A New Method for Positioning of Mobile Users by Comparing a Time Series of Measured Reception Power Levels with Predictions

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***Abstract*— Many modern applications for mobile phones are based on information about the exact position of the user. There are several methods, which fulfill this task. Some require extensions of the network or the terminals, others do not, but provide little accuracy. The method presented here uses exclusively standard measurements, network parameters, and data from the network planning process. The power level measurements the mobile reports to the network for handover and other radio resource management tasks are compared with the field strength values predicted by network planning tools. Using a single report is a well-known positioning method, which is not very accurate, because it is very sensitive to fading and other random variations of the signal levels. In the new method, a series of several reports is used. This series corresponds to a path, on which the user moves. An efficient algorithm calculates the probability of the most probable path leading to each point in the search area. The estimated position is the weighted average of all of these points. Since searching the whole area of a network is not feasible in practice, the calculation effort is drastically reduced by a preprocessing step, which allows the preselection of the search area based on information about the current serving cell of the user.**

Extensive field trials in existing GSM networks have shown that the method works well and gives substantial improvement compared to other positioning methods, such as CI/TA. An average accuracy of 130m was observed in an urban environment and about 300m in rural areas.

As the UTRAN provides some measurements, which are very similar to those of GSM, it is possible to apply this method in UMTS networks as well.

I. Introduction

While location-based services are regarded as an important commercial application of mobile telecommunication networks, obtaining the accurate position of a moving user is still a challenging technical task. There are many methods available today, most of which demand the installation of additional hardware, such as a GPS receiver in the mobile or time measurement units at the base stations. The method presented in this paper does not require any changes of the infrastructure. It is based on standardized measurement data that are collected during normal network operation.

In GSM, the mobile continuously measures the received signal levels (RXLEV) of the serving cell and the neighboring base stations [1]. The six strongest levels are sent to the network in a measurement report, so that decisions about cell selection and handover can be made. These reports are compared with predictions obtained with network planing tools. Since every measurement is subject to a variety of perturbations, such as attenuation, fading, and other random variations, the evaluation of a single report is not very reliable. Using a time series of reports improves the accuracy significantly. In order to keep the calculation time manageable and to increase accuracy, some preprocessing is done, which allows a preselection of the area to be searched based on the serving cell and the current timing advance of the user. Though the algorithm is described for GSM networks here, it is applicable on other mobile telecommunication systems as well.

Alternative approaches using a Kalman filter can be found in [2], [3] and using pattern recognition [4], [5]. Our approach grew out from [6].

This paper is organized as follows: section II contains a description of the preprocessing algorithm, in section III the positioning algorithm is explained, section IV presents some results from field trials, and section V addresses the applicability of the algorithm to UMTS networks.

II. Preprocessing

Careful preprocessing of the prediction data is essential to reduce the calculation time of the positioning algorithm and to improve the accuracy of the calculated positions. If a location is requested, the mobile is usually in dedicated mode, which implies, that it has a well-defined serving cell, which is identified by a pair of *location area code* (LAC) and *cell identifier* (CI). For the rest of this paper, CI means the combination of both, i.e. a unique label that identifies a cell. The maximum area, where a user can be served by the serving cell, is a first restriction of the area to be searched. Some more information is provided by the *timing advance* (TA) [1], which is used by the base station to make the mobile transmit on the correct time depending on its distance to the BTS. The round-trip time is measured with a resolution of one bit, corresponding to a distance of 1100m. This means that the distance between the base station and the mobile is known with a theoretical resolution of 550m. In practice, however,

there is a measurement error of up to one bit, which increases the width of the TA rings and makes them overlap. Thus, the search area can be selected based on the a priori knowledge of the values of CI and TA. This area will then be searched by the actual positioning algorithm for the position of the user. It is the task of the preprocessing part of the algorithm to calculate these areas.

