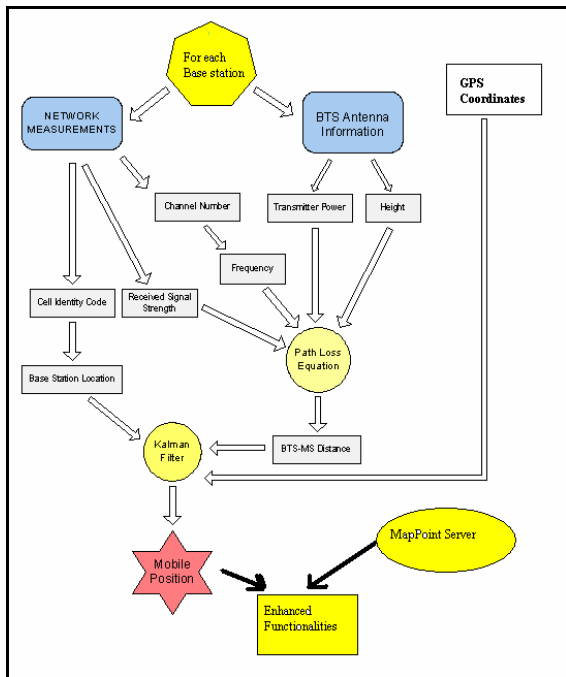

Figure 1. Block diagram for the general methodology

III. KALMAN FILTER MODEL

A. State Model

Let $X_k \begin{bmatrix} L_k \\ l_k \end{bmatrix}$ be the vector representing the position of the mobile station (MS) at time k in terms of latitude and longitude coordinates, i.e., L_k being the latitude and l_k the longitude. As the dynamic of the MS is not taken into account; that is, one assumes when the MS is connected to different BTSs, the MS location is assumed constant when all measurements are handled. This yields a static model in the state. In other words, the state model of the target is given by

$$X_{k+1} = X_k . \qquad (3)$$

B. Measurement Model

Two types of measurements occur: the BTS-MS distances calculated using Hata-Okumura propagation model and the GPS readings retrieved from the GPS receiver. The measurement equations subsumes two distinguished and uncorrelated models.

1) Distance-Based Measurement

Let $B_i \begin{bmatrix} L_i \\ l_i \end{bmatrix}$ be the vector representing the latitude and longitude of the ith base station (BTS).

Let $D_i(k)$ be the (noised) distance between the ith BTS and the MS position at time k; R is the earth radius (6378.135 km). **$D_i(k)$** can be defined using the spherical law of cosines as follows:

$$D_i(k) = a \cos[\sin(L_k)\sin(L_i) + \cos(L_k)\cos(L_i)\cos(l_i - l_k)] + e_1(k). \quad (4)$$

Where $e_1(k)$ is zero-mean Gaussian noise with variance-covariance matrix R_1.
As (4) is highly linear, it requires linear approximation at the estimate state X, which yields

$$D_i(k) = H_i(k).X_k + e_1(k) \qquad (5)$$

With

$$H_i(k) = \begin{bmatrix} \dfrac{\partial \hat{D}_i(k)}{\partial L_k} & \dfrac{\partial \hat{D}_i(k)}{\partial l_k} \end{bmatrix} \qquad (6)$$

Namely,

$$\frac{\partial \hat{D}_i}{\partial L_k} = R \left[\frac{\sin(L_k)\cos(L_i)\cos(l_i - l_k) - \cos(L_k)\sin(L_i)}{\sqrt{1 - [\sin(L_k)\sin(L_i) + \cos(L_k)\cos(L_i)\cos(l_i - l_k)]^2}} \right]$$

$$\frac{\partial \hat{D}_i}{\partial l_k} = R \left[\frac{\cos(L_k)\cos(L_i)\sin(l_i - l_k)}{\sqrt{1 - [\sin(L_k)\sin(L_i) + \cos(L_k)\cos(L_i)\cos(l_i - l_k)]^2}} \right]$$

As far as the R_1 estimate is concerned, one should notice that R_1 should capture the overall uncertainty pervading the distance measurement. In fact, due to technical specifications reported in [6], the estimation error, due to noise and interferences, must be in the range of

$$E = \Delta/4 + l.\Delta/8$$

with $\Delta = 1108m$ and l lies within the unit interval and accounts for speed of MS. Accordingly, Pent et al. [11] driven a probability distribution of the noise with a variance parameter

$$s_1 = \frac{\Delta}{2} \sqrt{\frac{1}{6}\left[\left(1 + \frac{l}{4}\right)^2 + \left(\frac{l}{4}\right)^2\right]} \qquad (7)$$

So, for a single BTS measurement, R_1 becomes one dimensional vector and coincides with (7).

2) GPS-Based Measurement

Since the GPS receiver is incorporated in the MS, so its location is explicitly linked to the MS location, up to noise measurements. This yields:

$$d(k) = X_k + e_2(k) \qquad (8)$$

Where $e_1(k)$ is zero-mean additive Gaussian noise with variance-covariance matrix R_2.

