Carrier Independent Localization Techniques for GSM Terminals

V. Loscrí, E. Natalizio and E. Viterbo
DEIS
University of Calabria - Cosenza, Italy
Email: {vloscri,enatalizio,viterbo}@deis.unical.it

D. Mauro, G. D'Aquila and G. Brasili
E-Guide S.r.l.
Contrada Corso - San Marco Argentano (CS), Italy
Email: {d.mauro,g.daquila,g.brasili}@e-guide.it

***Abstract*—Exactly determining the geographical position of a telecommunication device is an open research challenge for the personal and mobile communications community. In this paper we explore the terminal localization problem in a GSM system, and we develop a set of carrier independent solutions. Specifically, we introduce four different techniques, all based on the 6-strongest cells traditionally used in the GSM standard. Through extensive simulations we show that our technique can achieve remarkable results without requiring any additional equipment in the core network or the mobile devices.**

I. Introduction

Historically the need to localize a mobile user was born for security matters. In 2001 in USA [1] and in 2002 in Europe [2], authorities for telecommunications imposed that all the emergency calls from cellular phones had to be localized with a high accuracy. After some years positioning techniques have become commercially very attractive, because they can be used in order to offer a set of additional services to cellular system users. The existing 2G/3G cellular networks do not offer built-in features, which allow the positioning with sufficient accuracy. To cope with this issue, providers must install some additional equipment at the network base stations (network-based systems) or add GPS or another localization technology to the wireless phone (handset-based systems). An inexpensive solution should permit a high localization accuracy with a low technological impact on the network infrastructure. In this paper we want to design a localization method which belongs to the Information Service category [3], this means that the positioning error can not be larger than 300 meters. Thus, we develop a set of low-cost techniques for GSM terminals localization, which improve the accuracy without requiring any additional hardware in the network. In fact, our techniques are based on location fingerprinting [4], and they all use the power measurements of the 6 strongest cells performed by the mobile stations. The device that needs to be localized, sends this information to the localization server provider, which in turn searches for the point in the map which better matches in terms of measured power. The search is facilitated and more accurate if, along with the power measurements, the network can use the Cell Identifier of the base station (BS) which is serving the mobile station (MS) and the position of the mobile estimated at the last round of localization. The techniques we propose and compare are:

- *Power Cell-Id 6 (PCI6)*: it searches among the points in the map which have the serving Cell-Id in the set of the six strongest cells, and it returns the position of the point that most strongly matches with the measured powers.
- *Power Cell-Id 6 Previous Position (PCI6PP)*: the same as PCI6 but using the additional information on the mobile's previously estimated position.
- *Power Cell-Id 1 (PCI1)*: it searches among the points in the map which have the serving Cell-Id as first in the set of the 6 strongest cells, and it returns the position of the point that most strongly matches with the measured powers.
- *Power Cell-Id 1 Previous Position (PCI1PP)*: the same as PCI1 but using the additional information on the mobile's previously estimated position.

In order to evaluate the four techniques we implemented a simulator and analyzed their performance in terms of localization accuracy, measured as the distance between the terminal's actual position and the position estimated by the technique. The rest of the paper is organized as follows. In Section II we survey the literature of existing positioning techniques in GSM. In Section III we give the details of the techniques developed. In Section IV we explain the simulation environment and show the results. Finally, we conclude the paper in Section V.

II. Related Works

A simple method to localize devices in a cellular network is the Cell-Identifier technique (CI). It is based on the knowledge of the geographical position of cells and determines the terminal's position through the identification of its serving cell. Unfortunately, the accuracy of this technique is strongly dependent on the density of cells. High density areas localize a device with an accuracy of a few hundreds meters, while in low density areas the positioning can be affected by errors of some kilometers. The accuracy improves when the information of the Cell-Id is used along with network measurements of timing advance (TA). The TA value indicates the time delay for the mobile station to send one unit of information to the base station. For this technique the accuracy is limited to 550 meters and depends on the distance between mobile station and base station. Both the cited methods are transparent for

978-1-4244-2644-7/08/$25.00 ©2008 IEEE

the network, because they do not require the installation of new hardware.

