Estimated accuracy of location in mobile networks using E-OTD

Master Thesis
in
Information and Communication
Technology

By
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Abstract

This master thesis was performed for Telenor Research and Development, department Fornebu, Norway. The assignment was to evaluate the accuracy of the Enhanced Observed Time Difference (E-OTD) location method.

Location related services are described as the next revolution on services and functionality in the mobile network. Location technology will help the operator to estimate the location of a mobile station in the network. But different location services require different accuracy of the location estimate. It is therefore important to find out what location method(s) is suitable for the operators needs.

This report will give an overview of the most important location technologies for the GSM network on the market today and examples of the most common location services. It will also describe the network architecture needed to implement the E-OTD method.

The main subject of the report is evaluation of the E-OTD location method. The basics and the calculation methods are described in detail. A simulation model for the E-OTD method was also created during the work of this master thesis. This model and the results of the simulation runs are explained and shown.

The E-OTD method requires network update in the form of Location Measurement Units (LMUs) to compensate for the GSM network not being synchronised. These units will provide the operator with upgrade costs. It was therefore evaluated the requirements for LMUs in the work of this master thesis, and the results is shown and discussed in this report.

Preface

This thesis, *"Estimated accuracy of location in mobile networks using E-OTD"*, is a part of the master of engineering degree in Information and Communication Technology (ICT) at Agder University College. The theses, written for Telenor Research and Development, division Fornebu, evaluate the estimated accuracy of the E-OTD location method in the GSM network. It has been a comprehensive and challenging task, which required understanding of the E-OTD location method.

First we would like to emphasis that this report has the purpose of covering both the demands of Telenor R&D and the formal demands of a thesis at Agder University College. This limits us to write a balanced structured report satisfying all users of this report.

We started the thesis January '02 by getting an overview of the E-OTD method. Early in February we presented the preliminary study to our supervisor and contact at Agder University College.

The preliminary study introduced a progress schedule that we followed during the rest of the thesis. We performed a literature study, constructed a MATLAB model and simulated the characteristics of E-OTD based on our model. We kept on studying the literature to fill some holes in the thesis, and in the end we spent a lot of time to evaluate the results. The most time consuming part of this thesis, has been the programming of the simulation model in MATLAB. The model and the input parameters are the property of Telenor R&D, and will not be published nor distributed to the public.

Magne Pettersen has been our contact and supervisor at Telenor Research and Development. He has done a great job supporting us during the whole project, and contributed to many constructive discussions during the thesis. We would also like to thank Ragnar Eckhoff for his help with MATLAB, and Per Hjalmar Lehne from Telenor R&D. Hermann Lia has been our contact for Agder University College during the project. He has been a great help structuring the report. We would like to thank him for giving us advice and guidance throughout the project.

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1 Introduction

Location-based services are forecast to be soon one of the most important sources of operator revenue. It is estimated that by 2006 mobile location services will generate revenue of more than 20 billion USD. Worldwide, mobile location connections will rise from 2 million in 2001 to 565 million in 2006. This will represent 29% of all mobile connections. This is according to a report from Ovum Ltd. [40].

The provision of location services is a way for the operator to differentiate on the market, reduce churn and increase revenues. By using the mobile network and infrastructure, or by use of integrated GPS receivers, it is possible to pinpoint the location of a MS by a few metres. Accessing this new type of information opens up a whole new range of use of the mobile terminal.

1.1 Master thesis

The master thesis is performed at Agder University College, Department of Technology, Institute of Information and Communication Technology (ICT), Norway. As a general rule all master thesis must at least fulfil some standard requirements. First and foremost the thesis shall give an independent deepening within a central sphere of the ICT Master study itself. Secondly there is a formal requirement designed by the university college, which is described below.

The text below is a translation from Norwegian into English and describes the main contents of the subject code (IKT6400). The text is intended to be a guidance and not any absolute requirement set by Agder University College:

“The master thesis assignment is an independent section of work within a central sphere of the study. The work shall have a character of research i.e. the thesis must have elements of new knowledge or methods. Pure design, development, programming tasks should be avoided. Normally a preliminary study of 2 weighted points in size is performed. The preliminary study can be; literature search, preliminary exploration search, mapping of the status on the current topic or an intensive training period of methods or techniques. The master thesis assignment shall be put into a report that describes the problem, results and the work. Prototypes and/or other products that are developed could enter as a part of the solution. The assignment shall also be orally presented in a presentation.”

The general evaluation criteria are given on the basis of a written report on the subject, any products or prototype that is part of the master thesis, and a final presentation. The subject supervisor and an external examiner evaluate the thesis [21].

1.2 A description of the assignment

The assignment is to evaluate the accuracy Telenor Mobile can get on their location estimates when implementing E-OTD in the GSM network. The thesis is performed for Telenor Research and Development, division Fornebu, Norway.

The assignment has been divided into two main parts. The first part examines the most significant location technologies on the market today, with special emphasis on E-OTD. The second part of the assignment is to estimate which accuracy Telenor Mobile can get on their location estimates by implementing E-OTD in their mobile network. The hardware upgrades (LMUs) needed for E-OTD is expensive and Telenor R&D wants an estimation of the density of LMUs that is required to accomplish a reasonable location estimate.

1.3 Original task description

The original task description was given by Telenor R&D. The text is translated from Norwegian into English. The original task description is as follows:

Project title: Estimated accuracy of location in mobile networks using E-OTD
Description of the project: Location specific services are expected to be of great importance within the area of mobile communication both on short and long term. Examples of services may be assistance in navigation, mobile information services or emergencies. Location specific information can also be used in order to achieve improved accessibility and to reduce traffic on overcrowded cells in the network, or in fighting crime.

The benefits of these services depend on the quality of the estimated position and it is crucial, in this context, to achieve the greatest possible level of precision.

Existing location-servers for GSM are usually based on a technique, which uses base station information and the *timing advance-parameter* (cell id + TA). Experiments have shown that this relatively simple technique has evident limitations concerning precision, especially in rural areas. This calls for evaluation of more advanced techniques.

It is particularly interesting to evaluate the precision of *enhanced observed time difference* (E-OTD). The E-OTD positioning method generally relies upon measuring the time at which signals from the Base Transceiver Station (BTS) arrive at two geographically dispersed locations – the mobile phone/station (MS) itself and a fixed measuring point known as the Location Measurement Unit (LMU) whose location is known. The position of the MS is determined by comparing the time differences between the two sets of timing measurements. Because of the great demand for additional hardware, such as LMUs, the introduction of E-OTD will require significant investments.

The assignment will be to evaluate how accurate the estimate of the position will be when applying E-OTD in Telenor Mobile's network. This will be accomplished by combining simulations and reusing previously recorded measurements.

The simulations must be carried out in MATLAB and will be based on assumptions concerning an expected implementation of E-OTD, e.g. in regard to the number of LMUs and the precision of the time measurements.

The measurements available are simultaneous measurements of GSM parameters and the mobile station position using GPS. These will also provide information about the signal levels of the different base transceiver stations in the network for a given position.

1.4 Thesis boundaries

Because no E-OTD implementation is available for test purposes, we have simulated an implementation in MATLAB. The simulations are based on measured data from an earlier project performed by Telenor R&D [33], which looked into the position estimates done by using the *global cell id + timing advance* parameters.

1.5 Literature review

Information about location technologies is seldom found in any books. The information gathered for this thesis is mainly found on the World Wide Web, in internal reports from Telenor R&D and Ericsson and from papers and articles in the open literature. In addition to this, relevant information and a complete set of the specifications can be found on the homepages of Third Generation Partnership Project (3GPP). 3GPP is a group of equal partners, which provides globally applicable technical specifications for a 3rd generation mobile system based on the evolved GSM core network [46]. The library of Institute of Electrical and Electronics Engineers (IEEE) have also been widely used [49].

1.6 Report structure

Starting with the next chapter, the report is organised in the following way; chapter 2 gives an introduction to the use and background for location services. This is to show the reader how important location specific services are expected to be within the area of mobile communication, both on short and long term. The next chapter then discusses different location methods. This is done in order to bring key issues to the reader's attention. Chapter 4 gives an overview of the network elements used in the network to perform location services. Chapter 5 contains the main topic of this master thesis, the simulation of E-OTD. The chapter contains a basic description of E-OTD, a description of the simulations performed, and results from the simulations. An estimation of the density of LMUs needed to accomplish a reasonable location estimate is described in chapter 6. Chapter 7 contains discussions of relevant topics in the report. Conclusions are in chapter 8.

A list covering all abbreviations used in the report can be found as the very last chapter.

2 An introduction to location services

Location related services are described as the next revolution on services and functionality in the mobile network. Examples of services using mobile location could be:

- Location sensitive billing
- Location of emergency calls and roadside assistance
- Driving directions and assistance
- Mobile yellow pages (e.g. where is the nearest pizza restaurant?)
- Tracking (packages, cars, people, busses etc.)
- Location based messages (commercials)

The quality of the services will all depend on the accuracy of the location estimates. This accuracy depends on the location technologies used, and on the network topology. However not all services requires the same accuracy on the location estimate.

This chapter will focus on the two main forces for implementing location services for the operator, government requirements and commercial services.

2.1 Government requirements

Some regulations have accelerated the research of location technologies. The Enhanced 911 (E-911) regulative by the US Federal Communications Commission (FCC) pushes location technologies in the USA. In a series of orders since 1996, the FCC has taken action to improve the quality and reliability of 911 emergency services for wireless phone users, by adopting rules to govern the availability of basic 911 services and the implementation of E-911 for wireless services.

In Europe the European Commission in 1998 established a universal 112 call number to support emergency services to both landline and mobile users. 112 calls will enable wireless and landline telephone callers in countries that are members of the European Union (EU) to dial a single number, 112, for fire, medical, and police emergencies. 112 calls are the European equivalent of the US 911 call. On July 12, 2000 the Commission of European Communities issued a proposal for a directive on universal service and users' rights relating to electronic communications networks.

2.1.1 Enhanced 911 (E-911)

The FCC's wireless 911 rules seek to improve the reliability of wireless 911 services and to provide emergency services personnel with location information that will enable them to locate and provide assistance to wireless 911 callers much more quickly. To accomplish these goals, the agency has required that wireless carriers implement an E-911 service, subject to certain conditions and schedules. The wireless 911 rules apply to all cellular licensees, broadband Personal Communications Service (PCS) licensees, and certain Specialized Mobile Radio (SMR) licensees.

The Phase I requirements of the FCC rules implemented that as of April 1, 1998, or within six months of a request by the designated Public Safety Answering Point (PSAP), whichever is later, covered carriers are required to provide to the PSAP the telephone number of the originator of a 911 call and the location of the cell site or base station receiving a 911 call. This information assists in the provision of timely emergency responses both by providing some information about the general location from which the call is being received and by permitting emergency call takers to re-establish a connection with the caller if the call is disconnected.

Wireless carriers must provide to public safety answering points:

- Telephone number of a wireless 911 caller
- Cell site or base station receiving a wireless 911 call

Wireless carriers are required to provide Automatic Location Identification (ALI) as part of phase II E-911 implementation beginning October 1, 2001, as detailed below. Originally, the FCC's rules envisioned that carriers would need to deploy network-based technologies to provide ALI. In the past several years, there have been significant advances in location technologies that employ new or upgraded handsets. In September 1999, the FCC revised its rules to better enable carriers to use handset-based location technologies to meet the Phase II requirements. In particular, the FCC established separate accuracy requirements and deployment schedules for network-based and handset-based technologies. In August 2000, the FCC made minor adjustments to the deployment schedule for handset-based technologies. The E-911 phase II requirements for accuracy can be found in Table 1 [19].

Table 1. Accuracy required for locating mobile terminals in phase II E-911

Solutions	67% of calls	95% of calls
Handset based	50 m	150 m
Network based	100 m	300 m

2.1.2 Enhanced 112 (E-112)

While on the surface the Enhanced 112 (E-112) services appears to be similar to the US emergency 911 services, it will be some time before the EU will have services comparable to the US services. One of the roadblocks facing the EU is the diversity of currently offered emergency services in the member states.

On July 12, 2000 the Commission of European Communities issued a proposal for a directive on universal service and users' rights relating to electronic communications networks. Article 22 of the proposal addresses the European emergency number topic. It states [18]:

- Member states shall ensure that, in addition to any other national emergency call numbers specified by the national regulatory authorities, all users of publicly available telephone services, including users of public pay telephones, are able to call the emergency services free of charge, by using the single European emergency call number '112'.
- Member states shall ensure that calls to the single European emergency call number '112' are appropriately answered and handled in a manner best suited to the national organization of emergency systems and within the technological possibilities of the networks.
- Member states shall ensure that undertakings which operate public telephone networks make caller location information available to authorities handling emergencies, where technically feasible, for all calls to the European emergency number '112'.
- Member states shall ensure that citizens are adequately informed about the existence and use of the European emergency call number '112'. Paragraph 1 of Article 22, states that emergency services should be available to all users of public networks. These also include wireless networks. Paragraph 3 requires that caller's location information should be available to the authorities handling emergencies.

To provide technical expertise for E-112 location objectives, the European Community established the LOcation of Cellular Users for Emergency Services project (LOCUS). LOCUS was a 14 months project that started on July 27, 2000.

To facilitate the implementation of emergency services, the Commission set up the Co-ordination Group on Access to Location Information by Emergency Services (CGALIES). The main task of CGALIES was to identify the relevant implementation issues regarding enhancing emergency services in Europe with the provision that location information be provided in a timely and financially sound manner and to build a consensus on the Europe-wide implementation.

On February 28, 2002, the CGALIES issued a final report on implementation issues related to access to location information by emergency services (E-112) in the European Union. The report complements and facilitates the political discussion in the European Parliament and the Council on the new regulatory framework for E-112. The proposed requirements can be divided into tree levels:

- “Call routing”, i.e. requirements associated to the determination of the appropriate emergency response centre the call must be routed to.
- “Dispatching”, i.e. requirements associated to the determination of the appropriate local emergency team to be despatched by the emergency response centre.
- “Caller finding”, i.e. requirements associated to the “accurate” determination of the caller’s location to enable the local emergency team to find the victim as quickly as possible.

The requirements associated to the two first levels are shown in Table 2.

Table 2. Mobile call routing requirements for E-112

	Urban	Suburban	Rural
"mobile call routing" requirements	~ 1 km	~ 10 km	up to ~ 35 km

The requirements associated to "Mobile caller finding" are the most demanding ones. Two additional environments have been considered for specification (indoor and highway/crossroads), as well as two different cases: "caller can provide general information about his location" and "caller can not provide any information" (according to statistics provided by member countries in the EU, the latter case represents approximately 6% of mobile emergency calls).