The whole method is based on a rectangular grid with typical resolutions of 5…100m, which is also the resolution used by common network planning tools. The prediction data contain the predicted received powers of all observable base stations for each grid point (*pixel*). If the resolutions of the grid for the positioning algorithm and that of the predictions grid differ, the signal levels may be interpolated. The result of the preprocessing is a mapping that assigns a set of pixels to each possible pair of CI and TA. These sets describe the *maximum* area, where a user can be served from the corresponding cell with the respective TA. This definition of the areas implies, that they may overlap with respect to CI and TA.

In the first step, the total cell areas are calculated based on the predicted power levels, on some network parameters (such as handover margins and antenna directions), and on settable parameters of the algorithm. The calculation of the cell areas comprises several procedures, which remove pixels, where the user is surely served by another cell or where the signal level is lower than the level required for a connection. There are also pixels added, such as a security margin at the borders. "Holes" and "islands" are removed. Finally, the border of the areas is smoothened. It should be pointed out again, that no harm is done by adding a few pixels, except for a slightly higher calculation effort for the positioning algorithm. Making the search area much too large, however, can decrease the positioning accuracy.

When the cell area is known, the areas corresponding to the different values of TA can be calculated. They result from intersections of rings of a width of 550m plus an error margin of about another 550m (see above) and a radius corresponding to the value of TA around the BTS. This is illustrated in Fig. 1, where the case of a sectorized cell is shown.

The sequence of preprocessing steps is executed for the full region under investigation. If single elements of the network are changed (for example deployment of a base station or change of transmitting power), a delta calculation is possible, which re-calculates the affected cells only.

The result of the preprocessing algorithm are sets $S(\mathrm{CI}, \mathrm{TA})$ of pixels for all CI and (reasonable) TA. Each pixel $p \in S(\mathrm{CI,TA})$ has a position $\vec{X}_p$ and predicted power levels $P_p^{(i)}$ for all cells i that are observable at $\vec{X}_p$. These data are stored permanently, so that they can be used by the positioning algorithm upon request.

III. Positioning Algorithm

Once the preprocessed data have been calculated, the position of a user can be determined based on the measured power levels. The known values are the CI, the TA, and the RXLEV of the serving cell and the strongest neighbor cells. All values

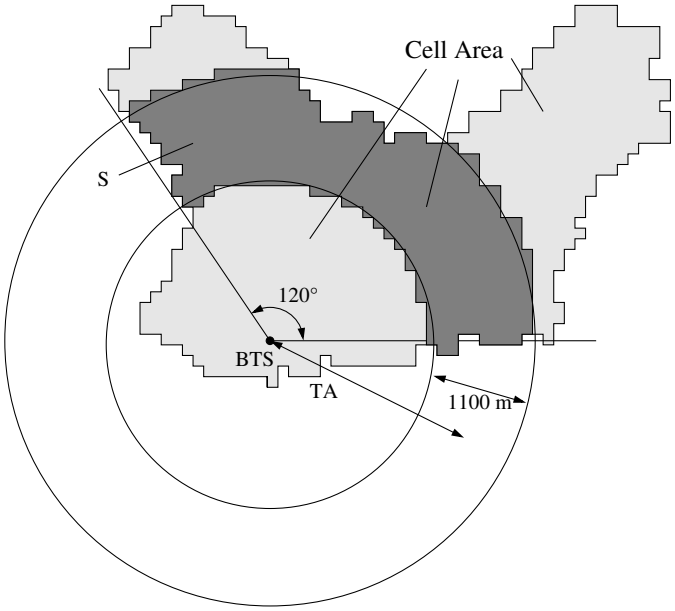

Fig. 1. Search area determined by preprocessing algorithm

are reported periodically. A time series of M (typically 6 or 12) sets of RXLEV values $\{R_m^{(i)}\}$ measured by the mobile are is used. Here $m = 1 \ldots M$ are the subsequent measurements, which are usually separated by 480ms in GSM, and i is an index of the observed cells. There is a slight difference between the serving cell and the neighboring cells. For the neighboring cells, the RXLEV value is measured based on their BCCH, which is always transmitted with the same power. On the contrary, the RXLEV of the serving cell is measured on a traffic channel, which is power controlled. This means, that the current transmit power of the channel has to be known, so that the pathloss or equivalently the reception level at reference power can be calculated.

