

Mobile Station Locating in GSM

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Abstract - The positioning of a Mobile Station (MS) will become mandatory in the U.S. to support wireless emergency calls in the near future. Also, lots of other applications are foreseen for the location service, when implemented. In this paper the authors will study the feasibility of the Global System for Mobile Communications (GSM) to MS location. The TDMA based GSM system offers some inherent means of calculating the location of the MS. In the MS there is already implemented a set of measurement functions that can be used to locate the MS. In this paper we investigate the use of Timing Advance (TA) and Observed Timing Difference (OTD).

INTRODUCTION

The exact location of the MS is not currently known in the GSM network. During a call the serving Base Transceiver Station (BTS) is known and thus the location of the MS is known within an accuracy of one cell. There are however many needs to locate the MS more exactly. The locating procedure must therefore be flexible to allow implementation of different services.

NEEDS FOR LOCATION

There is a multitude of possible applications for the Locating Service. The applications can be classified as government applications, operators' applications and commercial applications [1].

Government Applications

In some countries there are plans to legislate certain requirements for the MS locating.

- **Emergency Calls.** A growing number of emergency calls are made from mobile telephones. It has been estimated that in the major U.S. metropolitan areas 10% of the 9-1-1 calls originate from mobile phones [2].
- **Electronic Surveillance.** This application allows the authorities to track the location of any MS for law enforcement purposes.

Operators' Applications

These applications are needed by the network operator in order to provide special services for subscribers or to run the network more efficiently.

- **Home Zone Calls.** In order to compete with the fixed line operators, the cellular operator may want to offer mobile calls from a certain "home" area a lower price.
- **Handover.** In the handover algorithms the information about the location of the MS may be useful.

Commercial Services

These services consist of a pure positioning service offered by the operator as well as value added services that are based on the positioning service and offered by some independent service provider.

- **Positioning Service.** The operator may provide the user with the positioning service. The user can for example locate himself on the map, the location information can be used in the navigation system or a company could use this service to manage its fleet.
- **Value Added Services.** The locating can add value to other telecommunication services. For example, a mobile subscriber can order a taxi without knowing his position or the customer can ask information about transportation, accommodation or other services available near his current location.

CRITERIA FOR LOCATION METHODS

With the help of these criteria the different location methods can be compared and evaluated. Also the usability of the selected method must be assessed using these requirements.

- **Minor changes to existing network and terminals.** Ideally the existing terminals could use the locating service without modifications, in practice software modifications may be necessary.
- **Large, predictable coverage area.** The coverage area for the locating service should be large, ideally the same as the coverage area for calls. It should also be possible to predict the coverage area in advance.
- **Accurate locating.** The locating accuracy requirements are somewhat flexible. E.g., in the case of emergency calls, even a rough estimate is an improvement. In practice, a locating accuracy of one hundred meters or less would be satisfactory for many cases. It should also be possible to know exactly the maximum possible error of the location estimate.

- Light-weight protocol. The protocol used should be light-weight without an unbearable increase of the signaling traffic. This is especially critical for the air-interface. The requirement depends on the generality of the application and the obtained value of the location.
- Usability. The locating service should be able to locate both a stationary and a moving MS. The user should be able to make calls without disturbance when the Location Service is on. With the commercial services the network operator should be able to charge the users of the positioning service based on real use. The Location Service must not require any specific actions from the user.

POSSIBLE METHODS FOR LOCATION

The location technologies can be categorized in three groups: terrain navigation, radio location and proximity method.

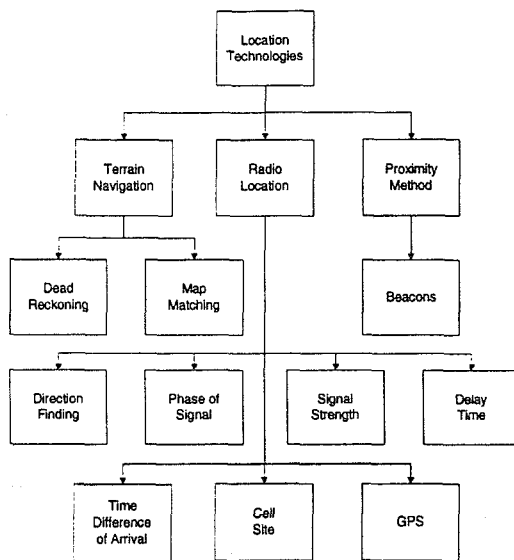


Fig. 1. Location technology categories [3]

In this study we have concentrated in the functions already available in the GSM.