The proposed requirements are obtained through a questionnaire among the member countries in the EU, and are shown in Table 3 [18]. The caller's position must be available within 30 seconds of call initiation.

Table 3. Proposed requirements for location accuracy in E-112

	Indoor	Urban	Suburban	Rural	Highway/ crossroads
Caller can provide general information	10 – 50 m	25 – 150 m	50 – 500 m	100 – 500 m	100 – 500 m
Caller can not provide any information	10 – 50 m	10 – 150 m	10 – 500 m	10 – 500 m	10 – 500 m

In addition to this positioning information, emergency services indicate that it can be useful for an emergency centre to receive as quickly as possible a first rough estimate of the caller's location (and to receive later the accurate position information). According to a questionnaire among EU member countries, the required accuracy for this initial positioning information is generally situated between 200 and 300 m (for all environments). The initial position should be available approximately 7 seconds after the call is initiated.

Emergency services also indicate that the availability of location information could be used not only to determine the caller's location, but to recognise that several calls are for the same incident ("call cluster"). The associated accuracy requirements are approximately 150 m in urban areas, and 500 m in suburban and rural areas. In such a case, location information must be available before the call is handled, that is to say a few seconds after the initiation of the call.

Emergency services also pay a lot of attention to the reliability of the location information, which is to the degree of confidence they may have in the position estimate. Consequently, emergency services want to be provided not only with a mobile position estimate (X, Y co-ordinates), but also with an indication of the reliability associated to the position estimate.

The questionnaire mentioned earlier shows that 67% can be considered as the minimum acceptable reliability level associated to the position estimate. It is probable that a refinement of this requirement would lead to a more demanding reliability (> 95%). However it must be noted that for any positioning technology, specifying a too stringent reliability requirement would lead to a very large geographical area which could become useless for emergency services. It is necessary to find a balance between the level of accuracy and the level of reliability [18].

In some ways, the EU E-112 task is more complicated than the US E-911 project. In the US the efforts to standardize the emergency numbering system has been going on for many years. The European Union, on the other hand, must build a uniform system from the diverse emergency systems offered by its member countries.

The lack of adequate standardisation is another roadblock that may restrict implementation of location-based services. The absence of standards for location testing performance is problematic and so is the lack of interoperability standards for location-based services.

The implementation and maintenance cost of emergency services is another concern because the technologies that may best meet the requirements could also be expensive. Deploying these technologies before an appropriate business plan is in place would represent a financial risk for telecommunication operators.

Furthermore, location data is only useful if the emergency entities are able to exploit it. The problem is a lack of requirements and specifications at the level of emergency response centres. In addition to that, there is a great diversity in organization and equipment among the emergency response centres in the EU. Upgrading all these centres in order to achieve a homogeneous level of service across the EU will be difficult. In the best-case scenario, emergency response centres would be ready to handle location information only after 2005-2006 [43].

2.2 Location based services

The new upcoming implementation of location technologies opens up a whole new world of services, communicating and sending messages based on the location of the user (MS).

2.2.1 Safety

A wide range of safety solutions open up by use of location technology:

- *Emergency alert services*, services like E-911 and E-112 will be provided with the location of the caller. This way, valuable time is saved, and the caller can concentrate on more important matters, like describing the scene or helping people.
- *Roadside assistance*, in the same way as with emergency alert services, if your car have a breakdown, it would be very useful to know exactly where the car is placed, saving both time and money.
- *Safety alarm*, social workers, watchmen and alone-working people like forestry workers, can send out a distress signal with an exact position, just by using the MS.

2.2.2 Location based charging

Location based charging allows a subscriber to be charged different rates depending on the subscriber's location or geographic zone, or changes in location or zone. The rates charged may be applicable to the entire duration of the call, or to only a part of call's duration. This service may be provided on an individual subscriber basis, or on a group basis. E.g. when provided on an individual basis, this service could apply reduced rates to those areas most often frequented by the subscriber by taking into consideration the subscriber's daily route and life style. Different rates may be applied at country clubs, golf courses, or shopping malls. E.g. a "home" zone may be defined centred around a user’s home, an agreed larger area, work or travel corridor or some unrelated zone. Additionally, different rates may be applied in different zones based on the time of day or week.

In addition to being applicable on an individual basis, this service may be applicable on a group basis, which may be desirable e.g. for business groups. Locations may be defined for business groups to include corporate campuses, work zones or business zones with different charging rates. Individual and group subscribers should be notified of the zone or billing rate currently applicable, and be notified when the rate changes. Location based charging may be invoked upon initial registration. A charging zone would then be associated with the subscriber's location. When the subscriber moves to a different zone, the subscriber would be notified.

2.2.3 Fleet and asset management / tracking services

Fleet and asset management services allow the tracking of location and status of specific service group users. Examples may include a supervisor of a delivery service who needs to know the location and status of employees, parents who need to know where their children are, animal tracking, and tracking of assets. The service may be invoked by the managing entity, or the entity being managed, depending on the service being provided.

Fleet management may track the location of vehicles (cars, trucks, etc.) and use location information to optimise services.

Asset management services, for example, may range from asset visualisation (general reporting of position) to stolen vehicle location and reporting of location when an asset leaves or enters a defined zone.

2.2.4 Traffic monitoring / tracking

Mobiles in cars could be anonymously sampled to determine average velocity of vehicles and detect and report congestion.

Congestion, average flow rates, vehicle occupancy and related traffic information can be gathered from a variety of sources including roadside telemetric sensors, roadside assistance organisations and ad-hoc reports from individual drivers.

2.2.5 Enhanced Call Routing

Enhanced Call Routing (ECR) allows subscriber or user calls to be routed to the closest service client based on the location of the originating and terminating calls of the user. The user may optionally dial a feature or service code to invoke the service. In addition to routing the call based on location, ECR should be capable of delivering the location information to the associated service client. For example, this capability may be needed for services such as Emergency Roadside Service. This could be used for the purpose of dispatching service agents for ECR service clients that can make use of this information.

2.2.6 Location based information services

Location based information services allow subscribers to access information for which the information is filtered and tailored based on the location of the requesting user. Service requests may be initiated on demand by subscribers, or automatically when triggering conditions are met, and may be a singular request or result in periodic responses. Examples of location based information services are described below.

City sightseeing: This would enable the delivery of location specific information to a sightseer. Such information might describe historical sites, providing navigation directions between sites, facilitate finding the nearest restaurant, bank, airport, bus terminal, restroom facility, etc.

Location dependent content broadcast. The main characteristic of this service category is that the network automatically broadcasts information to terminals in a certain geographical area. The information may be broadcast to all terminals in a given area or only to members of a specific group (perhaps only to members of a specific organization). The user may disable the functionality totally from the terminal or select only the information categories that the user is interested in. An example of such a service may be localized advertising. E.g. merchants could broadcast advertisements to passers-by based on location information. *Mobile Yellow Pages*. The Internet has also changed how people find phone numbers. Instead of thumbing through the yellow pages or calling directory assistance you simply could go online and search the number. Wireless takes this one step further by adding the location of the subscriber to the search. Now the phone number of the nearest location can be ascertained as opposed to all locations within the nearest area. Mobile Yellow Pages services provide the user with the location of the nearest service point, e.g. Italian restaurant. The result of the query may be a list of service points fulfilling the criteria (e.g. Italian restaurants within three kilometres). The information can be provided to the users in text format (e.g. name of the restaurant, address and telephone number) or in graphical format (map showing the location of the user and the restaurants).

Finding friends. Friend finders services are now available that allow users to find the locations of their friends or family. The service uses Short Message Services (SMS), it operates in Europe and Southeast Asia and has become extremely popular. The service automatically notifies a user when a selected person (who also has a wireless device) is nearby or has entered into a specified area. Such a service could be designed to notify a parent when a child has arrived at home, school, or other specified location.

Driving directions and navigating. Another industry that is working at exploiting location technology is the automotive market. An application can be dynamic route guidance. Dynamic route guidance can be described as a 'traffic-aware' turn-by-turn navigation system. A dynamic route guidance system would incorporate information or knowledge of road conditions in order to provide instructions on the quickest route to an end destination. Many factors can affect road conditions such as road closures, accidents, lane closures, construction, heavy congestion, major events, etc, and this information could be used by the system. Another alternative approach to providing dynamic route guidance would be to use speed information as the most important information element. Vehicle speed or how fast vehicles are travelling on a particular segment of a highway would be very useful in determining the shortest travel time to a destination and the availability of speed information would make a system more traffic-aware.

2.3 Summary

From the carriers point of view, location based services can be divided into three main categories. These categories are:

- Safety and security (E-911 and E-112)
- Commercial services
- Network internal operations (Location assisted handover)

According to a resent study [43], the US and Europe are the major growth regions for location based services, but the characteristics and issues vary within these regions. In the

US, the focus of location based services has been safety and security, but new services that provide content and integration of cellular services will drive future growth. The European market desires commercial services like access to in-vehicle travel portals with driving directions and navigation. Another important issue is the use of accurate location estimates to optimise the internal network. The information about the location of the mobile stations may be used not only to provide a subscriber service, but also may be used for network internal operations such as location assisted handover. This internal use of the information may lead to higher traffic capacity and improved call completions.

The focus on safety and security in the US is not surprising. The Enhanced 911 (E-911) regulative by the US Federal Communications Commission (FCC) pushes location technologies in the USA. Several previous LBS market studies published by other research groups in 2001 and before described a similar trend. The September 11, 2001 events are likely to strengthen the emphasis on safety and security in the USA.

While the carriers in the US have to act in accordance with the FCC rules, carriers in Europe have no specified rulings for the time being[1].

[1] This will probably change in 2005-2006 as described in subsection 2.1.2

3 Positioning methods

The positioning methods can be divided into three main categories: Network– and handset based technologies, and hybrid technology. In this chapter these three categories are briefly discussed, and important capabilities are identified and evaluated. This is done in order to give the reader an overview of the most common methods. The E-OTD-method will be described in detail in chapter 5. There are more location technologies than discussed in this paper, only the most important ones are discussed.

3.1 Network based technologies

Network based technologies have the advantage that they can be used with old mobile terminals. All the required updates for these methods to work, will be in the network

3.1.1 Cell-ID (CGI) and TA

All the required parameters for this method to work are implemented in the network today. The only update that is needed is a mobile positioning centre that calculates the position estimate.

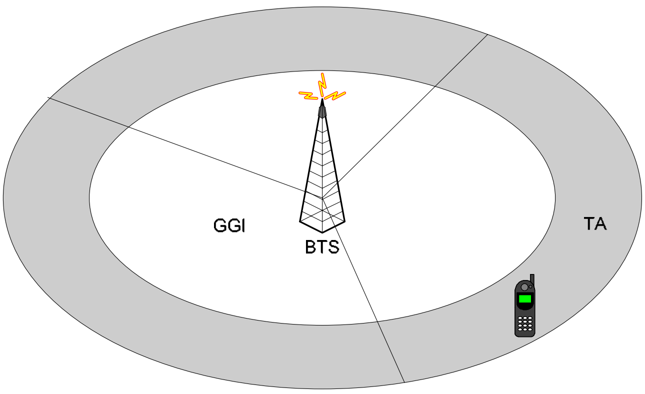

Figure 1. CGI with TA method

The single-cell timing advance (TA) positioning method uses the Cell Global Identity (CGI) and the Timing Advance (TA) parameter to determine the location of the MS. The CGI identifies the cell the MS is located in. A cell can be a circular (omni) or a triangular sector. The TA parameter is an estimate of the distance from the MS to the serving BTS. TA values are divided into 64 slots (0-63), each with a radius of 550 m. This means that a MS which is 600 m away from the serving BTS, will have a TA value of 1. By using the TA value, the location of the MS can be constrained further than the cell identity, as the location of the terminal can be narrowed to a circle or a sector in steps of a 550 metres radius from the BTS.

The accuracy of this method varies according to the size of the cell. The radius of a cell may vary from 100 m to 35 km (CGI). In cells that cover a limited geographical area, the accuracy is fairly good, but it decreases fast as the distance between the transmitter and receiver increase. Accuracy will also depend on whether the cell is an omni cell or a triangular sector cell [33].

3.1.2 Time of Arrival (TOA) / Uplink time of arrival (UL-TOA)

The uplink time of arrival (UL-TOA) method is quite similar to E-OTD, except that the calculations are performed by the network and not by the MS. This method works by having all BTSs within range listening to a burst from the MS. When a base station receives this burst, it records the time when it was received and sends it to a server. The server gathers the information from multiple BTSs and by comparing the time of arrivals and the BTSs positions, the server can by triangulation calculate the position of the MS [4].

The accuracy of this method varies according to the knowledge of surrounding BTSs, propagation of the received signals and synchronisation of the clocks in the network. Since this solution is entirely network based, the investment cost for the operator is high. The number of LMUs needed for this solution is higher (1:1 to 1:2) than the E-OTD method [16].