Among the non-transparent solutions we cite the Angle of Arrival (AOA) [5], the Time of Arrival (TOA) [6] and the Time Difference of Arrival (TDOA) techniques. The first is based on the angles of incidence of the signal transmitted by the mobile station and received by, at least, two base stations. The second depends on the time required for the signal from the mobile station to reach, at least, three base stations. Finally, the third needs the knowledge of the time difference of arrival of the signal from a mobile station to three different base stations. The accuracy of these three solutions ranges between 100 and 300 meters [7]. All of them are classified as network-based systems, because they all need some additional technology to be integrated into the base stations to measure certain signal characteristics. The Enhanced Observed Time Difference (EOTD) [6] technique is very similar to the TDOA, but it is handset-based. The position of the mobile station is determined by comparing the time differences between two sets of timing measurements, performed by the mobile station and by the Local Measurements Unit (LMU). The accuracy of this method can reach 50 meters [7]. Also in this case the network architecture requires to be enriched with a new entity, the LMU. For this reason none of them can be considered an economically viable and scalable solution. Furthermore, they all suffer from the non-line-of-sight (NLOS) error and multipath, especially in urban and suburban areas.

On the other hand, the last cited problem can become an important source of information when the local behaviour of the signal is exploited. All the information that depend on the location of the mobile station can be used as "fingerprint" to support positioning. Specifically, the fingerprinting technique uses the terminals' received signal strength (RSS) and it, usually consists of two phases: surveying and localization. The surveying phase collects in a database the RSS measurements for all the points of interest in a map. During the localization phase the mobile station measures its current RSS and queries the database in order to search for the best match through an appropriate algorithm. A good example of GSM fingerprinting is presented in [8] and [9], where authors reach an accuracy of 5 and 75 meters, indoor and outdoor, respectively. In these works the surveying phase of fingerprinting is realized by collecting samples with a granularity of 1.5 meters and belonging to 35 GSM channels. The localization algorithm use the K-nearest neighbors algorithm, which consists of averaging the location of the K closest neighbors (or training points) in the radio map. We claim that such a fine granularity can be pursued only in small indoor environments, while our objective is to design a technique for the Information Services category, which means the consideration of outdoor scenarios. Moreover commercial phones limit access to the 6 strongest cells. For this reason the software of terminals would need to be enhanced in order to provide signal strength measurements for a richer set of channels.

In this paper we are interested only in the techniques which do not require the handset to be provided with a GPS receiver, so we do not take into consideration GPS, Assisted GPS (AGPS) or GPS Hybrids methods.

For a deeper survey of the existing localization techniques in GSM the reader can refer to [10].

III. Positioning Techniques

As we already outlined the techniques we developed in this work are inexpensive, network transparent and based on fingerprinting. In this way, the localization engine can be made totally independent of the carrier. In this section we show how the two typical phases of fingerprinting are accomplished by the proposed techniques.

A. Surveying Phase

The first phase of fingerprinting is called surveying or training phase. The main purpose of this phase is the creation of a database that associates the geographical positions of points considered important in a given area with the received signal strengths. This phase is usually carried out by measuring the RSS from a certain number (typically 6) of base stations. The training phase requires an amount of efforts proportional to the extent of the area, where the positioning has to be realized. For this reason, usually an RF planning tool based on refined propagation models is used in order to determine approximate values of powers in areas too large or too difficult to be measured on the field. In our work at each of the N points, $\mathbf{x}^{(i)}$, in a 2D map is associated in the database the decreasing ordered set of the six strongest values of measured powers, $\mathbf{p}^{(i)} = (p_j^{(i)}), j = 1, \ldots, 6$, and the identifiers (Cell-Id or Base Station Identity Code) of the corresponding cells, $\mathbf{C}^{(i)} = (C_j^{(i)}), j = 1, \ldots, 6$, as in the following tuple $T^{(i)}$:

$$T^{(i)} = (\mathbf{x}^{(i)}, \mathbf{p}^{(i)}, \mathbf{C}^{(i)}), \quad i = 1, \ldots, N$$

In order not to overload the terminals with too many data, we decide that the database created during the surveying phase is located within the localization engine and it will be retrieved only when a device localization has to be performed. The training phase is the same for all the techniques we propose.