The search area S is selected by CI and TA from the stored results of the preprocessing as described in section II. All power levels are given logarithmically, e.g. in dBm. The algorithm now calculates for every pixel $p \in S$ the path that leads to this pixel with the minimum summarized difference between the measured and the predicted field strengths.

The algorithm is explained here for the simplifying case that no handover and no change of the TA occur during the observation interval. Furthermore, a constant set of cells $i = 1 \ldots N$ is assumed. This is done to show how the method works in principle and to keep the notation simple. In a real world implementation, however, the general case can easily be dealt with.

A. Calculation of the difference

A deviation measure of the difference between the measured and the predicted power levels at a pixel p for report m is required for the positioning algorithm. The difference between the (logarithmic) power levels of cell i at pixel p is

$$\delta_{p,m}^{(i)} = R_m^{(i)} - P_p^{(i)}, \tag{1}$$

where $R_m^{(i)}$ is the RXLEV of cell i in the m-th report, and $P_p^{(i)}$ is the predicted signal level of cell i at the pixel p. A natural measure is the sum of the squared differences over all N observed cells

$$d_{p,m}^{\text{simple}} = \sum_{i=1}^{N} \left(\delta_{p,m}^{(i)}\right)^2, \tag{2}$$

but this approach cannot compensate systematic shifts, which are often caused by attenuation effects. A better way of calculating the difference is to subtract the average value of $\delta_{p,m}^{(i)}$ before squaring, which leads to

$$d_{p,m} = \sum_{i=1}^{N} \left(\delta_{p,m}^{(i)} - \bar{\delta}_{p,m}\right)^2 \tag{3}$$

$$= \sum_{i=1}^{N} \left(\delta_{p,m}^{(i)}\right)^2 - \frac{1}{N}\left(\sum_{i=1}^{N} \delta_{p,m}^{(i)}\right)^2. \tag{4}$$

This expression is formally equal to N times the variance of $\delta_{p,m}^{(i)}$. It does not change if all reports are shifted by a constant offset.

B. Accumulation of the minimum distance

The reports from 1 to M are processed sequentially. In the first step, the differences $d_{p,1}$ are calculated for every pixel $p \in S$ for the first report and stored in $\{D_p^{(1)}\}$. For every subsequent report m, $D_p^{(m)}$ is calculated as

$$D_p^{(m)} = d_{p,m} + \min_{s \in \text{Neigh}(p)} D_s^{(m-1)}. \tag{5}$$

Neigh$(p) \subseteq S$ is a set of pixels from which the user could have moved to the pixel p within the time that separates the reports m and $m-1$. Its size is usually quite small (e.g. p itself and its nearest neighbors). The actual choice depends on the size of the pixels and the assumed maximum velocity of the user. After all M reports have been processed, the minimum deviation measure sums

$$D_p \equiv D_p^{(M)} \tag{6}$$

are available for each pixel p.

C. Calculation of the position

The position of the user is calculated from the values D_p and the actual positions of the pixel centers $\vec{X}_p$. Several methods can be chosen at this stage. An obvious choice would be to take the pixel with the minimum D_p as the end point of the most probable path. But comparison with experiment shows that this is not the optimum method; this is plausible, because the probability information about all other pixels is disregarded even if their probability is only slightly smaller than the optimum value. A better performance is obtained, if all pixels are taken into account and the position is estimated as the weighted average of the positions of all pixels in S.

$$\vec{x}_{\text{est}} = \frac{1}{W}\sum_{p \in S} w_p \cdot \vec{X}_p, \qquad W = \sum_{p \in S} w_p. \tag{7}$$