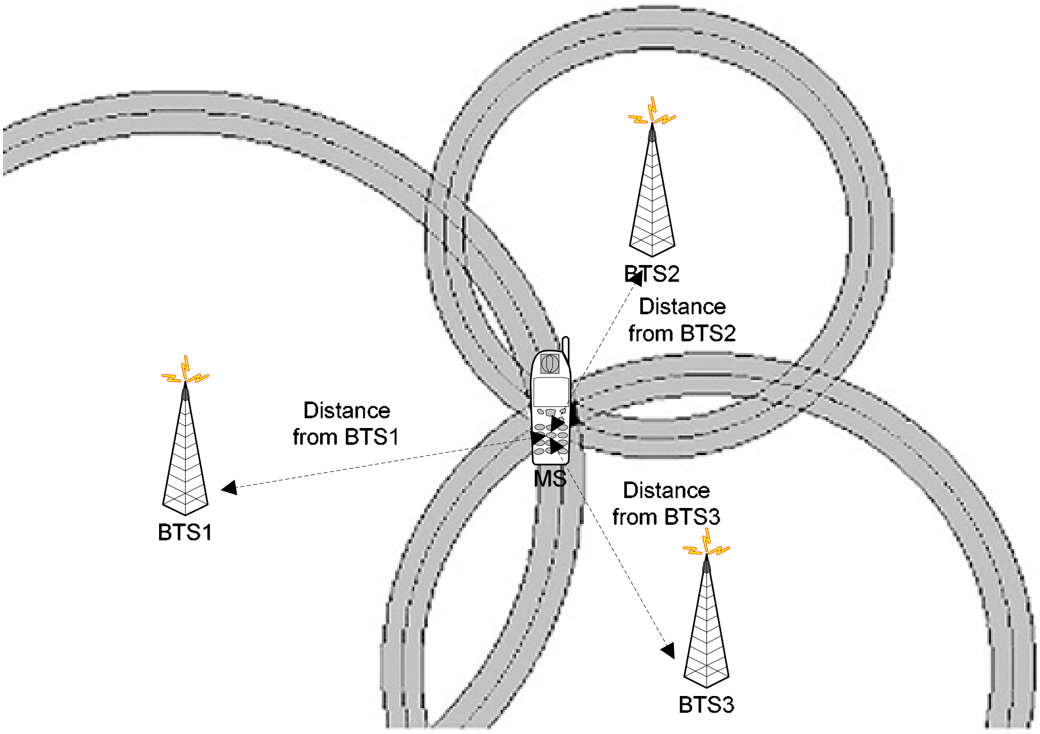

Figure 2. Time of arrival (TOA) method

3.1.3 Angle of arrival (AOA)

The angle of arrival (AOA) method requires the installation of directional antennas or antenna arrays. The method determines location of the MS based on triangulation. The intersection of two directional lines each formed by a radial from a BTS define a unique position for the MS [4]. This method requires the MS to have knowledge of a minimum of two BTSs (or one pair). If available, more than one pair can be used (most common is tree BTSs which yields two pairs).

The accuracy of this method varies according to the knowledge the bearing towards the surrounding BTSs. The method also requires line-of-sight to the involved BTSs for the position estimate to be accurate.

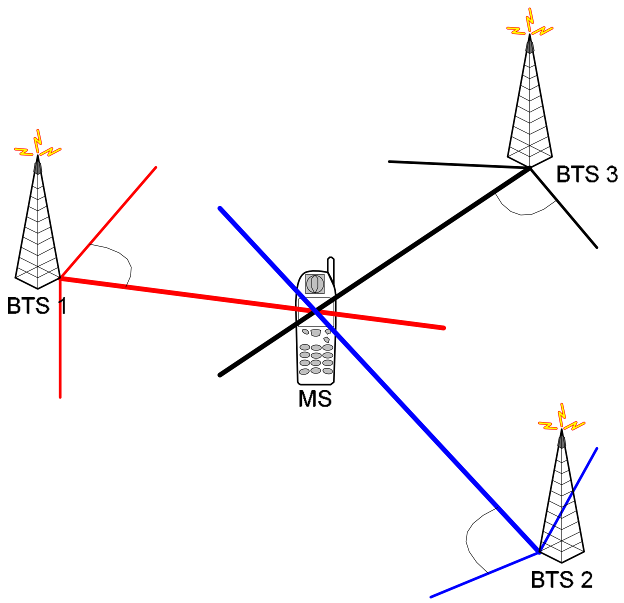

Figure 3. Angle of arrival (AOA) method

3.2 Handset based technologies

Handset based technologies have the best accuracy, but need new or upgraded mobile terminals.

3.2.1 Assisted GPS (A-GPS)

The assisted GPS (A-GPS) method, use a GPS receiver in the MS to find the MS position. The satellite navigation system developed by the US military makes use of the signals from 27 satellites to calculate the position on earth, both horizontally and vertically with accuracy better than 10 meters [4]. A GPS terminal, wherever it is in the world, needs to be able to see four or more satellites, and when a GPS receiver receives a signal from the satellites, the time of arrival of the signal is used to calculate the receiver's position.

This method has high accuracy outdoors, but is complicated indoors or certain urban areas because the GPS needs contact with the GPS satellites to function. When a GPS receiver is switched on, it does not know the precise time and location. Thus, it takes some time for the GPS receiver to obtain its position. To solve this problem with the time consuming period to get detailed positioning information in the GPS receiver, assisted GPS (A-GPS) is used.

A-GPS means that for the GPS to "kick-start", additional data about the MS location is provided by the network or by the MS itself. These two methods are known as network A-GPS and MS A-GPS. In network A-GPS the information is provided to the MS by the SMLC. In MS A-GPS, additional information can be received by the MS in form of special broadcast messages defined in [25].This additional information can be CGI for the serving BTS and/or TA. The method can also used with E-OTD to provide additional information about the MS location.

GPS uses a higher frequency band than GSM, and new mobile terminals must be equipped with two antennas (GPS and normal GSM). Because the GPS receiver has high power consumption, the new mobile terminals require higher battery capacity. Thus, the method has high cost for the consumers, who need new mobile terminals to use this method. This cost can on the other hand be covered by the operator by subsidiaries.

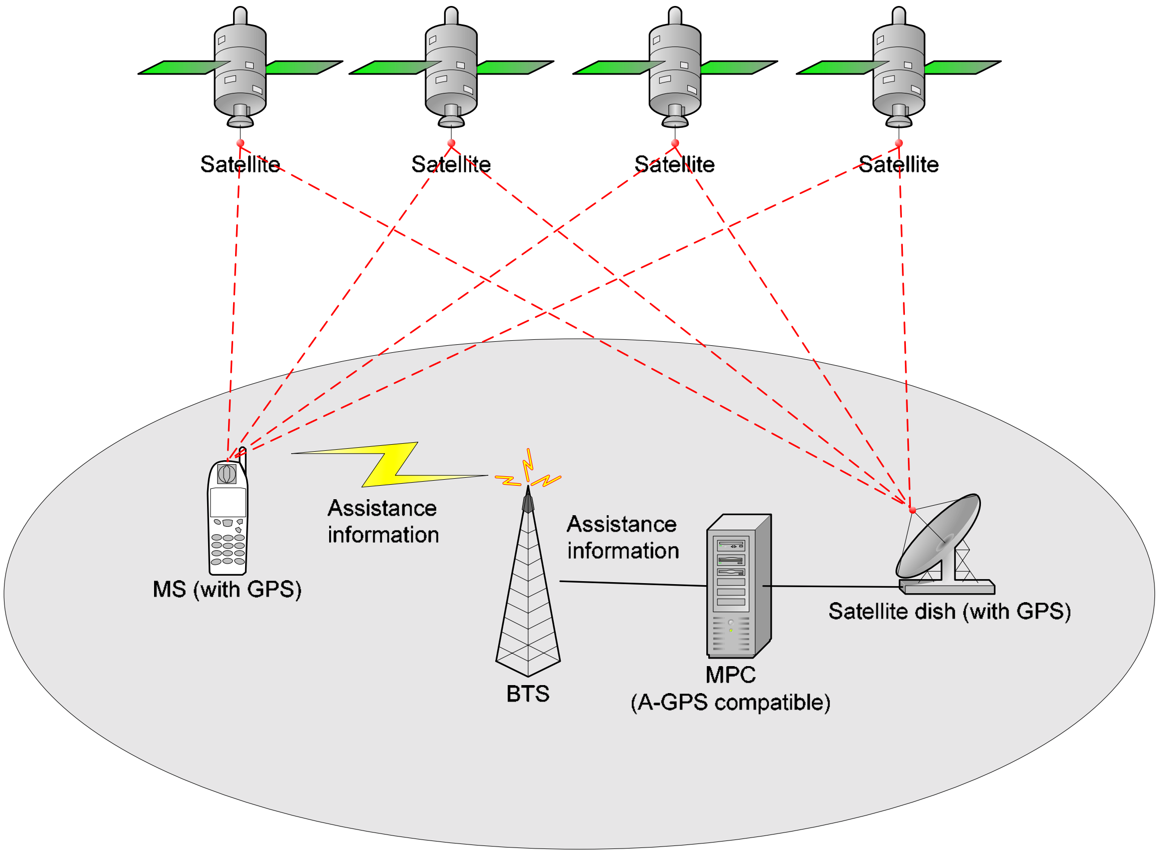

Figure 4. Assisted GPS (A-GPS) method

3.3 Hybrid technology

In this category, upgrades are needed both on the mobile terminals and in the network. The software in the mobile terminals must be upgraded and new elements must be deployed in the mobile network.

The E-OTD method belongs to this category. E-OTD will be described in detail in chapter 5.

3.4 Comparison of location technologies

Table 4 shows a brief comparison of the different location methods. The data are based on information from different vendors such as Ericsson, Nokia and Cambridge Positioning Systems.

Table 4. Comparison of location technologies

Method	Accuracy	Coverage	Cost
CGI + TA	Limited accuracy Guideline estimate: 100-1100 m	Indoor / outdoor: no limitations	In network: MLCs In handset: no cost
TOA / UL-TOA	Better accuracy than CGI + TA, but not as good as A-GPS Guideline estimate: 50-200 m	Indoor / outdoor: no limitations	In network: MLCs and LMUs In handset: no cost
AOA	Guideline estimate: 300 m	Indoor: limited coverage Outdoor: some limitations in case line-of-sight cannot be obtained	In network: directional antennas and MLCs In handset: no cost
A-GPS	High accuracy Guideline estimate: 10 – 20 m	Indoor: limited coverage Outdoor: some limitations in case line-of-sight cannot be obtained	In network: MLCs and hardware to provide D-GPS information. In handset: additional HW
E-OTD	Better accuracy than CGI + TA, but not as good as A-GPS Guideline estimate: 50-400 m	Indoor / outdoor: no limitations	In network: MLCs and LMUs (less LMUs than in UL-TOA required and less expensive LMUs) In handset: “no cost” (added SW only)

3.5 Transmission of location data

The transmission of location data from the network to the user (MS) can be done in different ways; the tree most common solutions today are by Short Message Service (SMS), a SIM toolkit (STK) and by the Wireless Application Protocol (WAP).

3.5.1 SMS

Some systems make use of Short Message Service (SMS) to send location data between the MS and the network. The main advantage of this method is that almost all MS today can receive and send SMS. The main disadvantage is the time factor. Originating and terminating SMS messages are sent via the Short Message Service Centre (SMSC). The SMSC is a “best effort” service, which means that there is no time requirement for when the SMS message will be forwarded to the recipient. When there is overflow in the SMSC, messages can also be deleted without being forwarded.

3.5.2 STK

SIM toolkit (STK) is a client-server architecture where the Subscriber Identity Module (SIM) card acts as the gateway to the operator's server which houses the applications. The mobile handset is the client.

The main benefit of the STK is that it makes it possible to have more user friendly applications than is possible using SMS. With STK, the SIM card is provided with a set of menus which a user can navigate, to either pull or push information. These menus can be downloaded over the air to the STK-compliant handset, but generally the operators distribute the SIM cards with the applications already on them.

3.5.3 WAP

Using Wireless Application Protocol (WAP), content and applications are internet based. This gives the main advantage of being able to deliver additional information with the location data. Maps with different services plotted, will increase the value of the location estimate for the user.

A handicap for WAP using circuit-switched GSM networks is that users can experience long call set-up times (over twenty seconds) and are billed according to time usage. This will change with the GPRS technology, in which the user is always connected.

3.6 Positioning methods in GPRS

The network infrastructure, frequencies and radio communication in GPRS is based on the existing GSM system. The positioning methods will in GPRS be just the same as the positioning methods in the GSM system.

3.7 Future in UMTS

The LMUs in the GSM network are required due to the unsynchronised base transceiver station clocks. In the UMTS network, LMUs will be redundant due to the UMTS network being synchronised. The basic principles for the positioning methods will be identical to those used in GSM. Due to the UMTS network being synchronised and the smaller and much more densely populated cells, the accuracy of using certain positioning methods is expected to improve.

4 LCS Architecture

This chapter gives a brief introduction to network elements required to perform location estimates based on the E-OTD method. A comparison of the two main LCS architectures for the E-OTD location method[2] is also discussed. State descriptions and signalling flows can be found in [23],[26],[27], but this is out of scope for this report.

4.1 Network elements

Figure 5 shows the generic LCS architecture with all the network elements.

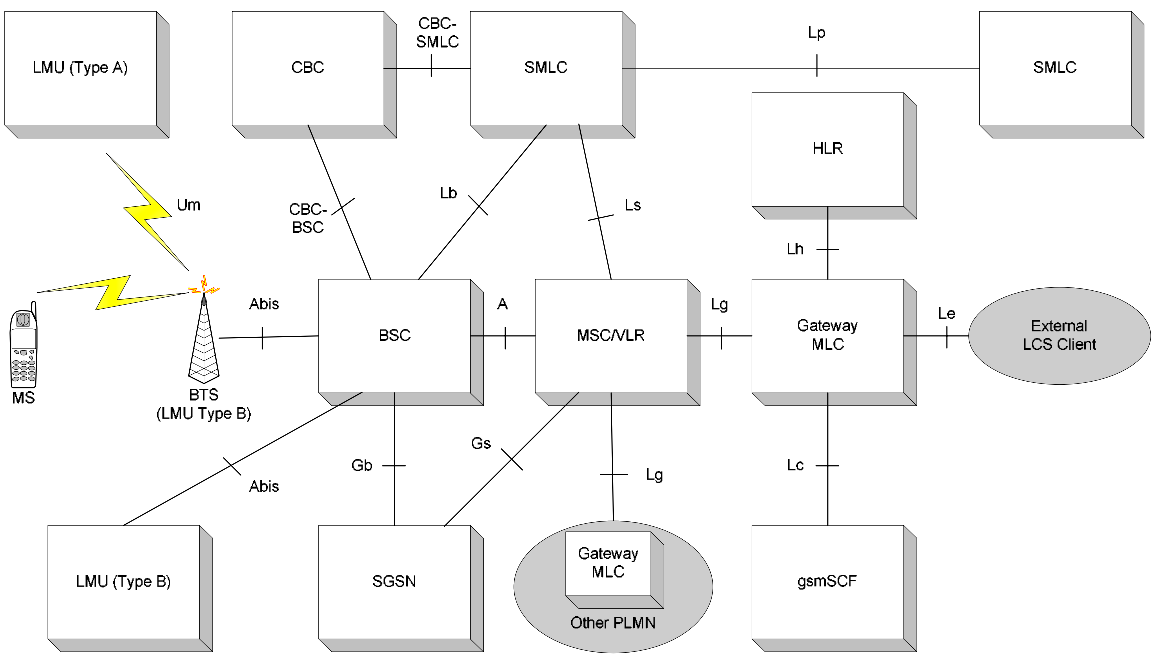

Figure 5. Generic LCS Architecture

4.1.1 MS

To perform location with the E-OTD method, the Mobile Station (MS) must make accurate Observed-Time-Difference measurements (OTD - the time interval that is observed by a MS between the receptions of bursts from two BTSs). Specifically, the E-OTD capable MS[3] shall be capable of measuring the reception of bursts transmitted from a BTS on a periodic and

[2] An architecture is an arrangement and interconnection of system components. In contrast, a location method is the way in which location measurements are undertaken.