Received Signal Level

The RX level can be used to estimate the distance between MS and BTS. However, rapidly changing propagation conditions will cause problems in the out-door environment.

The RX level is already measured in the GSM, this information is thus available at no extra costs. In spite of many problems, it might be possible to use the RX level in addition to some other method.

Cell Information

In urban areas where pico or nano cells are used, it may be sufficient to know just the serving cell. If this information is combined with the RX level information, the location of the MS can be estimated rather accurately. Unfortunately pico and nano cells are not yet used in GSM networks, but in the future the cell information may provide an easy way to locate the MS.

Delay Time Between MS and BTS

In a TDMA system the time delay between the MS and the serving BTS must be known to avoid overlapping time slots. This is called Timing Advance (TA) in the GSM. If we want to know TA also to other BTSs, the MS must communicate also with the neighbour BTSs. When TA to at least three BTSs is known, the location of the MS can be calculated.

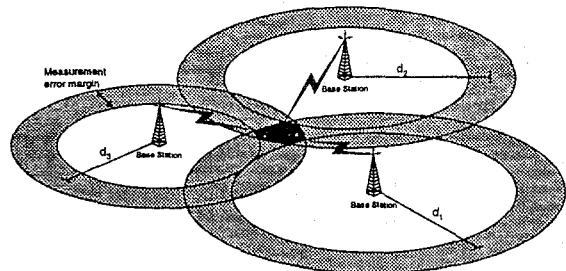


Fig. 2. The location estimate of the MS based on TA

The MS location can be found in the intersection of the circles drawn around at least 3 BTSs. The radius of the circle is obtained from TA. The width of the circle depends on the measurement accuracy of TA.

Time Difference of Arrival

This method concentrates on the timing difference of the received signals, not on the absolute delay time. In the GSM system this is called Observed Time Difference (OTD) and it is already measured by the MS. In order to support the so called pseudo-synchronous handover, where a new TA to be used with a new BTS is told to the MS in the handover command, the MS must keep track of the timings of the neighbour BTSs that it is monitoring with an accuracy of ± 1 bit period. The OTD denotes the timing difference between the serving BTS and the neighbour BTS measured by the MS [4].

The MS location estimate is calculated from the OTD based on the fact that the possible location for the MS observing a constant OTD value between two BTSs is a hyperbola. The MS can be located in the intersection of two hyperbolas obtained with three base stations and two OTDs. If more

OTDs are available the possible location area can be reduced [5].

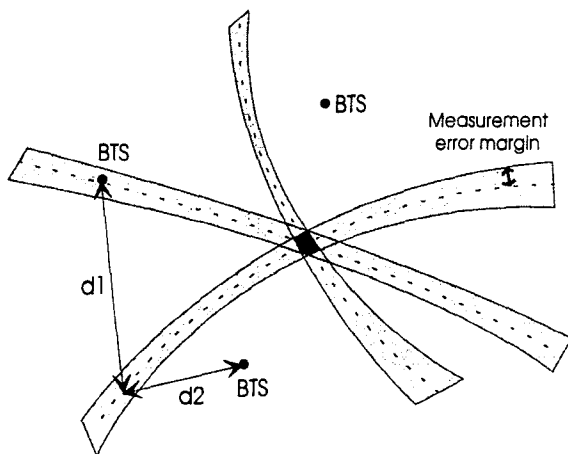


Fig. 3. The location estimate based on OTD

The dashed line represents the measured OTD, i.e., the distance difference to two BTSs is constant. The measurement result is not exact, thus the gray area represents the possible area for the MS based on that OTD measurement. The black area at the intersection of all hyperbolas is the possible area for the MS.

There are three error components in this method: (1) the BTS timing error in the transmission with respect to the other BTSs, (2) the MS timebase error between subsequent receptions and (3) the MS measurement error of the received signal, composed of the detection error and the error due to a missing line of sight (LOS) component.