B. Localization Phase

Generally, during the positioning phase, mobile terminals perform some kind of measurements which will be used by an appropriate algorithm for determining the location in the map with the likeliest characteristics. In GSM, every 480 ms the mobile stations send the values of measured powers to the serving base stations on the Slow Associated Control Channel (SACCH). Hence this information is available at the terminals and, when the localization is required, it can be sent to the localization engine through a dedicated data channel. Specifically the mobile station sends a pair $(\mathbf{q}, S)$, consisting of a decreasing sorted vector, $\mathbf{q} = (q_j), j = 1, \ldots, 6$, of measured power values and the Cell-Id of the serving base stations, S. Also the Cell-Ids are available at the terminal because they are broadcasted by the base stations on the Broadcast Control Channel (BCCH). The localization algorithm receives these vectors as inputs and looks for the point in the map with the most similar characteristics, in terms of the metric:

$$L^{(i)}(\mathbf{q}) = (\sum_{j=1}^{6} p_j^{(i)} - q_j)^{1/\alpha}, \quad i = 1, \ldots, N. \tag{1}$$

The value of α determines the kind of norm. Specifically, we choose $\alpha = 2$, that is the *Euclidean* norm. The resulting position, $\mathbf{x}^{(k)}$, will have index in the database given by:

$$k = \arg \min_{1 \leq i \leq N} L^{(i)}(\mathbf{q}) \tag{2}$$

The main problem in the research of the best matching is that the algorithm should calculate the function $L^{(i)}$ for each of the N points of the map. In order to shrink the set of candidates we propose four techniques that, by using additional information, incrementally improve the accuracy of localization.

1) Power Cell-Id 6 (PCI6): The first additional information that can be profitably used in the positioning is related with the identifier of the serving base station. In fact, if a base station is serving a mobile station that is located in the point i of the map, it is because its signal has been considered one of the strongest for that area, and its Cell-Id should be present in the vector $C^{(i)}$. In practice, the searching algorithm excludes all the points of the map which do not have the serving base station in any position of the set of the 6 strongest cells.

2) Power Cell-Id 6 Previous Position (PCI6PP): If positioning is performed periodically also historical information can help in localizing the device. Thus, we imagine that the previously estimated position of the terminal is stored somewhere on the handset or on the localization server, and this information is available to be used by the searching algorithm. In this way it is possible to determine a circumference that has the previously estimated position as center and radius r. The radius is dependent on the localization frequency and positioning error. The research will be limited to the points of the circumference which have the Cell-Id of the serving base station in any position of the set of the 6 strongest cells.

3) Power Cell-Id 1 (PCI1): For this technique we consider as candidates only the points of the map which have the Cell-Id of the serving base station in the first position of the set of the 6 strongest cells.

4) Power Cell-Id 1 Previous Position (PCI1PP): The same considerations made for the PCI6PP are valid also in this case. Hence the research will be shrunk to the set of points inside the circumference that have the Cell-Id of the serving base station in the first position of the set of the 6 strongest cells.

IV. Simulation and Results

In this section we describe the environment used to analyze the four techniques presented in the previous section and their performances.

TABLE I
SIMULATED ENVIRONMENT

Area Dimension	5km x 5km
Number of Pixels	$N = 10000$
Side of Pixels	50 meters
Number of Base Stations	$N_{BS} = 25$
Type of Antennas	Omnidirectional
Carrier Frequency	900 MHz

A. The reference environment

Usually the training phase of fingerprinting is accomplished by real measurements on the field. As explained in Section III-A, often this process can be too complicated, and for this reason RF planning tools are used. These tools are based on propagation models which take into account the network layout and environment under investigation. This is the approach used in this work, where we consider a urban scenario. The most relevant parameters of the environment we simulate are shown in Table I.

The pixel is the smallest geographical element where the localization will take place, so we can not expect localization errors smaller than the side of a pixel. Since we could not use advanced radio planning tools, we created a simulation environment based on a simplified propagation model (free space). The database has been populated with the power records computed in the center of each pixel by using the propagation model.