[3] An E-OTD capable MS is a MS with special software to be able to handle E-OTD.

predictable basis. The measurement results are used by the system or the E-OTD capable MS for determining location of the MS. An E-OTD capable MS, supporting the MS based E-OTD method, shall be capable of doing idle mode E-OTD measurements with the same accuracy as in dedicated mode.

4.1.2 LMU

E-OTD uses Location Measurement Units (LMUs) to support its positioning mechanisms. LMU is additional measurement hardware in the GSM network and it is needed to make accurate Observed Time Difference (OTD) measurement of signals from multiple Base Transceiver Stations (BTSs). An LMU shall be capable of measuring the Relative Time Difference (RTD) between bursts transmitted from a BTS on a periodic and predictable basis. The measurement results are used by the system for determining location of a Mobile Station (MS). The GSM standards have defined two operative modes of the LMU; type A and type B depending on how the LMU communicates with the BTS. An LMU in mode A[4] can only by accessed over the normal GSM air interface, so there is no wired connection to any other network element [23].

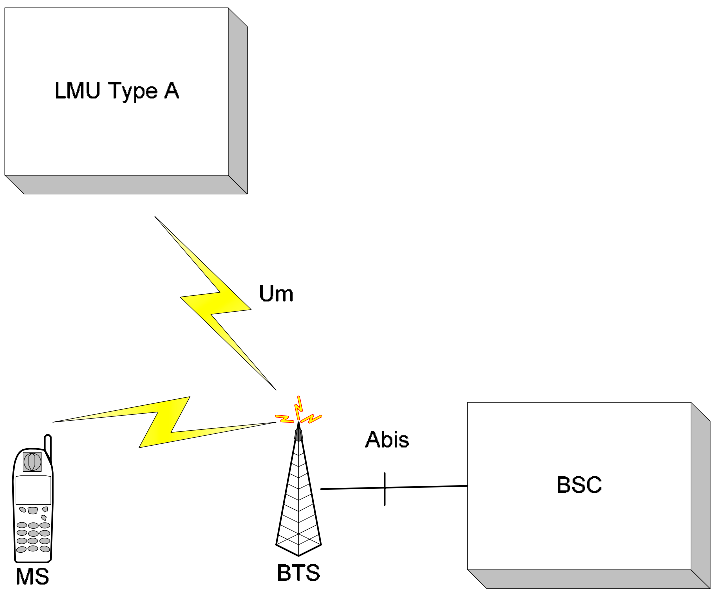

Figure 6. LMU type A

In mode B the LMU is accessed over the Abis interface from the BSC. The standard supports both standalone LMUs connected directly on the Abis and LMUs connected via the BTS.

[4] With an NSS based SMLC, a type A LMU also has a serving MSC and VLR and a subscription profile in an HLR.

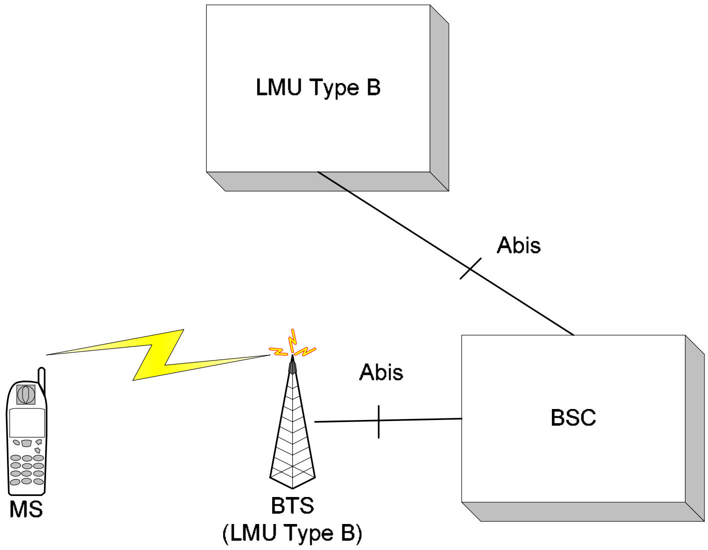

Figure 7. LMU type B

4.1.3 PLMN

A Public Land Mobile Network (PLMN) is a network that is established and operated by a recognized operating agency for the specific purpose of providing land mobile telecommunications services to the public. A PLMN may be considered as an extension of a fixed network such as a Public Switched Telephone Network (PSTN).

4.1.4 CBC

The Cell Broadcast Centre (CBC) handles the cell broadcast messages to chosen network elements. In MS based E-OTD this function is especially important due to the fact that in this mode of operation the MS will produce a position estimate based on received parameters. Those parameters are sent from the network in special broadcast messages (SMSCB) defined in [25].

SMSCB messages can be received when MS is in idle mode. When MS is in dedicated mode the same information that was received in idle mode via broadcast channel may be requested by the MS from the SMLC via point-to-point messaging defined in [11].

4.1.5 BSC

The Base Station Controller (BSC) forwards the circuit switched calls to the MSC/VLR. The BSC can control one or more BTS.

4.1.6 BTS

This network component is responsible for the radio-link protocols witch enables communication with the MS over the air interface. A Base Transceiver Station (BTS) can consist of one or more transceivers (TRXs) depending on the BTS serve an omdirectional or a sector cell.

4.1.7 MLC

In the GSM standard a new network element for the purpose of handling location services is introduced. The new network element is called Mobile Location Centre (MLC) and is responsible for a set of tasks such as privacy, authorization and authentication, delivery of location information to authorized applications, billing and charging, access to BTS co-ordinates and other physical parameters required for location, and the calculation of the final location estimate based on received signal measurements from both the MS and the BTS[5]. An MLC can be either a serving MLC (SMLC) or a Gateway MLC (GMLC).

4.1.8 SMLC

The Serving Mobile Location Centre (SMLC) in GSM is responsible for obtaining and handling measurements from the LMUs. The SMLC manages the overall coordination and scheduling of resources required to perform positioning of a mobile. It also calculates the final location estimate and accuracy. It is also responsible for obtaining measurements results from the target MS in E-OTD[6]. There are two types of SMLC depending on the LCS architecture; NSS based SMLC and BSS based SMLC. An NSS based SMLC supports positioning of a target MS via signalling on the Ls interface to the visited MSC. A BSS based SMLC supports positioning via signalling on the Lb interface to the BSC serving the target MS. Both types of SMLC may support the Lp interface to enable access to information and resources owned by another SMLC.

4.1.9 GMLC

The Gateway MLC (GMLC) is a GSM PLMN node that can be accessed by external LCS clients allowing the MS to access applications not residing on the operator's own ISP domain. The GMLC may request routing information from the HLR via the Lh interface. After performing registration authorization, it sends positioning requests to and receives final location estimates from the MSC via the Lg interface.

4.1.10 MSC

The Mobile-Services Switching Centre (MSC) handles the circuit switched connections between MSs and networks. It performs all of the switching and signalling functions for the subscribers in its coverage area. The MSC contains functionality responsible for MS subscription authorization and managing call-related and non-call related positioning requests of GSM LCS. The MSC is accessible to the GMLC via the Lg interface and the SMLC via the Ls interface

[5] E-OTD can be both handset - or network based.

[6] This also applies to A-GPS.

4.1.11 VLR

The Visitor Location Register (VLR) is responsible for maintaining a set data for the serving network. These data are obtained from the subscribers HLR and stored at the VLR[7].

4.1.12 HLR

The Home Location Register (HLR) contains LCS subscription data and routing information. The HLR is accessible from the GMLC via the Lh interface. For roaming MSs, HLR may be in a different PLMN that the current SMLC

4.1.13 gsmSCF

The GSM Service Control Function (gsmSCF) contains functionality contributing to the service logic to implement off switch services involving mobility, a functional entity that contains the Customised Applications for Mobile Enhanced Logic (CAMEL) service.
The Lc interface supports CAMEL access to LCS and is applicable only in CAMEL phase 3.

4.1.14 LCS Client

An LCS client contains an LCS component with one or more client(s) which by using location information can provide location based services.
An LCS client is a logical functional entity that requests from the LCS server in the PLMN location information for one or more than one target MS within a specified set of parameters such as Quality of Service (QoS). The LCS Client may reside in an entity (including the MS) within the PLMN or in an entity external to the PLMN.

4.1.15 GMSC

The Gateway Mobile Services Switching Centre (GMSC) contains the same functionality as the MSC, but has the responsibility of connecting to external PLMNs. Some or all of the MSCs can be Gateway MSCs (GMSC). The GMSC

4.2 Different LCS Architectures

Two different types of LCS architectures have been standardized in by ETSI [23]; The BSS centric architecture and the NSS centric architecture. This section will give a brief introduction to these architectures with focus on the E-OTD method.

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[7] The MSC and VLR are implemented as one physical node and thus named MSC/VLR.

4.2.1 BSS centric architecture

In the Base Station Subsystem (BSS)[8] centric architecture the SMLC is situated in the BSS. One of the benefits with this solution is that no LMU related information is passed to the MSC/VLR and HLR, thus reducing the signalling load in the NSS. Another benefit is the possibility to use non air interface LMUs (LMU type B). In the BSS Centric Architecture, all radio interface related information remains in the BSS.

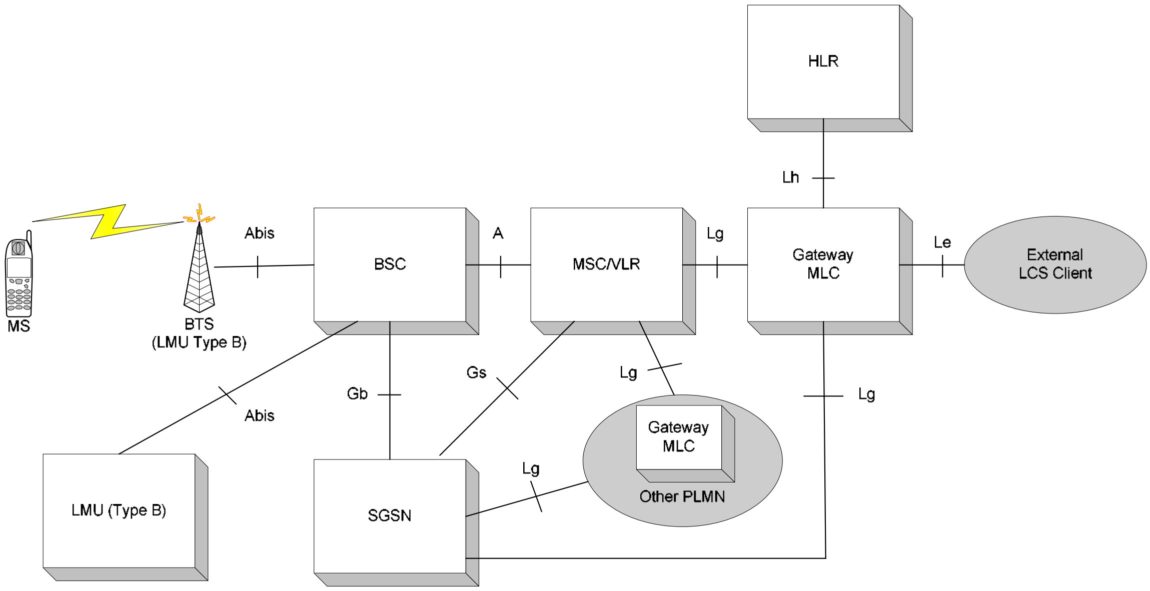

Figure 8. BSS based LCS architecture

4.2.2 NSS centric architecture

In the Network Subsystem (NSS) centric architecture a significant portion of the LCS functionality resides in the NSS. This increases the signalling load in the network since LMU related information must be sent to NSS. The absence of change to the BTS avoids the risk associated with modifications to the large number of such remotely located units.

[8] The Base Station Sub system is a system of base station equipment, which is viewed by the MSC through a single interface as being responsible for communicating with the MS in a certain area.

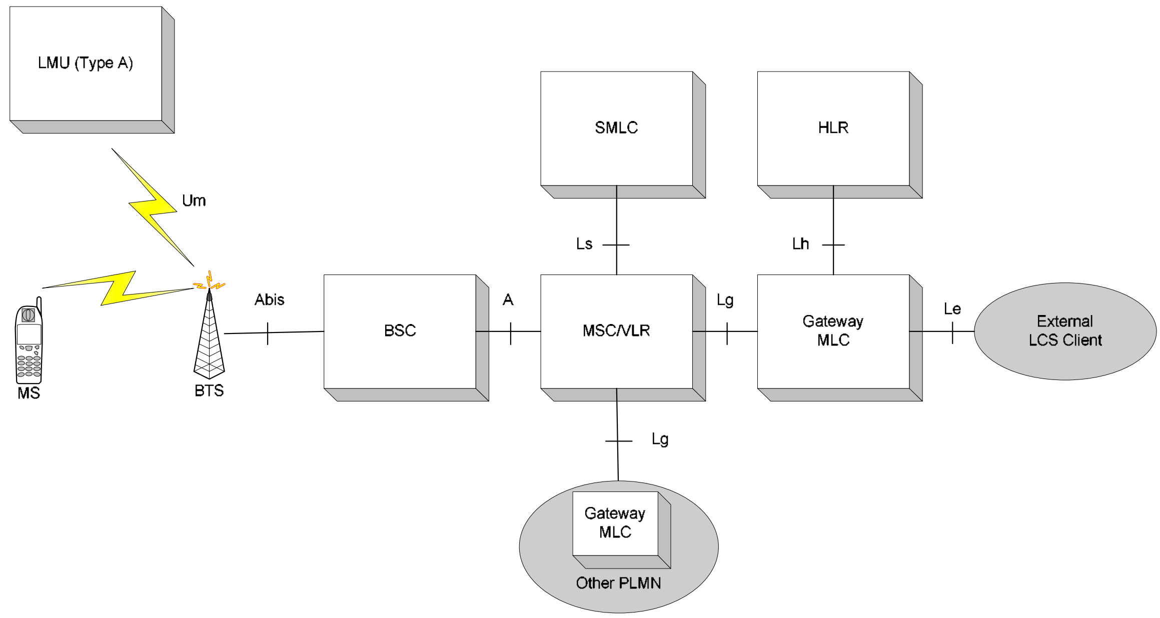

Figure 9. NSS based LCS architecture

4.2.3 Comparison of LCS Architectures

The NSS centric architecture has the advantage of minimizing the number of network elements affected by the addition of LCS. One downside of the NSS centric architecture is the increase in signalling load in the NSS. Tests conducted by NOKIA, described in [28], show an increase as high as 50 times the normal signalling load in the NSS when utilizing a NSS centric architecture. A comparison of cost shows that multiple BSC can be upgraded in the BSS centric architecture with the cost of one separate SMLC required in the NSS centric architecture. The BSS based LCS architecture is in line with current 3G proposals for MS positioning. This facilitates the evolution from the current GSM to the future GSM based 3rd generation systems.