The first two error components are negligible, the main error source is the missing LOS component of the received signal or the incapability to detect it. It is obvious that the detection accuracy of ± 1 bit period in current specifications is far too lax for practical purposes. We have a strong belief that fundamental improvements are possible with the current component technology and in this study we have assumed $\pm 1/8$ bit period accuracy.

Evaluation of the different methods

Observing the cell identity or the RX level requires only minor software changes, but the accuracy that they offer is very poor. When pico and nano cells are taken in to wide use, the cell identity can be applied.

The TA method can be implemented with only software changes in the network, but the OTD method requires changes also in the MS design, in the software and possibly also in the hardware. The OTD method is theoretically better for two reasons:

- The coverage area is larger because the MS has to only detect the arrival of the BTS signal but not necessarily decode it and because the downlink (BTS to MS) direction is more favourable for communication due to greater BTS transmission power. If the TA method was used, the MS must be able to communicate with the neighbour BTSs.
- The accuracy in the OTD method is better because only the changes in the synchronization error between the MS and the BTSs degrade its performance. In the delay time method also the absolute synchronization error has an influence: in fact, from the BTS's point of view it does not make any difference if the timing delay is due to the distance between the MS and the BTS or the synchronization error of the MS.

Of course, since the TA to the serving BTS is already known, it is advantageous to use this information also.

IMPROVING MEASUREMENT PROCESS

At the moment the MS performs the OTD measurements, but the rate is too low for the locating purposes. Currently the OTD measurements are performed by observing the beacon frequency, the carrier where Frequency Correction Channel (FCCH) and Synchronization Channel (SCH) are situated. First the rough timing is achieved by the help of FCCH, then the accurate timing is obtained by decoding the burst on SCH. Because of the sophisticated frame structure of the GSM, it can be guaranteed that the MS can listen to SCH and FCCH bursts of the other BTSs during a call between transmission and reception.

Unfortunately the rate is too low: Currently, at most 2.1 seconds is needed to make the first OTD measurement. After this, making one OTD measurement takes at most 1440 ms and on an average 660 ms. In practice, because while waiting for the occurrence of the SCH of a specific neighbour, another SCH can be received, 6-8 neighbour SCH blocks can be decoded in 2-3 seconds. The exact speed depends on the distribution of the SCH blocks in the TCH idle frames of the serving cell.

New OTD measurement method

The key idea in the improved OTD measurement process is to use the other bursts than the SCH burst for timing. This would allow increasing the OTD measurement rate, because it would not be necessary to wait until the SCH burst fits to the measurement window. As there is a normal burst in almost every time slot of the Broadcast Control Channel (BCCH) carrier, there is a lot of synchronization data available and the measurement can be made very fast.

When we want to measure just the timing of the adjacent cells, it is adequate to receive the Training Sequence (TS) of

the normal bursts only. In every TDMA frame it is physically possible to receive at least one TS and in the idle frame it is possible to receive several TSs if the frequency is not changed between the TSs in one TDMA frame. Several TSs would be used for averaging the measurement results.

With this method the OTD measurement frequency may be up to some hundreds of measurements per second. The drawback of this method is that because the Base transceiver Station Identity Code (BSIC) is not decoded, the MS may measure accidentally a signal from a wrong BTS transmitting in the same frequency. In practice the error probability is quite low.

Effect of DTX and half rate codec

Using Discontinuous Transmission (DTX) and half rate speech codec will allow even more time for the MS to perform the OTD measurements. It enables to make more measurements in one interval and to achieve better results.

Measurement of the TA

The accuracy of the delay time estimate between the MS and the BTS can be improved using the measurement result that the BTS uses to determine the TA instead of the actual TA value. Thus the quantization error due to one bit resolution of the TA is avoided.

PROCESSING OF MEASUREMENT RESULTS TO LOCATION ESTIMATE

The Location Service Center (LSC) represents all the functions that are needed to calculate the location estimate based on the measurement data. The LSC's place in the network is not defined, it may be situated in one network element or it may be decentralized into several physical elements.

The MS may preprocess the measured OTD values based on the fact that the error due to reflection always causes the BTS to seem to be further away. The MS may also detect reflected signals based on the shape of the impulse response. If the LOS signal is received, the multipath components are entirely suppressed by the powerful direct signal component and thus it should be possible to detect the LOS situation [6,7]. If the MS informs the LSC which measurement results are based on reflected signals, the LSC can try to correct these measurement results, e.g., by subtracting some area specific coefficient from the measurement result. If enough unreflected measurement results are received, the reflected results can be ignored.