The weight is determined by the assumption, that the square root of each deviation measure is roughly Gaussian distributed with a standard deviation σ_D. This means that the likelihood to observe D_p, when p is the true position during the last measurements, is given by [3]

$$p(D_p) = \frac{1}{\sqrt{2\pi}\sigma_D} \exp\left(-\frac{D_p}{2M\sigma_D^2}\right). \tag{8}$$

Thus, the statistical weight of the positions is given by

$$w_p = \exp\left(-\frac{D_p}{2M\sigma_D^2}\right). \tag{9}$$

The actual value of σ_D depends on the statistical properties of the individual measurements, which on their turn depend on the fading conditions and on the measurement process. Since these factors are normally not known in detail, a semi-empirical value depending on the the cell type, the environment, and a fading model is used.

D. Estimation of an uncertainty circle

Although the estimated position is the most important result of a localization procedure, an estimation of the error radius is often required by applications. Chebychew's estimation provides an upper bound of the probability of the real position being outside a circle of radius r around the estimated position $\vec{x}_{\text{est}}$. This probability is less than or equal to $(\sigma_{\vec{X}}/r)^2$, where $\sigma_{\vec{X}}$ represents the standard deviation of the distance between the position of a pixel $p \in S$ and the mean position $\vec{x}_{\text{est}}$ under the weighting w_p. Thus, the probability that the real position is inside a circle of radius r is

$$p(r) \geq 1 - \left(\sigma_{\vec{X}}/r\right)^2. \tag{10}$$

If we use this lower bound as an estimation of the probability, the equal sign applies, and r can be calculated for a desired confidence level $\beta = p(r)$ as

$$r(\beta) = \frac{\sigma_{\vec{X}}}{\sqrt{1-\beta}}. \tag{11}$$

The standard deviation $\sigma_{\vec{X}}$ can be estimated from the positions of the pixels $\vec{X}_p$ and their statistical weights w_p as

$$\sigma_{\vec{X}}^2 = \frac{1}{W}\sum_{p \in S} w_p \|\vec{X}_p - \vec{x}_{\text{est}}\|^2 \tag{12}$$

$$= \frac{1}{W}\sum_{p \in S} w_p \cdot \vec{X}_p^2 - \vec{x}_{\text{est}}^2. \tag{13}$$

The validity of this estimation is investigated based on field trial data in section IV-C.

IV. Field trial results

A. Trial setup

The method has been verified in field tests. Results of a test in an operating GSM network in Germany are presented here. Two environments were tested: the center of a big city, which can be characterized as *dense urban* and a small city with its hilly surroundings (*rural*). The test area was served by GSM 900 and GSM 1800 micro and macro cells.

TABLE I

RESULTS OF THE FIELD TRIAL: AVERAGE ERRORS IN DIFFERENT ENVIRONMENTS AND SITUATIONS

Environment	Situation	CI/TA	New Method	Improvement
Urban	Total	250m	130m	48%
	Car	290m	133m	54%
	Outdoor	201m	109m	46%
	Indoor	397m	206m	48%
Rural	Total	544m	307m	44%
	Car	569m	333m	41%
	Outdoor	521m	270m	48%
	Indoor	451m	269m	40%

All data were collected on-line by tracing the measurements of the mobile. Ground truth was obtained from a GPS receiver where GPS was available and from detailed maps in urban canyon and indoor places. In total, about 250,000 measurement reports were collected. The locations comprised indoor and outdoor locations and measurements inside a car.

B. Positioning accuracy

The evaluation of the measurements shows that the method gives a substantial improvement of accuracy compared to the simple CI/TA method, which estimates the position as the center of gravity of the intersection of the cell sector with the TA ring. Some numbers can be found in Tab. I. The average error is about 40 to 50% smaller. Best performance is obtained in outdoor locations, because unequal attenuation effects are small there. The results in the rural environment are generally worse than those in the urban one. This can be explained by two effects. First, the cell areas are larger, which increases the chance of finding a wrong position, and second the number of observed cells is smaller, and an analysis shows, that the obtainable accuracy depends on the number of measured cells, because every RXLEV measurement adds some information [7]. The accuracies in Tab. I are sufficient for many applications.