5 Simulation of E-OTD

The main topic for this report is the simulations of the characteristics related to the E-OTD method. This chapter will describe these simulations. The E-OTD method will first be described in detail, both the general concept and the location calculation methods. Different sources of error and the impact they have on the location prediction will also be discussed. At the end of this chapter, the simulations and the results of these will be described and discussed.

5.1 Basics of E-OTD

The Enhanced Observed Time Difference (E-OTD) method is based on the measured Observed Time Difference (OTD) between arrivals of bursts from serving and other BTSs (Figure 10). Both normal and dummy bursts can be used. The measured time difference between pairs of base transceiver stations, are referred to as OTD. Because the transmission of frames from the base transceiver stations are not synchronised in the GSM network, the real time differences (RTD) between pairs of base transceiver stations is measured by an LMU.

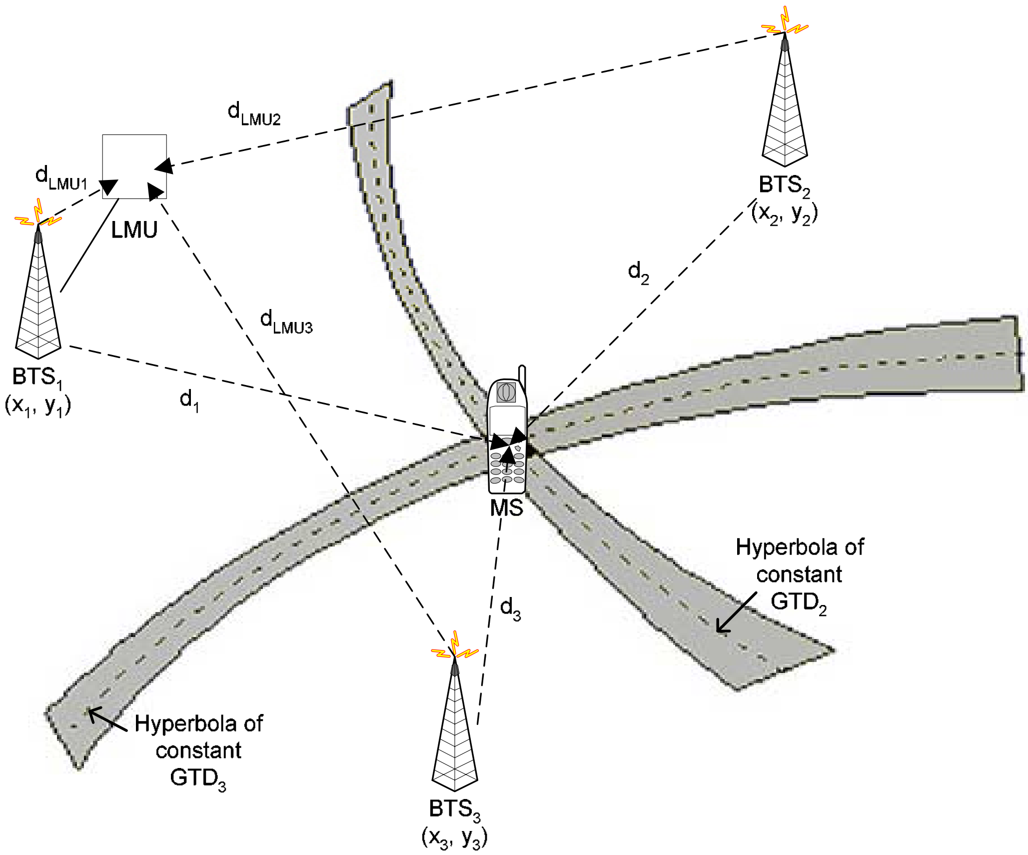

Figure 10. The E-OTD method.

In Figure 10, d_i is the length of the propagation paths from the BTSs to the MS and d_{LMUi} is the length of the propagation paths from the BTSs to the LMU. The position of the BTSs is denoted as (x_i, y_i). The dashed line represents the hyperbolas calculated from the GTDs. The intersection of the hyperbolas gives the location of the MS.

The three basic timing quantities associated with E-OTD location are defined as follows [23]:

- Observed Time Difference (OTD). This is the time interval that is observed by a mobile station (MS) between the receptions of signals (bursts) from two different BTSs in the cellular network. A burst from BTS_1 is received at the moment t_{Rx1}, and a burst from BTS_2 is received at the moment t_{Rx2}. Thus the OTD value in this case is: $OTD = t_{Rx1} - t_{Rx2}$. If the two bursts arrive exactly at the same moment, then OTD = 0.

- Real Time Difference (RTD). This is the relative synchronisation difference in the network between two BTSs. If BTS_1 sends a burst at the moment t_{Tx1}, and BTS_2 at the moment t_{Tx2}, the RTD between them is: $RTD = t_{Tx1} - t_{Tx2}$. If the BTSs transmit exactly at the same time that means that the network is synchronised and there is no need to calculate RTD, hence RTD = 0. RTD values are measured by the LMUs in the network, as described later in this chapter.

- Geometric Time Difference (GTD). This is the time difference between the receptions (by a MS) of bursts from two different base stations due to geometry. If the length of the propagation path between BTS_1 and the mobile station is d_1, and the length of the path between BTS_2 and the MS is d_2, then

  $GTD_{12} = \frac{d_2 - d_1}{c}$, where c is the speed of light. If both BTSs are equally far from the MS, GTD = 0.

The relationship between these quantities is:

$$GTD = OTD - RTD$$

OTD is the quantity measured by the mobile station to be located. RTD is a quantity related to the network (BTSs). GTD is a quantity related to the geometry of the situation (positions of the mobile and BTSs). GTD is the actual quantity that is useful for location purposes, since it can provide information about the position of the MS.

The E-OTD method can be either handset based or handset assisted. In handset based E-OTD, the MS performs OTD signal measurements and computes its own location estimate. In this case the network provides the MS with the additional information such as BTS coordinates and the RTD values. In handset assisted E-OTD, the MS performs and reports OTD signal measurements to the network and the network computes the MS's location estimate.

A location estimate can be produced in both idle and call modes. Continuous location (tracking) or single location can be requested.
The MS location estimate is calculated from the GTD (that is calculated from the measured OTD and known or measured RTD) based on the fact that the possible location for the MS observing a constant GTD value between two BTSs is a hyperbola (see Figure 10). The MS can be located in the intersection of two hyperbolas obtained with three base stations which gives two GTD values. If more neighbouring BTSs are available, the accuracy of the estimate will increase.

The calculation can be performed with two BTSs with different locations (serving and one neighbour) as described in [10] by extending the E-OTD method with additional information, e.g. by using a combination of E-OTD and the TA parameter.

Because the GTD values always will be subject to errors and uncertainties, as discussed in section 5.3, statistical solutions are normally sought, as described later in the description of the simulations.

5.1.1 Circular Variant (E-OTD-C)

Another method classified under E-OTD is a mixed time of arrival (TOA) and time difference of arrival (TDOA) approach. While the classic E-OTD method is known as hyperbolic E-OTD, this method is known as E-OTD circular (E-OTD-C). It measures the time of arrival of the signals from BTS to the LMU, in addition to the time of arrival of the signals from BTS to the MS.

There are five quantities associated with this method [23]:

- The observed time from a BTS to the MS (MOT) is a time measured against the internal clock of the MS
- The observed time from a BTS to the LMU (LOT) is a time measured against the internal clock of the LMU
- Time offset ε is the bias between the two internal clocks of the MS and LMU
- The distance from MS to BTS (DMB)
- The distance from LMU to BTS (DLB)

The relationship between these quantities is:

$$\text{DMB - DLB} = \text{c}\,(\text{MOT - LOT} + \varepsilon)$$

There will be one equation for each BTS. The MS location estimate is calculated by the intersection of circles centred on the BTSs (Figure 11). The E-OTD-C method requires a minimum of three BTSs with different locations. If more neighbouring BTSs are available, the possible location area can be reduced.

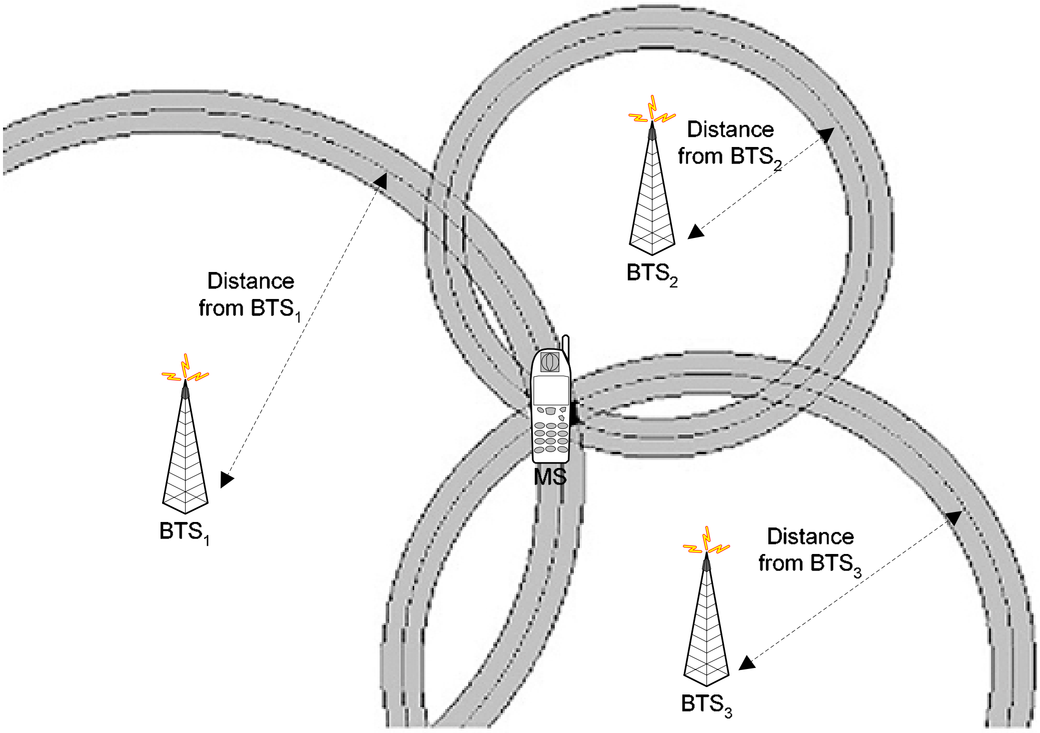

Figure 11. Circular enhanced observed time difference (E-OTD-C) method

Note that we in this report and simulations have used the hyperbolic E-OTD method and not the E-OTD-C method.

5.2 The mathematical elucidation for calculating GTD

As stated before, the E-OTD method is based on three parameters: Observed Time Difference (OTD), Real Time Difference (RTD), and Geometric Time Difference (GTD).
This section will give a more in depth description of those parameters, and explain the mathematical background for our simulation model.

For all equations in this chapter the notation is as follows: subscript $_1$ denotes the quantity related to the serving cell and the subscript *i* denote the quantities related to the *i*th BTS involved in the measurement[9]. N is the number of BTSs involved in each measurement for both OTD and RTD.

[9] This is relative to serving cell, $_{i = 2,3...N}$

5.2.1 Real Time Difference

In principle, GTD_i can be determined by measuring the difference in reception of burst synchronously transmitted by the BTSs and received by the MS.
Due to the non-synchronised GSM network, the difference in transmission epochs must be taken into account. E-OTD needs to compensate for the difference in transmission epochs by performing RTD measurements conducted by LMUs deployed at known locations through the network. Let a burst be transmitted from the *i*th BTS and received by a LMU at an instance t_{TXi}. Let a burst be transmitted from the serving cell and received by a LMU at an instance t_{TX1}. Then RTD_i is:

Equation 1

$$RTD_i = t_{TX1} - t_{TXi}$$

5.2.2 Observed Time Difference

In E-OTD, the MS measures OTDs. The MS estimates OTD_i by subtracting the reception epochs of bursts transmitted by the serving cell and the *i*th neighbouring BTS. To estimate the reception epochs of burst, the MS measures the signals transmitted by each BTS on its designated Broadcast Control Channel (BCCH). Let a burst be transmitted from the *i*th BTS and received by a MS at an instance t_{RXi}. Let a burst be transmitted from the serving cell and received by a MS at an instance t_{RX1}. Then OTD_i is:

Equation 2

$$OTD_i = t_{RX1} - t_{RXi}$$

5.2.3 Geometric Time Difference

With the earlier definitions of OTD and RTD, GTD can be written as the difference between the OTD and the RTD parameter:

Equation 3

$$GTD_i = OTD_i - RTD_i$$

Equation 1 and 2 can be used in Equation 3 to derive Equation 4. GTD is a scaled measure of the relative distance (RD) between the MS and the pair of BTSs (BTS_1 and BTS_i).

Equation 4

$$GTDi = OTDi - RTDi = (t_{RX1} - t_{TX1}) - (t_{RXi} - t_{TXi}) = \frac{(d1 - di)}{c} = \frac{RD}{c}$$

Here c is the speed of light, and d_1, respectively d_i are the lengths of the propagation paths between the MS and BTS_1, respectively BTS_i. The possible position of an MS observing a constant GTD value is located on a hyperbola having foci at BTS_i and BTS_1. In a two dimensional scenario, the MS position is calculated via hyperbolic multilateration at the intersection of at least two hyperbolas [29]. The E-OTD method uses one of the available BTS as a reference BTS and uses it to calculate all GTDs. As a beneficial consequence, linear dependence between multiple equations is avoided.