B. Performance evaluation

We designed a simulator to evaluate the performance of the four proposed techniques. In the simulation we randomly generate the position $\mathbf{y}$ of the terminal which needs to be localized. The power vector measured by the terminal in the position $\mathbf{y}$ is generated as follows: $\mathbf{q} = \mathbf{p} + \mathbf{e}$ where the 6-component power vector $\mathbf{p}$ is computed using the propagation model and $\mathbf{e} = (e_1, \ldots, e_6)$ is a random Gaussian error vector with $e_j \sim N(0, \sigma^2)$. This error vector takes into account the inaccuracy of the propagation model and the variability of the environment within a pixel. Typical values for the variance are $\sigma^2 = 3, 6, 9, 12$ dB, which take into consideration the presence of obstacles and multipath, scattering and fading effects. The propagation model is also used to determine the 6 Cell-Id corresponding to the 6 power values in the vector $\mathbf{p}$. The implicit assumption is that Cell-Id of the serving base station does not change after adding the error vector $\mathbf{e}$. The localization algorithm estimates the pixel k to which the terminal most likely belongs, according to the localization technique under investigation. The positioning error, ϵ, is calculated as the *Euclidean* distance, expressed in meters, between the actual position of the terminal, $\mathbf{y}$, and the position estimated through the localization algorithm, $\mathbf{x}^{(k)}$, which is the center of the k-th pixel:

$$\epsilon = \left\| \mathbf{y} - \mathbf{x}^{(k)} \right\|$$

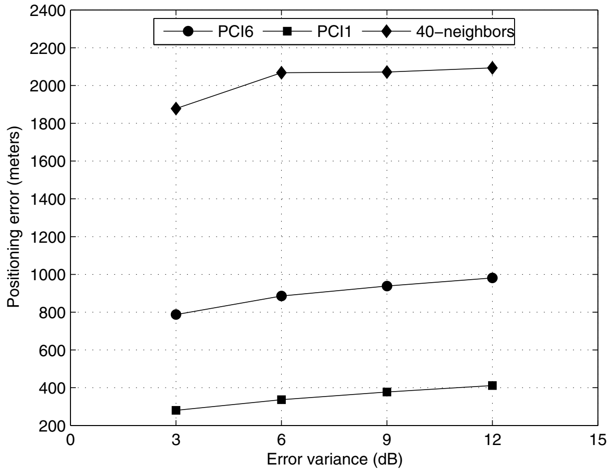

Fig. 1. Positioning error for the K-neighbors, PCI6 and PCI1 techniques.

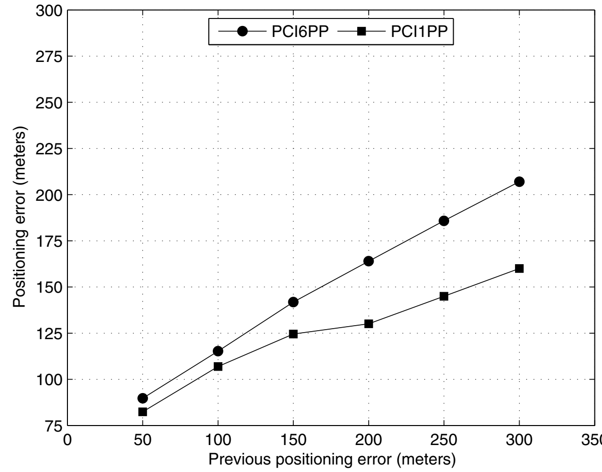

Fig. 2. Positioning error for the PCI6PP and PCI1PP techniques with $\sigma^2 = 3$ dB.

In our results we report the standard deviation σ_ϵ of the positioning error σ_ϵ^2, which is obtained over 1000 runs in order to guarantee a confidence interval of 95%. For the techniques based on the previously estimated position (PCI6PP, PCI1PP) we fix the radius to $r = 300$ meters, which is compatible with the maximum allowed terminal speed and the maximum positioning error. In particular, we consider for a urban environment, the maximum allowed terminal speed is 50 km/h, which means a sojourn time in the pixel of, at least, 3.6 seconds and a sojourn time in the area of radius r of, at least, 43.2 seconds. Hence the localization frequency should be larger than $f = 1/43.2$ Hz in order to track the movement in a different pixel.