One may try to detect the erroneous location estimates with other techniques. E.g., if the location estimates based on successive measurements or the mobile speed monitoring algorithm indicate that the MS is moving with a certain

speed, a single location estimate that indicates that the MS is moving considerably faster can be ignored. The accepted location estimates can be processed, e.g., by averaging or applying different types of filters, in order to improve accuracy and reliability.

SIGNALING FOR LOCATION

There are currently no methods of transferring the measurement results and the location estimates between the MS, the LSC and location information destination.

The measurement information is divided between the MS and the serving BTS. The most critical part is the transferring of the OTD measurement results from the MS to the network, because during a call no free signaling capacity is available. In the network there are no restrictions on implementing the needed signaling with new messages or with new information elements in existing messages.

Between BTS and MS

In the GSM system the MS sends constantly Measurement Report Messages on SACCH (Slow Associated Control Channel). The message contains the results of the measurements gathered from the serving and neighbour BTSs.

It is possible to exploit the Measurement Report Message in transferring the location data from the MS to the serving BTS. There are a lot of advantages in using that message:

1. The Measurement Report Message is sent frequently, the maximum rate is one message in each 480 ms. The frequent sending of the measurement result helps the LSC to locate the moving MS accurately.
2. No extra load on the air interface is generated, because the existing Measurement Report Message is used. There will thus be no degrading of the transmission quality.
3. Using only the least important part of the message in transferring the location information, only a little harm is done to the handover and power control processes using the measurement information.
4. The MS can easily set the sending parameters either dynamically or according to the orders by the network.
5. The sending can take place when the user is making a call.

One scenario would be that the network tells the MS the parameters for sending measurement information. The parameters could be the rate of the sending and the minimum number of the neighbour cell measurements that

must be sent. When a modified Measurement Report Message is to be sent, the MS indicates it with a flag bit.

ASSESSING USABILITY AND ACCURACY

The coverage area for the OTD method was assessed by measuring the number of BTS sites the MS can receive. The following measurements were done by using an external car antenna inside a car.

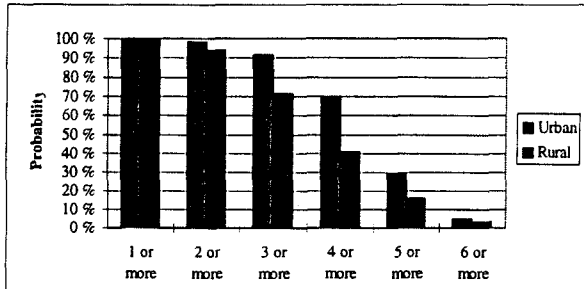


Fig. 4. Number of received BTSs in urban and rural environment.

The measurement in an urban environment was made in a metropolitan area of 800 000 inhabitants. Over 92% of the time three or more BTS were received. If the external antenna was used outside the car, 97% of the time over three BTS were received.

The results from a rural environment are from a 350 km long measurement route. Over 71% of the time more than three BTS were received.

In the urban environment the location seems to be possible almost everywhere, at least outdoors. In the rural environment the situation is more difficult, the location is not possible in a significant part of the rural environment.

It should be noted that if the requirements of location were taken into account in the network planning, it would be possible to increase the area where three or more BTSs can be received.

Estimation of errors

As said, the major source of error is a missing line of sight (LOS) component of the received signal or incapability to detect it. The failure to detect the leading edge of the signal will result in a location estimation error. We call this error NLOS error (error due NLOS situation). Unfortunately the NLOS error has not been subject to research before. Many impulse response measurements have been made, but the focus has been on the shape of the impulse response, not on the absolute timing of the impulse response. That is why we have been obligated to use rough estimates for NLOS error.

In many environments the NLOS situation was found quite common, actually only flat rural environment offers almost all the time a LOS connection to the BTS [7,8]. But in cities (when macro cells are used) the waves propagate over the roofs and the reflections and the diffractions are caused by obstacles near the MS, thus causing only short excess delays [9].

Simulation of the accuracy

To assess the achievable location accuracy with the OTD method we decided to implement a location simulator.