5.2.4 MS location calculation

The positioning problem in absence of measurement errors can be formulated with a set of N-1 equations describing hyperbolas having their foci at the BTSs coordinates (x_1, y_1) and (x_i, y_i). The hyperbolic equation is written as:

Equation 5

$$c*GTD_i = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_i - x)^2 + (y_i - y)^2}$$

In an error free case, a unique and exact solution can be found at the intersection of the hyperbolas at $P = [x, y]$.

Exact non-iterative solutions for this ideal problem can be found in [7] and [30], but it is out scope for this report to find an exact solution for every measurement in each measurement scenario.

In a real case however, errors will be present and a statistical solution must be sought. In the simulation model, an optimisation routine was used to produce a location estimate. From Equation 5, moving the square root terms to the other side, we obtain Equation 6 where the difference between c*GTDi and the square root terms is denoted Fi:

Equation 6

$$F_i = c*GTD_i - \sqrt{(x_1 - x)^2 + (y_1 - y)^2} + \sqrt{(x_i - x)^2 + (y_i - y)^2}$$

In the error free case all Fi are identically equal to zero at the solution where the hyperbolas intersect. In the simulations a least square optimisation was used, to minimise the sum of the Fi squared. The position estimate for each measurement point was then found, as from Equation 7, where M is the number of BTS-pairs available

Equation 7

$$[x, y]_{opt} = \min_{(x,y)} \sum_{i=1}^{M} F_i^{\;2}$$

The optimisation was performed using standard optimisation routines in MATLAB e.g. a function utilising the Simplex method of Nelder and Mead described in [31]. Another approach to this estimation problem can be found in [32].

5.3 Main sources of error in the location estimation

The main sources of error giving a decreased location accuracy of the E-OTD method could be:

- Multipath propagation
- Base transceiver station clocks unsynchronised
- Base transceiver station clocks drift

5.3.1 Multipath propagation

Multipath affects the time based location systems, causing error in the timing estimates (OTD) even when there is a Line-of-Sight (LOS) path between the MS and BTS. Multipath is multiple copies of the same signal arriving at different times. This makes it hard to estimate when the first signal arrived, and the accuracy of the location estimate is decreased.

One of the main influences on the location accuracy using the E-OTD method is the NLOS propagation. In urban and indoor environments the E-OTD method will suffer from the absence of a line-of-sight signal component. Signals reflected from buildings, will decrease the location accuracy. The signals reflected or diffracted take a longer path than the direct path. This will produce a longer time of arrival measured. The OTD value will be affected by this, giving a decreased accuracy of the location estimate.

5.3.2 Base transceiver station clocks unsynchronised

GSM networks are normally not synchronised. This will lead to the OTDs measured having an offset. This is, as explained earlier, why the LMU is needed in the network to compensate for this offset. The BTS clocks can give an error of approximately 15 – 60 m not being synchronised [27]. The LMU can correct this time difference. The RTD value measured by the LMU can reduce the error due to the unsynchronised network, to approximately <15 m.

5.3.3 Base transceiver station clocks drift

BTS clock drift is another source of error. In GSM the BTS shall use a single frequency source of absolute accuracy better than 0.05 ppm for both RF frequency generation and clocking the timebase. The same source shall be used for all carriers of the BTS [27].
This could have impact on the calculated GTD value. However the BTS clock drift is assumed to be linear. This means that even if the clocks drift, they drift with the same amount of time, giving the same time difference.

5.3.4 Unable to perform location prediction with E-OTD

The E-OTD method can not be used in the following cases:

- Only one or none neighbouring cells
- When using repeaters in the network

When the MS only observes one or none neighbouring cells, the E-OTD method can not be used. This is because the E-OTD method uses triangulation to estimate the MS location. With only two BTSs (serving and one neighbour), triangulation can not be performed. This is expected to be a problem in rural areas, where the density of BTS is low. The calculation can be performed with two BTSs with different locations (serving and one neighbour) as described in [10] by extending the E-OTD method with additional information, e.g. by using a combination of E-OTD and the TA parameter.

When using repeaters in the network, E-OTD becomes almost impossible to use. When measuring the time of the received signal, it is hard to determine if the signal has been through a repeater or not. Going trough a repeater, the measured time will be much longer than it actually is. This will cause a major error in the measured OTD value, giving a location estimate with severe errors.

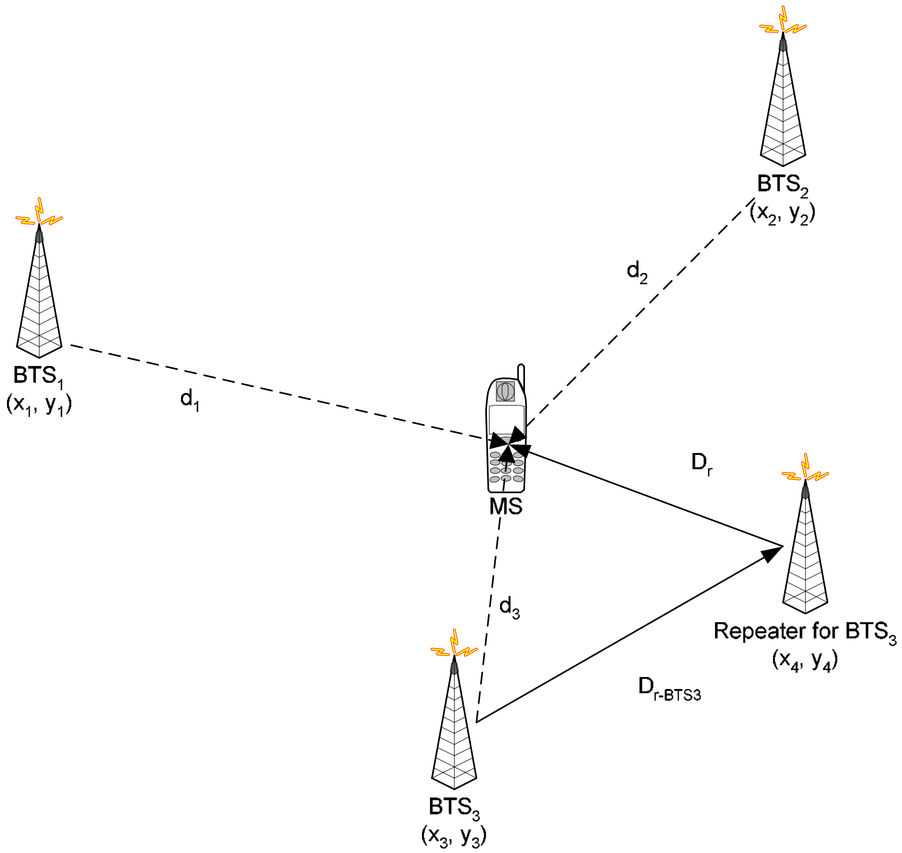

Figure 12. E-OTD deployment scenario with an in-band radio repeater

In Figure 12, d_1, d_2 and d_3 (giving t_1, t_2 and t_3) are the direct propagation paths between the BTSs and the MS, and $D_{r\text{-}BTS3}$ and D_r (giving t_r and $t_{r\text{-}BTS3}$) are the indirect propagation paths to the MS via the repeater. The propagation delay between the MS and BTS_3 via the repeater can be expressed as:

$$t_{1r} = t_{r\text{-}BTS3} + t_r$$

Referring to Figure 12, the measurements are conducted at a MS with reception from both BTS_3 and its associated repeater. When measuring the downlink of BTS_3, this MS will detect two distinct correlation peaks corresponding to the two propagation paths. For other MS locations, the E-OTD measurement results may correspond to either a direct path or a path via the repeater. In either case, the E-OTD method has no way to resolve this ambiguity. This will cause an increase in the measured OTD value and a significant decrease in the accuracy of the location estimate.

5.4 Measurement parameters and measurement scenarios

The measurements used in the simulation of E-OTD in our project were obtained by Telenor R&D in a measurement campaign performed during summer 2001 [33]. The goal of the previous measurement campaign was to evaluate the accuracy of the cell-id and timing advance (CGI+TA) location method for various measurement scenarios. The experimental approach in the campaign was to perform simultaneous measurements of GSM parameters using TEMS GSM test equipment, the actual position using GPS and position estimates from a Mobile Positioning Server (MPS).

5.4.1 Basis for measurement parameters

This section will give a brief introduction to how the measurements in the previous campaign were obtained and which parameters were logged.

5.4.1.1 TEMS equipment

Test Equipment for Mobile Systems (TEMS), is a system from Ericsson used to measure different parameters in the GSM network. TEMS is used by wireless network operators to plan, optimise and expand GSM networks. The TEMS system used consisted of a MS with special software, and additional computer software. An overview of the equipment can be seen in Appendix B.

An event is defined by the parameters position, cell-id, the six strongest neighbouring cells and absolute time. The equipment used to collect and log these data was a GPS receiver, the TEMS system, and a PC. The TEMS system delivers data 2 times/second, and the events were time stamped by the PC clock.

The measurements were done from a van with an external GSM antenna. A 10 dB attenuator was inserted in the feeder to simulate the conditions where the MS is used inside a car.

The position of the vehicle (MS) was measured with differential GPS. The differential correction data is delivered by The Norwegian Mapping Authority (Statens Kartverk), giving an accuracy of typical 1 – 5 meters [48]. This removes GPS position errors as a significant error source in the simulations.

As mentioned above, the TEMS-system measures several parameters, mostly related to the radio protocol between the BTS and the MS. The collected data from TEMS are defined in Table 5.

Table 5. TEMS parameters logged

Parameter	Description
Position	MS position(in WGS84 format)
GGI	Unique cell identifier (for serving cell)
ARFCN	ARFCN (for serving and neighbouring cells)
BSIC	BSIC (for serving and neighbouring cells)
RxLev	Measured Rx level (for serving and neighbouring cells)
Absolute time	PC clock

Here, ARFCN (Absolute Radio Frequency Channel Number) is a channel numbering scheme used to identify specific RF channels in a GSM radio system and BSIC (Base Station Identity Code) is a unique code contained in messages on the broadcast channels of a cell or base station that uniquely identifies the base station. These two parameters were used to distinctively identify the neighbouring cells involved in the measurements, since no CGI were available for the neighbouring cells.

5.4.1.2 Mobile Position System

The Mobile Position System from Ericsson consists of more building blocks where the location server, or as named by Ericsson: *Mobile Position Centre G-3.0* (MPC) is the central part. The current system is MPC V 3.0. The MPC collects the necessary input data from the network nodes involved, and the position estimate is calculated using cell-id and TA. The location estimates retrieved from the MPC were logged in the rate 1-4 times/second.

The parameters retrieved from the MPC were logged to a computer locally, for later processing and comparison with the data logged by the TEMS in the vehicle.

5.4.1.3 Methodology

In the previous measurement campaign, Telenor personnel drove various routes with the TEMS equipment in the van and logged TEMS parameters. Simultaneously they interrogated the MPC using a polling script, thus generating two log files. These two log files were merged based on time stamps, to obtain a complete list of parameters needed to evaluate the cell-id and timing advance method.

As stated before, our simulation model is based on the parameters obtained during the previous measurement campaign. All other parameters needed for the simulation of E-OTD are calculated in our simulation model.

5.4.2 Measurement Scenarios

Cell size and radio-propagation characteristics vary greatly from environment to environment. It is therefore essential to perform separate measurements in areas with different network topology and geography to be able to evaluate how different propagation properties are influencing the accuracy of the location method. Two different measurement scenarios have therefore been investigated. This is an urban area and a rural area.

5.4.2.1 Urban area

Urban-area measurements were performed in an area consisting of both micro GSM900 and GSM1800 cells. Micro cells are average sized radio cells with diameters of 1 to 2 kilometres [50]. These types of cells give large capacity for a small area. The road structure is generally quadratic and separated by five- to eight-story buildings. The tall buildings can cause a blocking of the direct-signal component. This will lead to at least one-time reflected received signals.

5.4.2.2 Rural, relatively flat area

Measurements were carried out in a rural area with macro-cell structure. Macro cells are cells with diameters of 20 to 30 kilometres [50]. Macro cells give small capacity for a large area. The geography is relatively flat with small hills, farmland and woods.

5.5 The simulation model

As mentioned earlier in the report, a simulation model was created in MATLAB. A block diagram of the program can be seen in Figure 13.

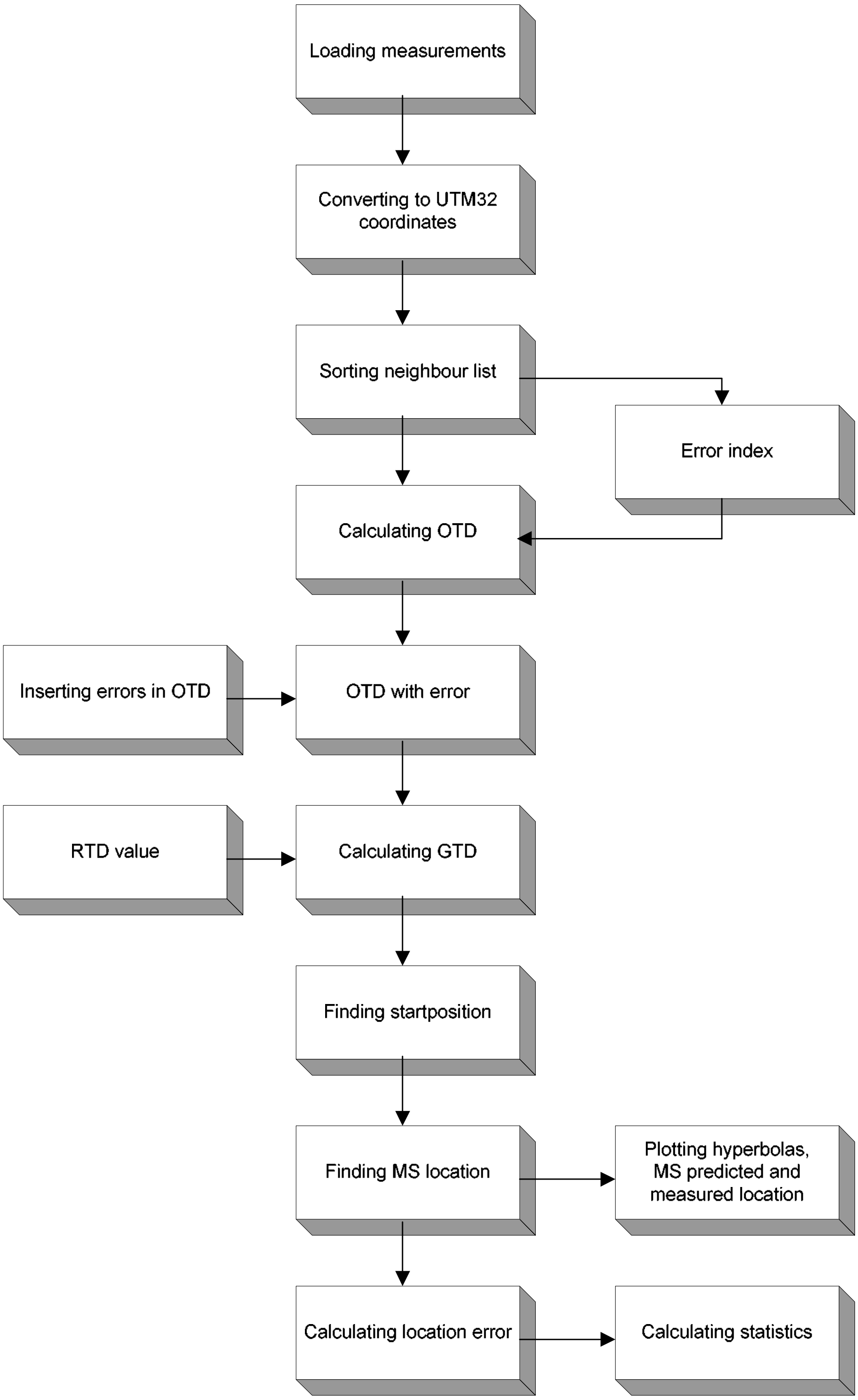

Figure 13. Block diagram of the simulation model in MATLAB

5.5.1 Loading measurements

The measurements described in subsection 5.4.1.3 consist of several text files which are tab delimited. The program starts by reading these files.