Since, the accuracy of the GPS reading are mainly dependent on the number of GPS satellites used to obtain the underlying readings, it is common to have R_2 dependent of the number of satellites. More formally, the variance-covariance matrix should be inversely proportional to the number of satellites used to obtain the GPS readings. Indeed, the more the GPS readings make use of high number of satellites, better the accuracy of the GPS positioning is, and therefore, smaller the variance-covariance matrix R_2 is. In other words, there exists a constant parameter **a** for which

$$R_2 = \boldsymbol{a} / N_{sat} \qquad (9)$$

Where N_{sat} stands for the number of satellites pointed out by the GPS receiver.

The parameter **a** can be determined as a function of the total variation of latitude and longitude occurring at initial BTS; namely,

$$\boldsymbol{a} = k. \begin{bmatrix} \Delta L_i \\ i \\ \Delta l_i \\ i \end{bmatrix} \qquad (10)$$

Where k is a positive coefficient and Δl_{i_i} (ΔL_{i_i}) stands for the largest difference of longitude (latitude) of the base stations.

Notice that such weighting is important especially due to the fact that in rural like environment where information on GSM signal is weak, the GPS reading, if available should be privileged over GSM-based positioning.

C. Kalman filter equations

The various measurement models can be stacked into a single linearized model Z(k) whose observation matrix H and variance-covariance matrix R are given by

$$H(k) = \begin{pmatrix} \dfrac{\partial \hat{D}_1(k)}{\partial L_k} & \dfrac{\partial \hat{D}_1(k)}{\partial l_k} \\ \dfrac{\partial \hat{D}_2(k)}{\partial L_k} & \dfrac{\partial \hat{D}_2(k)}{\partial l_k} \\ . & . \\ . & . \\ \dfrac{\partial \hat{D}_m(k)}{\partial L_k} & \dfrac{\partial \hat{D}_m(k)}{\partial l_k} \\ 1 & 1 \end{pmatrix} \qquad (11)$$

$$R = \begin{pmatrix} \boldsymbol{s}_1 & 0... & & 0 \\ 0 & \boldsymbol{s}_1 & 0... & & 0 \\ . & . & ..... \\ 0 & & \boldsymbol{s}_1 & 0 \\ 0_2 & & & 0_2 & R_2 \end{pmatrix} \qquad (12)$$

Where m stands for the total number of BTS and 0_2 for a 2x2 zero matrix.

The resolution of the Kalman filer equation leads to the following iterative algorithm, which, after initializing the initial variance-covariance matrix P_k, we have:

Filter gain: $K_k = P_k.H^T.\left(HP_kH^T + R\right)^{-1}$

State estimation: $\hat{X}_{k+1} = \hat{X}_k + K_k.\left(Z - \hat{Z}\right),$

Update of state covariance: $P_{k+1} = \left(I - K_kH\right)P_k$

In state update, Z represents the vector carrying all the measurements, i.e.,

$$Z = [\, z_1\ z_2\ ..z_m\ \ d(k)^T\,]^T$$

z_i stands for the distance MS-ith BTS as calculated by the propagation model and d(k) corresponds to GPS readings. $\hat{Z}$ corresponds to the predicted measurement according to expressions (5) and (7) (without additive noise), while I stands for the identity matrix.

Notice that, alternatively to using one single stack vector of all measurements, Kalman filter has also been proved to be effective by iterating measurements in the sense that each measurement contributes to update the state X_k and P_k of the model. This creates lower dimension matrices.

IV. EXPERIMENT

A. Positioning Estimation

In order to test the feasibility of our approach, we tested the positioning of our system in the Birmingham area. We deliberately choose highly urban environment in which the GSP signal is quite poor due to the lack of satellite visibility. Besides, we used information obtained through Google earth image as a reference to quantify the positioning error. Figure 2 shows the Google earth image of the MS positioning area. In order to elicit the measurements that will be employed in the filter, Table 1 and Table 2 provide the result in terms of signal strength as obtained using Netmonitor software and the BTS-MS distances obtained using Hata-Okumura propagation model, respectively.

Figure 2. Illustration of Google Earth image of MS location

Table 1. Signal strength measurements table

CH	Cell ID	BTS Street Name	Signal Strength (dB)
642	42201	Broad Street	-73
652	49496	Halloway Head	-90
646	4198	Morville street	-88

Table 2. Distance calculation using Hata-Okumura model

BTS	Hata model distances (Km)
Broad Street	0.203
Halloway Head	0.562
Morville Street	0.5

The application of Kalman filter yields a position, which is shown in Figure 3. As it can be seen this achieves an accuracy of around 70m, which constitutes a substantial improvement over classic Timing advance measurement whose accuracy is around 500m in urban environments.