Because all the neighbour BTSs can be measured several times in a second, the MS moves so little between the measurements, that the speed of the MS had no significant effect to the location accuracy. However, due to transmission and processing delays the location estimate of the moving MS will be late and the delay depends on the speed of the MS.

The assumptions used in simulations were: the probability to detect a LOS component of the signal from the serving BTS is 90%, and from the neighbour BTS 50%, the average distance to the serving BTS is about 2 km and to neighbour BTSs about 4-6 km. The measurement error is expressed in bits, one bit corresponds to 3.6 us or 1100 meters.

The following figure presents the effect of the maximum measurement error (NLOS error + detection error) to the mean location accuracy. The detection error was $\pm 1/8$ bit and the NLOS error from the serving BTS was half of the NLOS error from the neighbour BTSs. The simulations were done with three or four BTSs. If more than four BTSs are heard the accuracy is better, but the improvement is smaller than between three and four BTSs.

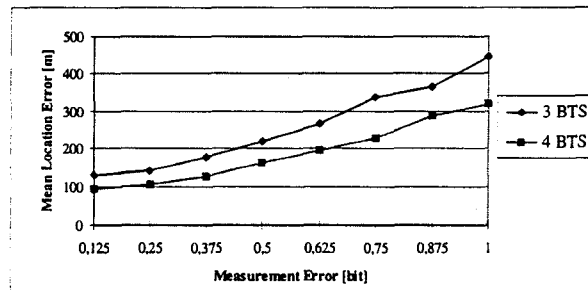


Fig. 6. The effect of MS's maximum measurement error to the mean location accuracy

The mean location accuracy was observed to have a quite linear dependency on the measurement error. The big measurement errors are caused by the NLOS errors, because compared to the NLOS error the order of the detection error is smaller.

The effect of correcting reflected measurement results was also simulated. Corrected estimates were calculated in the following way: Reflected signals were detected with the accuracy of 95%. If the signal was reflected the OTD measurement result was corrected, i.e., in this simulation we subtracted half of the possible maximum NLOS error.

The corrected estimates are on an average about 20% better than the raw estimates. Correcting reflected estimates in reality is not so simple, however, this presents some kind of an estimate of how much the detection of reflected signals could improve the location accuracy.

Conclusions

The reliability of these simulation results depends on the initial assumptions made. The results presented here are only tentative, in reality the situation is more complex. These results can, however, be used to assess achievable order of location accuracy, and how different elements affect the accuracy. Field tests made in real environment are needed to verify the simulation results.

SUMMARY

This document examines the possibilities to locate MS making as little changes as possible to the network and MS. Only the solutions that were based on the GSM network architecture were studied.

There are several ways to implement the location of the MS. The method can be based on the already measured Observed Timing Difference (OTD) provided that the measurement accuracy is increased. In addition, Timing Advance (TA) to the serving BTS can be used in the calculations. Current OTD measurement rate is not enough, thus a new measurement method was developed.

According to the simulations made, the mean location accuracy of 100-200 meters is achievable. In some environments the measurement error caused by the reflected signal may, however, degrade the location accuracy considerably. More research is needed to verify the simulation results in a real environment.

When comparing the OTD method to the set criteria, it can be noted that the OTD method can be implemented mainly with software changes. In order to achieve high accuracy, it might also be necessary to make hardware changes to the MS. The coverage area is large, it is necessary only to detect a signal from three BTSs, not to be able to decode it. The coverage area for the Location Service can be predicted with the same accuracy as the whole network coverage area and the area may be increased by increasing the transmitted power of the BCCH signal. The signaling needed for the OTD method can also be implemented without major problems. The usability of the OTD method is good: the

method is applicable for a moving MS, works when a call is on and, since the location is calculated in the LSC, the operator may connect the billing system easily. Thus the OTD method fulfils the criteria rather well.

The processing of the raw measurement results to reliable location estimate offers a multitude of research items. It is supposed that with the help of intelligent processing the mean location error and especially the maximum errors can be reduced considerably.

ACKNOWLEDGEMENTS

The improved measurement process was invented by Mr. Jukka Ranta, Nokia Mobile Phones. The coverage measurements were made by the Network Planning Department of Nokia Telecommunications.

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Biographies



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