5.5.2 Converting to UTM32 coordinates

The coordinates recorded in the measurement files are on WGS84 (latitude, longitude) format. These coordinates were converted to UTM32 (x, y) coordinates. This format is much more appropriate for our calculations.

5.5.3 Sorting neighbour list

The records in the text files consist of serving BTS and the six strongest neighbouring cells. However, the neighbours were not sorted. The neighbours were therefore sorted in a list, with the strongest (highest RXLEV) first.

5.5.4 Error index

Some of the measurements lacked certain parameters, such as location, ARFCN or BSIC, due to imperfections in the measurement equipment. These measurements were removed, and not taken into account when calculating the MS position. A measurement only having one or none neighbours was also removed. This was done because the E-OTD method requires three or more BTS to produce a position estimate.

5.5.5 Calculating OTD

When finished sorting the neighbours and with only valid measurements remaining, the OTD values were calculated. This was done by subtracting the t_{Rx} value for the neighbour cells from the t_{Rx} value for the serving cell. The general formula for this is $OTD_i = t_{Rx1} - t_{Rxi}$, giving two OTD values for three BTSs. The t_{Rx} values were calculated from the distance between the MS location and the BTS location divided by the speed of light. This is the “perfect” OTD value, with no clock errors, multipath or propagation delay involved. When calculating the MS position with these values, the position error becomes 0.

5.5.6 Inserting errors in OTD

Now we have an OTD value. But in real life things are not “perfect”. That is why an error value must be inserted into the simulation model. This is to simulate the error sources described in section 5.3. It is possible to introduce a propagation channel model for each area type to produce realistic values for the OTD uncertainties that are due to the propagation channel. This is identified as future work. The simulation model is designed in the way that a channel model can easily be implemented. For information on further work, see section 8.2.

5.5.7 OTD with errors

For calculating a realistic OTD value, the “perfect” OTD value is added with the error value.

5.5.8 RTD value

The RTD value is the real time difference measured by the LMU. We have set the RTD to 0 in our simulations, but have taken the errors the RTD value could give into account when calculating the statistics. The simulation model is designed in the way that a measured RTD value easily can be added on a later stage. For information on further work, see section 8.2.

5.5.9 Calculating GTD

For calculating GTD, the OTD and RTD values are used. The general formula for this is:

$$GTDi = OTDi \;\; RTDi$$

5.5.10 Finding start position

In order to provide the *finding MS location* function (see next subsection) with an appropriate position from which the optimisation is started, a new function was introduced. The *finding start position* function divides the current measurement area into a grid. The function is designed in the way that the resolution of this grid is adjustable. In our simulations, we have used a resolution of 10 m, giving a grid consisting of 10 m^2 blocks. A function value of Equation 5 described in subsection 5.2.4 was calculated for each of the blocks in the grid. The output was the (x, y) values of the block with the smallest function value (~0). This position was used as a start position for the optimisation.

Another solution to this problem is to use a random search method like Optimized Step Size Random Search (OSSRS) described in [34] to arrive at the region of the optimum and then switch to a deterministic method like the Simplex method of Nelder and Mead currently used in our function.

5.5.11 Finding MS location

For finding the MS location, a least square optimisation was used with the Equation 7 described in subsection 5.2.4. However, there was a problem with this optimisation only finding a local minimum and not a global minimum. That is why we used the finding start position for providing a good starting location for this optimisation. The output of this function is the location estimate for the MS.

5.5.12 Plotting hyperbolas, MS predicted and measured location

In order to manually check the location calculation, a graphical plot was made. These plots show the hyperbolas calculated on basis of the GTD value. In addition the measured MS position and the calculated one are plotted. BTS locations are also shown. An example of this plot is shown in section 5.9, and in Appendix C.

5.5.13 Calculating location error

The location error was calculated by using Equation 8 described later in section 5.8.

5.5.14 Calculating statistics

Different statistical data was calculated. The statistics include a probability density function, cumulative density function and the percentiles of the location error, as described in section 5.8. In addition, background statistics like the total number of measurements, the number of neighbours observed and the number of valid measurements were calculated. For the results of the simulations, see section 5.9.

5.6 Simple channel model

As mentioned in subsection 5.5.7, an error was inserted into the OTD parameter; this error acts as a simple channel model in the absence of a more complex channel model. The simple channel model is based on several simulation runs of the OTD parameter and assumptions about the geography of the measurement scenarios.

By comparing the average T_{RX} values obtained when simulated in absence of errors and the propagation conditions in each measurement scenarios, we can construct a simple channel model. In the urban measurement scenario NLOS components caused by the reflection and diffraction of signals, are present and these components will decrease the accuracy. In the rural measurement scenario, a LOS component is assumed to be present and it is assumed that the OTD parameter is less influenced by reflected and diffracted signals.

By adding an error of larger magnitude on the OTD parameter for the urban area then the rural area, we compensate for the different propagation conditions. The results are summarised in Table 6.

Table 6. Parameters for simple channel model.

Error	Magnitude	Area
α_1	$\pm 1*10^{-6}$	Urban
α_2	$\pm 1*10^{-7}$	Urban / Rural
α_3	$\pm 1*10^{-8}$	Urban / Rural
α_4	$\pm 1*10^{-9}$	Rural

5.7 Measurements statistics

Measurements with incomplete BTS data for serving cell or one of the neighbouring cells were discarded. Only the neighbouring cells with a signal level above -92 dBm were considered useful in the statistics. Measurements where the MS can observe only one or none neighbouring cells were also discarded from the simulation. This is because the E-OTD method requires OTD measurements from at least three BTSs to perform a useful location estimate. Table 7 summarises the number of measurements in the two area types and the number of serving cells represented. This represents a wide statistical data material, providing significant statistics.

Table 7. Overview of measurement statistic

Area	# measurements total	# measurements used	# cells
Urban area	5174	3029	72
Rural area	10850	2282	33

Table 8 shows the number of neighbouring cells observed by the MS for the two measurement scenarios. Two or more neighbours are necessary for the E-OTD method to operate.

Table 8. Overview of measurements and their neighbours

	urban area	rural area
Measurements with no neighbours	128	4680
Measurements with one neighbour	24	3410
Measurements with two neighbours	47	1661
Measurements with three neighbours	203	703
Measurements with four neighbours	497	268
Measurements with five neighbours	1107	76
Measurements with six neighbours	3168	52

Measurements with no –or one neighbour were discarded since E-OTD requires OTD measurements from at least three BTSs to be accurate (serving cell + 2 neighbouring cells). In our simulation a position estimate was produced for measurements with two or more neighbouring cells.

5.8 Statistical analysis

The statistical evaluation is based on computing the difference between the estimated position $(\hat{x}, \hat{y})$ and the true position (x,y). One possible error measure is to define the circular error:

Equation 8

$$ce_i = \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2}$$

Here subscript i denotes quantities related to the ith measurement. Statistics on the circular error will in our case be presented by:

- Plotting the cumulative distribution function (CDF) of *ce*
- Displaying CDF percentile values, 67%, 90% and 95% levels

Another possibility is to compute the root mean square error (*rmse*):

Equation 9

$$rmse = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left((x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2\right)}$$

Here N is the total number of measurements. The *rmse* calculation is very sensitive to occasional poor position estimates. A measure which is less sensitive to these outliers is obtained by omitting the 10% worst cases in the *rmse* calculation.

5.9 Results from the simulations

To test the reliability of the simulation model, simulation runs with the absence of error was performed. Total number of valid measurements for the urban area is 3029. The test shows that in 81.5% of these measurements, the simulation model found the right location of the MS. The percentage for the rural area was 75.3%, of a total of 2282 valid measurements.

A plot of the hyperbolas was made to be able to graphically check the result of the calculations. An example of a plot is shown in Figure 14. The plot shows the calculated hyperbolas, calculated MS position, measured MS position and BTSs used to perform the calculation. More examples of these plots can be found in Appendix C.

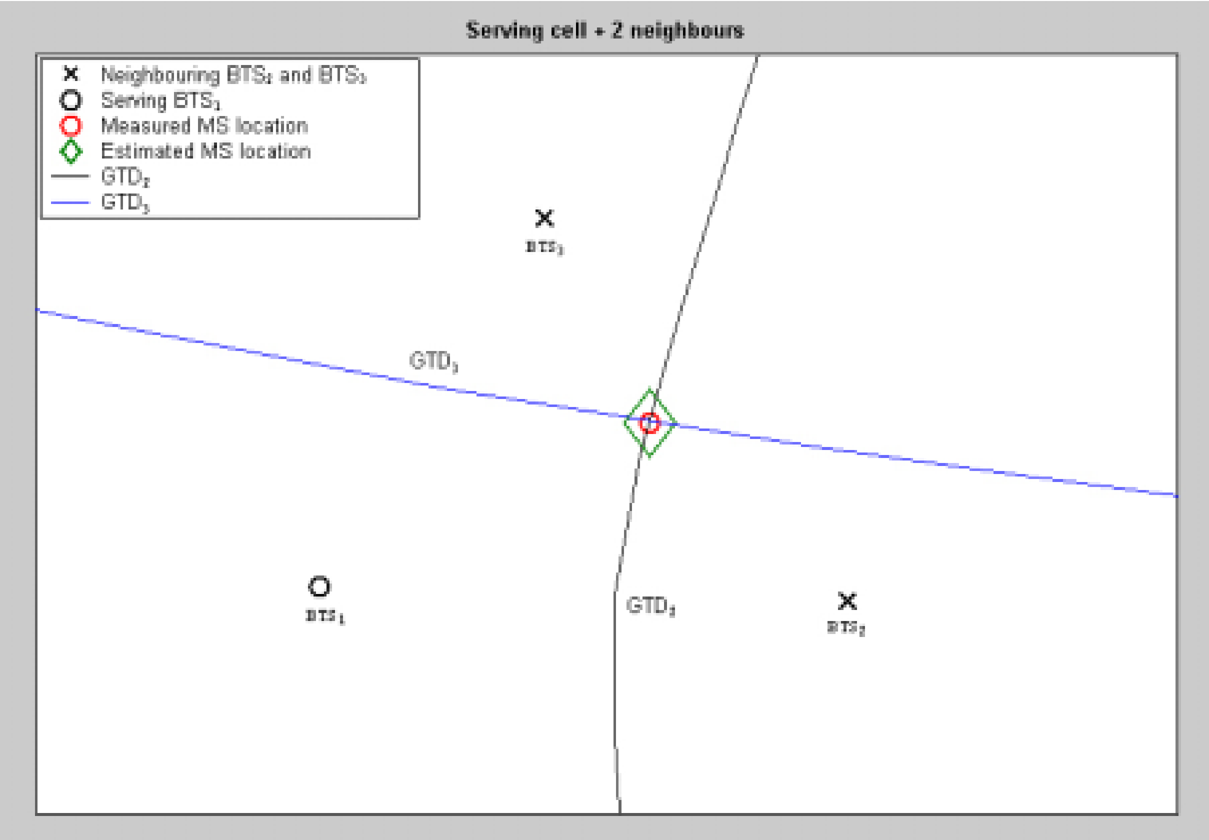

Figure 14. Plot of the calculated hyperbolas, BTSs, calculated and measured MS position.

Table 9 shows the percentiles for the estimated location, when simulated for the urban area with the values described in section 5.6.

Table 9. Percentiles for urban area.

Error \ Percentile	25	50	67	75	90	95
α_1	135	245	375	485	2915	6825
α_2	35	65	95	115	265	495
α_3	5	5	15	25	155	295

Figure 15 shows the cumulative density function for the urban area simulation runs.

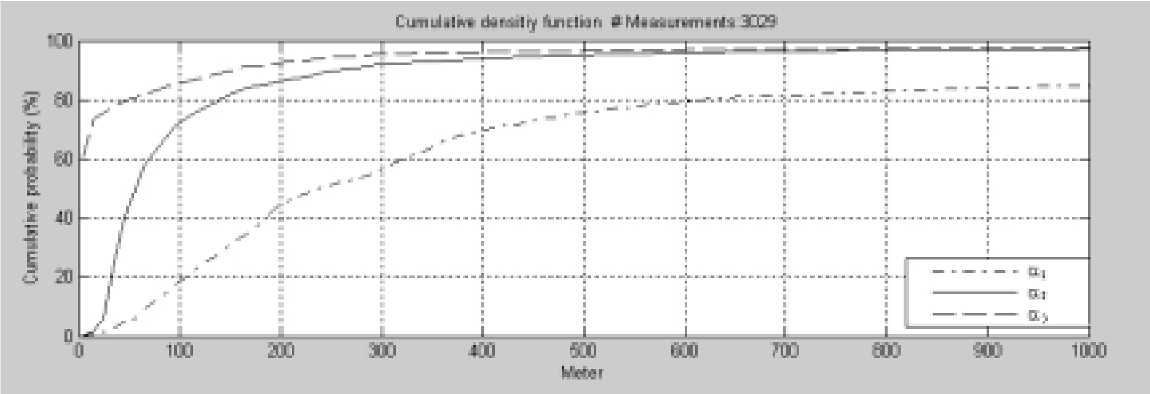

Figure 15. Cumulative density function for urban area.