For comparison purpose, we also used the location provided by Mobile Locate Ltd, which is one of the UK providers of mobile phone tracking services. As it can be seen the accuracy of such system is around few hundreds of meters, which is of few order of magnitude less accurate than the estimation provided by our system.
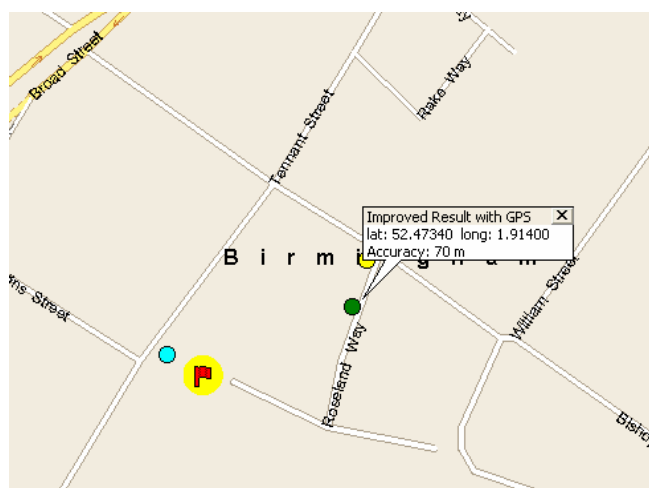

Figure 3. Position estimation and accuracy provided by the developed Kalman filter approach

Figure 4. Positioning using MobileLocate Ltd.'s service

B. Mobile Location services

The developed software referred as "GSM Mobile Locator" has been implemented in C# using Microsoft Visual Studio .NET 2003 is integrated in a PDA handset which is equipped with a GPS receiver, once the latitude/longitude coordinate of the MS is determined through the Kalman filter based methodology, the application communicates with Microsoft MapPoint server in order to enables location based services. The general methodology is shown in bloc diagram of Figure 5.
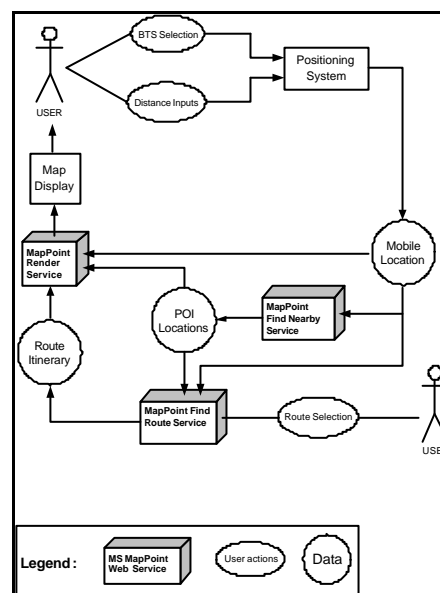

Figure 5. Block diagram of Location based services

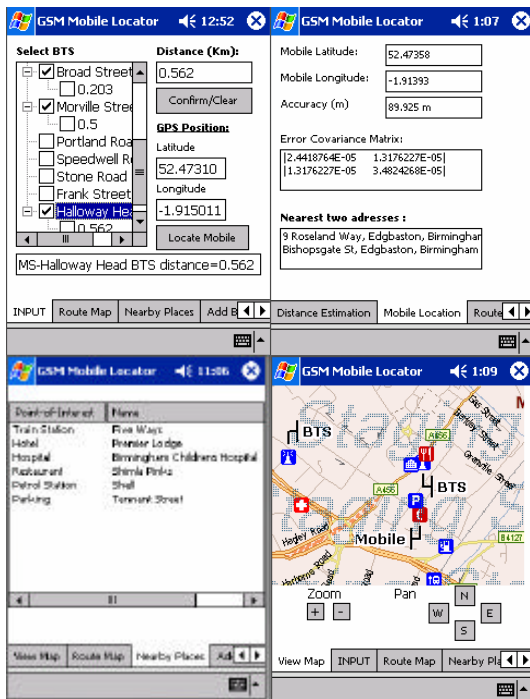Figure 6 shows some examples of results displayed in PDA.

Figure 6. Examples of PDA's display while enabling location based services

The upper plot exhibits an instance of result using Hata-Okumura modal, outcomes of Kalman filter in terms of state estimation, i.e., latitude, longitude coordinate of the MS and the associated variance-covariance matrix. While the bottom left and bottom right display the points of interest as indicated by signs of restaurants, hospital, train station, parking, petrol station nearby the location of the MS.

V. CONCLUSION

In this paper, a new low cost methodology for mobile positioning using GSM standard and GPS location together with enhanced services has been put forward. The proposal uses NetMonitor software to retrieve received signal strength pertaining to the emitting base transmitter station as well as each of neighbouring base stations. A matching with government database of BTS allows us to identify the location and characteristic of each underlying BTS. A Hata-Okumura propagation model was used to determine the MS-BTS distance using the signal strength information. Next, an extended Kalman filter model was developed to combine the different distances together with the GPS readings in order to determine accurate positioning of the MS in terms of latitude and longitude coordinate. Finally, a connection to MapPoint server allows the user to access several enhanced services related to map construction, identification of nearby points and route tracer, etc. An experimental has been carried out in Birmingham city centre and compared to typical commercial results of MobileLocation Ltd.

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