The results of our two techniques that do not use any additional information rather than the 6 strongest cells power values and the corresponding Cell-Id is shown in Fig. 1. In this figure we also plotted the simulative results of the technique proposed in [8]. Because of the smallest set of channels considered (6 instead of 35), and because of the coarser granularity (50 instead of 1.5 meters) and of the simplified propagation model of our training phase, the results of this solution are not satisfying even if we considered a high number of neighbors (K=40). The same can be said for the other two techniques, PCI6 and PCI1. From the literature we know that Information Services require a positioning error not higher than 300 meters, and this accuracy is achieved by the PCI1 technique but only for very low values of the error variance σ^2.

In order to overcome this inconvenient, we assume that the localization is performed periodically (more frequent than once every 43.2 seconds) and the terminal or the localization server keep the previously estimated position. Also the previous estimation is affected by a positioning error. Specifically, we consider an error $\epsilon = [50, 300]$ meters and evaluate the behaviour of the techniques PCI6PP and PCI1PP when the variance of the error vector varies.

As we can see from Figure 2, where $\sigma^2 = 3$ dB, these techniques perform better than those that do not use the history of terminal's movements. The information on the previously estimated position has reduced the area where candidates have to be searched, consequently reducing also the source of potential positioning errors. Furthermore, PCI1PP realizes a lower positioning error in resepct of PCI6PP. This is due to the fact that PCI1PP furtherly shrinks the number of potential candidates, by excluding from the set of investigation all those points which do not have the serving base station Cell-Id in the first position of the vector $\mathbf{C}$.

Another interesting observation is that the searching area is strictly related with the error committed on the previously estimated position. The higher is the error of the previous estimation, the higher is the error in the terminal positioning. In fact we have a minimum, for both the techniques, in correspondence of a previous positioning error of 50 meters. In this case PCI1PP is able to localize the mobile station with an error of ≈ 82 meters.

In Figure 3, we show the same techniques of the Figure 2, but the power vector is affected by an error of 6 dB. In this case the results are obviously worst than in the case of 3 dB because of the higher uncertainty on the vector $\mathbf{q}$. In the case of the Figure 3 the minimum error is realized for the PCI1PP technique when the previous error is ≈ 50 meters and is ≈ 96 meters.

We are able to localize a terminal with smaller accuracy and specifically we have an increase in the minimum error of ≈ 10 meters. Of course, the situation gets worse and worse when the variance of the error increases as we can see in 4 and 5, where σ^2 is equal to 9 and 12 dB respectively. We can notice from all the diagrams of the techniques PCI6PP and PCI1PP that the error made on the previous estimation does not degenerate by causing a higher error in the following round of localization. Instead simulations show that the error

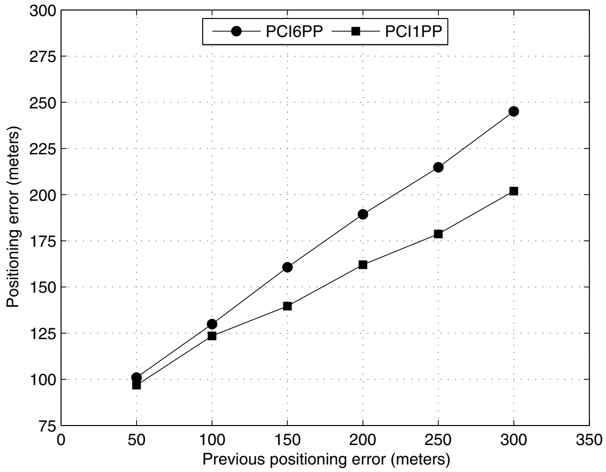

Fig. 3. Positioning error for the PCI6PP and PCI1PP techniques with $\sigma^2 = 6$ dB.

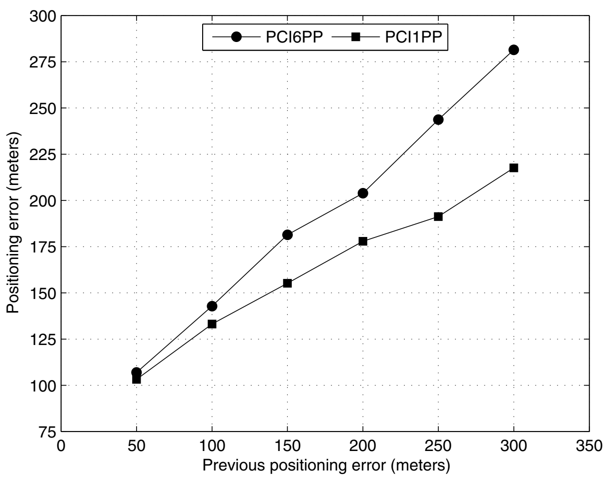

Fig. 4. Positioning error for the PCI6PP and PCI1PP techniques with $\sigma^2 = 9$ dB.

remains always limited and it is never larger than 300 meters.