C. Performance of the uncertainty circle estimate

In section III-D an estimation of the uncertainty radius r with a confidence β was derived. Having the results of the algorithm and the true positions, this estimation can be validated. Since only one position estimate is made for every measurement, the statistical properties are not directly accessible. However, if the same distribution is assumed for all positions in a certain area and the variable

$$Q := \frac{\|\vec{x}_{\text{true}} - \vec{x}_{\text{est}}\|}{\sigma_{\vec{X}}} \tag{14}$$

is defined, the distribution function $f(q)$ can be calculated from the set of values of Q. The statement of the error estimation can then be reformulated as follows: The probability

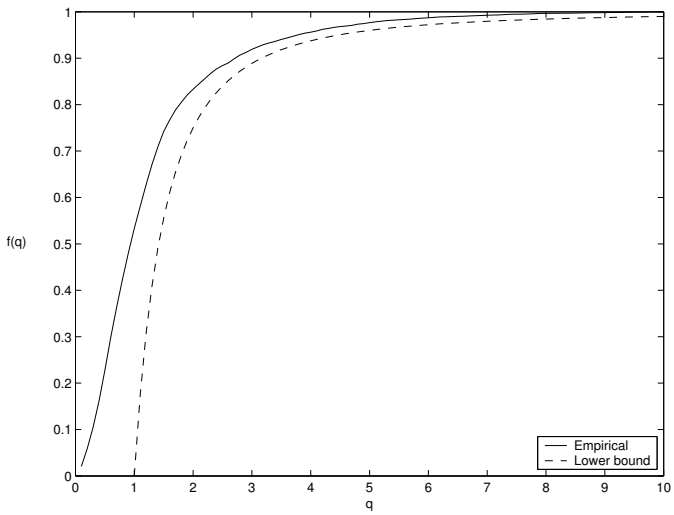

Fig. 2. Comparison of empirical error distribution with its lower bound

that $Q \leq 1/\sqrt{1-\beta}$ is greater than or equal to β, which is equivalent to

$$f(1/\sqrt{1-\beta}) \geq \beta. \tag{15}$$

Replacing $1/\sqrt{1-\beta}$ by q yields

$$f(q) \geq 1 - 1/q^2. \tag{16}$$

In figure 2 this lower bound is compared with the empirical distribution function. Two facts can be seen from this figure: First, the inequality really holds; second, the difference is quite small at the large confidence levels that are relevant in practice. Thus, the error estimation given by Eq. (11) provides a reliable error radius.

V. APPLICABILITY ON UMTS

Although the position method was developed for GSM networks in the previous sections, a detailed analysis shows, that it is applicable with little modification in UTRAN networks as well. Measurements corresponding to those from GSM (RXLEV, TA) do exist. RXLEV is replaced by RSCP (*Received signal code power*) or pathloss measurements, TA by the pair RTT (*Round trip time*) and *UE Rx-Tx time difference* [8]. The RTT measurement was designed for positioning purposes. It has a much higher resolution and accuracy than the TA in GSM. According to [9], the required accuracy is 0.5 chips, which is equivalent to 78 m.

VI. CONCLUSION

The positioning method presented in this paper is a substantial improvement of the existing CI/TA method. While improving the positioning accuracy significantly, it does not require any changes in the mobiles or in the network infrastructure. Nor is any individual calibration necessary. All that is needed is an entity, for example the SMLC, which is once initialized with preprocessed prediction data. It can then estimate positions and their errors from standard measurement reports. The method can be used both to answer individual

position requests or to obtain the positions of many users in order to get information about the spatial distribution of traffic in the network. It has been verified in extensive field trial in dense urban and in rural environments. Application in UTRAN networks is easily possible.

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