We can conclude outlining that the techniques that use the previously estimated positions are good candidate for Information Services because they are able to localize a mobile terminal with a low error, ranging from 80 to 220 meters.

V. Conclusion

In this paper we presented a set of positioning techniques for Information Services based on location fingerprinting that are carrier independent and network transparent. All of them use power measurements of the 6 strongest cells. As the required accuracy of Information Services is less than 300 meters, the techniques based only on this information are not sufficient for GSM. We showed how the use of the previously estimated position can help to achieve this goal. These methods show that the positioning error is always smaller than 300 meters

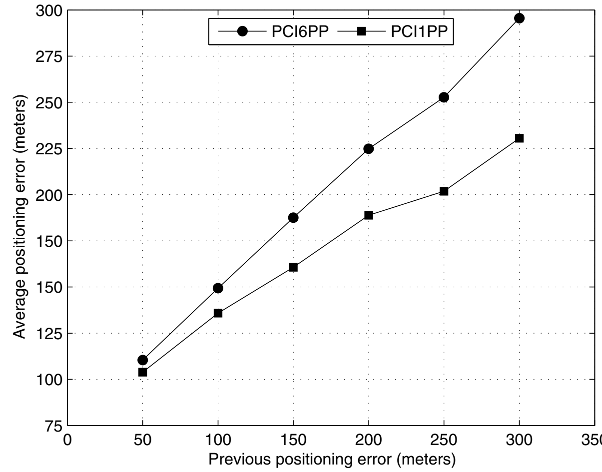

Fig. 5. Positioning error for the PCI6PP and PCI1PP techniques with $\sigma^2 = 12$ dB.

and, when the environmental conditions do not perturb the measurements (low variance of the error vector), it goes down to about 80 meters. This suggests that our techniques can be used not only for Information Services but also for different services that may require a higher accuracy.

References

[1] Federal Communications Commission, “Revision of the Commission’s Rules to Ensure Compatibility with Enhanced 911 Emergency Calling Systems,” in *CC Docket,* No. 94-102, 2001.

[2] Coordination Group on Access to Location Information by Emergency Services (CGALIES), “Report on Implementation issues related to access to location information by emergency services (E112) in the European Union,” 2002.

[3] M. Porretta, P. Nepa, G. Manara and F. Giannetti, “Analysis of Subscriber Radio Location Techniques through a Deterministic Propagation Model,” in *Proceedings of PIERS*, Volume 1, 2002.

[4] H. Koshima and J. Hoshen, “Personal Locator Services Emerge,” in *IEEE Spectrum,* Volume 37, Issue 2, Page(s) 41-48, 2000.

[5] ETSI TS 101 725, “Digital cellular telecommunications system (Phase 2+); Location Services (LCS); Mobile radio interface layer 3 Location Services (LCS) specification (GSM 04.71 version 8.1.0 Release 1999),” ETSI, 2000.

[6] ETSI TS 101 724, “Digital cellular telecommunications system (Phase 2+); Location Services (LCS); (Functional description) - Stage 2 (GSM 03.71 version 8.0.0 Release 1999),” ETSI, 2000.

[7] C. Frederic, “Location Service Study Report, D2.3.1I,” in *Mobile and Vehicles Enhanced Services,* IST-2000-30041, 2002.

[8] V. Otsason, A. Varshavsky, A. La Marca, and E. de Lara, “Accurate GSM Indoor Localization,” in *Lecture Notes in Computer Science,* Volume 3660, Page(s) 141-158, Springer 2005.

[9] A. Varshavsky et al., “Are the GSM phones THE solution for localization?,” in *Proceedings of IEEE Workshop on Mobile Computing Systems and Applications,* Page(s) 34-42, 2006.

[10] V. Schwieger, “Positioning within the GSM Network,” in *Proceedings of FIG Regional Conference,* 2007.