Table 10 shows the percentiles for the estimated location, when simulated for the rural area with the values described in section 5.6.

Table 10. Percentiles for rural area.

Error \ Percentile	25	50	67	75	90	95
α_2	55	95	175	325	1015	2345
α_3	25	25	25	25	475	1325
α_4	5	5	5	5	315	1125

Figure 16 shows the cumulative density function for the rural area simulation runs.

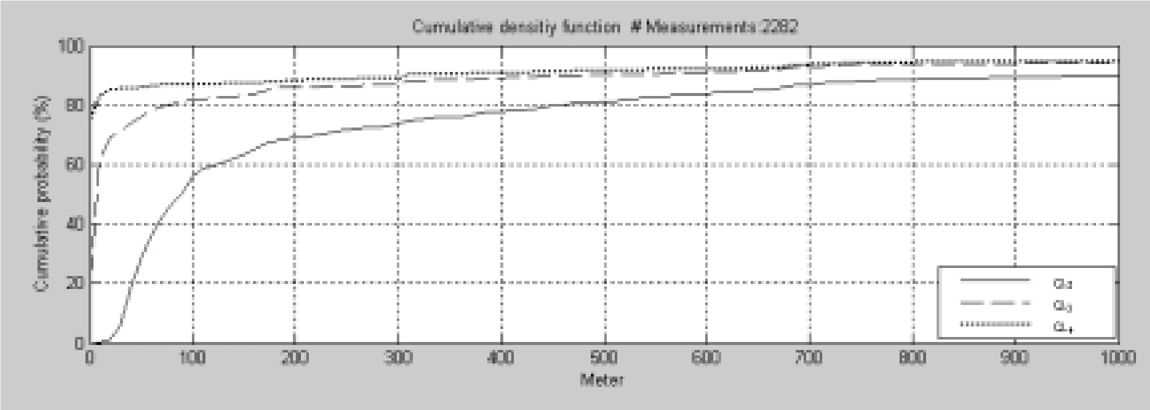

Figure 16. Cumulative density function for rural area.

Some simulation runs were performed with only two neighbouring BTSs, to show the difference when three or four BTSs are used in the E-OTD location estimate calculation. Figure 17 shows the results of these simulation runs in the urban area.

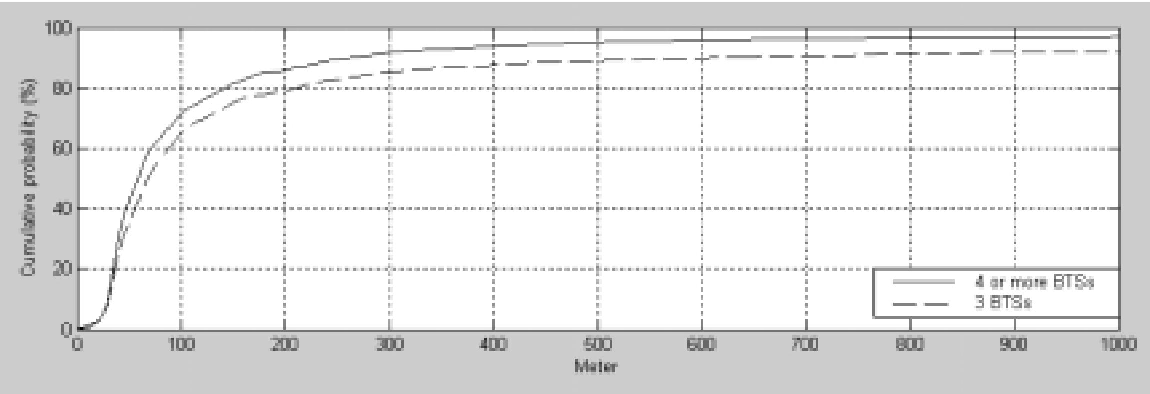

Figure 17. Difference when E-OTD is performed with three or four BTSs in urban area

Figure 18 shows the difference when E-OTD is performed with two or three neighbours in the rural area.

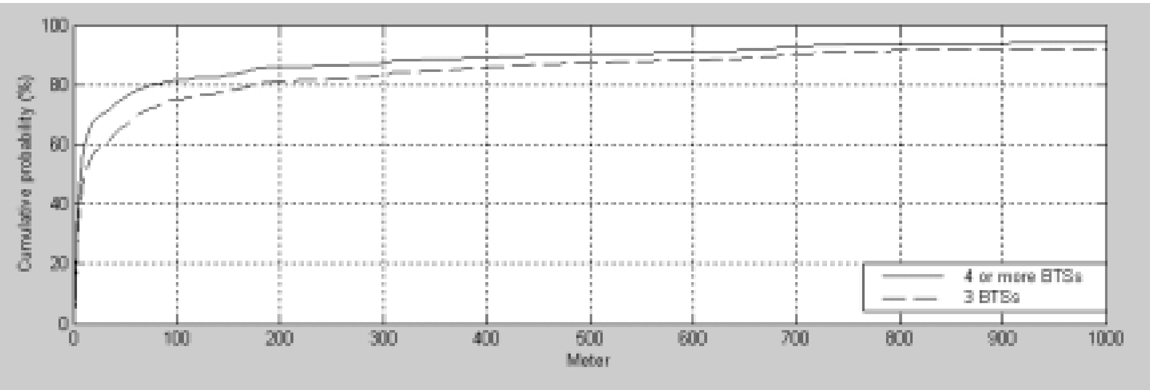

Figure 18. Difference when E-OTD is performed with three or four BTSs in rural area

5.10 Conclusion

A large amount of the total measurements, 74.6% in the rural area have only one or none neighbouring cell [Table 8 in section 5.7]. This makes it difficult to rely on E-OTD as the only location method in this area. E-OTD should be complemented with some other location method, e.g. CGI + TA. This is not a problem in the urban area. For the urban area 2.9% of the total measurements have only one or none neighbouring cell.

Our simulations show (Table 9 and Table 10) that the accuracy in the urban area can be from 35 to 265 m. (25 and 90 percentile), and in the rural area 25 to 475 m. when simulated with the middle error magnitude. The results from our simulations seem to be quite similar to what the vendors Cambridge Positioning System, Nokia, Motorola and Nortel have found ([15], [14], [5] and [35]). It should be noted that the evaluations these vendors have performed have been performed with different channel models, density and topology of the BTSs. The only thing that is similar is that the RTD value has been set to 0, thus yielding a synchronised network. The accuracy of the E-OTD method is quite good, which makes it a promising location method.

It can be seen in Figure 17 and Figure 18 that the location accuracy increases when performing E-OTD with four or more BTSs, as opposite to performing E-OTD with three BTSs. The difference in the location estimate when more than four, or just four BTSs involved, are minimal [35].

It is shown in Table 9 and Table 10 that the accuracy when including the 90 percentile of the measurements is quite good. But when including the 95 percentile, the accuracy decreases radically especially in the rural area. This is because a few of the measurements gives a rather large location error, while the majority of the measurements have good accuracy.

Table 9 and Table 10 show that the accuracy in the urban area is better than in the rural area when simulated with the same error level in the channel model. But as mentioned earlier, the propagation conditions in the urban area is assumed to be worse.

6 LMUs required to get an accurate location estimate

As explained in the previous chapter, to compensate for the clock drift in BTSs in an unsynchronised GSM network, LMUs must be deployed. The requirement for an E-OTD implementation to work is that every BTS must be visible for at least one LMU. It is of vital importance for an operator to know the number of LMUs required in the network. However, the measurements used in the simulation of E-OTD are not suitable to find the number of LMUs needed, since no information about signal strength is available at the position of each BTS. Therefore a different approach using data from a radio planning tool was adopted, as explained in this chapter.

6.1 Method

A new framework in MATLAB was constructed to estimate the number of LMUs needed to compensate for the clock drift. Telenor Mobil employs a system called ASTRIX to perform radio planning for the GSM network. ASTRIX uses digital map data to compute predictions of the signal level received by a MS at different points in the geography. The main idea is to use coverage predictions from ASTRIX for multiple neighbouring BTS inside a measurement scenario, and compare those predictions to the signal level threshold at the actual position of the serving cell. This is based on an assumption that LMUs will be positioned in the same site as a BTS, which indicates a BSS centric architecture, as explained in subsection 4.2.1. In this manner it could then be estimated which BTSs were visible to each other. The sensitivity limit for GSM is -102 dBm, but in real life a stronger average signal is required, to compensate for fading. The simulations have therefore been computed with a signal threshold of -92 dBm in addition to the theoretical threshold. This is done for every BTS inside a measurement scenario.

6.2 MATLAB framework

The ASTRIX files and the measurement parameters from the previous campaign were used. The format of ASTRIX files used in this framework is as follows: A unique filename consisting of cell id and UTM zone. Each file consist of a table were the first column is the (x,y) position were the predicted signal level is recorded and the second column consist of the predicted signal level. At the rural measurement scenario the resolution of the position is 100 meters, i.e. a prediction is recorded every 100 meters. At the urban measurement scenario the resolution is 10 meters. For each BTS the signal level at other BTS sites were found, and from this a neighbour list consisting of BTSs visible to each other was generated. Each line in the neighbour list consists of a BTS, and the BTSs visible to it. The line with the most BTSs was used as a starting point, and a LMU was “placed” at the first BTS. Then the second line was checked with the first, to find out if all the BTSs in line two were covered in the starting line. If they were, they had coverage of an LMU. If not, an LMU must be "placed" at the BTS which were not covered in the first line. The result was a list, were each line must see an LMU (Table 11). The number of LMUs needed, was then the number of lines in the list.

Table 11. Example of the resulting LMU list

LMU is placed at	Visible	Visible	Visible	Visible
BTS1	BTS2	BTS3	BTS5	BTS7
BTS4	BTS6	BTS8	-	-

6.3 Results

Results from the simulations are shown in Table 12. It can be seen that the ratio of LMUs versus BTS is 1:5 in the urban area and 1:4 in the rural area.

Table 12. LMUs required to get an accurate location estimate

Measurement scenario	Urban		Rural	
Signal level threshold	-102 dBm	- 92 dBm	-102 dBm	-92 dBm
Number of BTS	45	45	30	30
Number of LMUs required	7	9	5	7

It should be noted that the signal predictions from ASTRIX predicts signal strength on the ground, while the BTS antenna is several meters above the ground. The signal level will probably be higher at the height of the antenna, thus yielding a conservative prediction of signal strength.

In the urban area, which is very small geographically, most of the BTSs have overlapping coverage (e.g. signal strength above the limit at the other BTSs positions). The exception is the BTSs at the edges of the geographical area. The restraint of how many BTSs a LMU can handle will in this area be the main constraint.

7 Discussion

Different location services require different accuracy of the location estimate. The big issue, in addition to accuracy, is the degree of coverage of the location method. As shown in this report, the location technologies all have different advantages and disadvantages. The best solution will probably be to have a combination of CGI+TA, E-OTD and A-GPS implemented in the network. But this is a matter of cost and, as mentioned earlier, the requirements of the different location services the operator choose to offer their customers.

As shown in this report, E-OTD has limited coverage in rural areas. But when complemented with CGI+TA (already implemented in the network), good location coverage is still possible in this area. When implementing location services e.g. fleet management, weather reports and emergency services in this area, the location accuracy perhaps don't need to more accurate than up to 1 km. There will be no need for the accuracy of e.g. the A-GPS method, and the E-OTD method complemented with CGI+TA will be appropriate. On the other hand, if the operator chooses to implement location services e.g. route guidance and navigation services, the location accuracy need to be accurate up to 50 m. If the E-OTD method is to be used in this area, the density of BTSs needs to increase. If the operator plans to implement services that require this kind accuracy, the A-GPS method will be preferable in this area. The A-GPS method will give high cost for the consumers, who need new mobile terminals to use this method. This cost can on the other hand be covered by the operator by subsidiaries.

In the urban area, the accuracy and coverage is quite good when using the E-OTD method. The propagation properties will be the most vital obstacle in this area. But it is assumed that most of the location services available today will not have higher accuracy requirements than the E-OTD method can provide in this area.

According to many industry experts, including recent study reports from CGALIS and LOCUS, a combination of the A-GPS and E-OTD location techniques can reach a greater level of accuracy and a wider coverage than either method standing alone. A-GPS provides high accuracy in rural and sub-urban areas, but at the same time has a low to medium availability indoors. On the other hand, E-OTD provides a high availability and accuracy in dense-urban areas and indoors. Combining the two technologies provides high accuracy and availability in all areas: outdoors, sub-urban, dense-urban and indoors.

The difference in density of BTSs in the urban and rural area also requires different density of LMUs at these areas. The BTSs in the urban area is dense, and requires one LMU per five BTSs. The density of BTSs decreases as you move away from the urban areas. The rural area requires one LMU per four BTSs. For the E-OTD method to be performed, each of the BTSs involved in the location prediction must have a LMU visible. These LMUs have a high cost for the operator, and it must be taken into account when planning to implement a location technology. Does the operator need the accuracy of the E-OTD method in that particular area, or could a “low cost” method like CGI+TA cover the location accuracy the services requires?

The information about the location of the mobile stations may be used not only to provide a subscriber service, but may also be used for network internal operations such as location assisted handover. This internal use of the information may lead to higher traffic capacity and improved call completions.

The Enhanced 911 (E-911) regulative by the US Federal Communications Commission (FCC) pushes location technologies in the USA. In Europe a similar regulative is expected. The Commission of European Communities has issued a proposal for a directive on a universal service and users' rights relating to electronic communications networks. The rollout of new location technology in Norway will probably be marked driven since Norway is not a member of the European Union; therefore no carriers have to act in accordance with the upcoming E-112 rules.

8 Conclusions and future work

8.1 Conclusions

This thesis has shown an overview of different location technologies, location services and location architecture in the GSM network. In addition, the E-OTD method has been explained in detail, and its characteristics simulated by a simulation model.

Different location services require different accuracy of the location estimate. The big issue, in addition to accuracy, is the degree of coverage of the location method. As shown in this report, the location technologies all have different advantages and disadvantages. The best solution will probably be to have a combination of CGI+TA, E-OTD and A-GPS implemented in the network. But this is a matter of cost and the requirements of the different location services the operator choose to offer their customers.

As stated before, our results of the simulations of the characteristics in the E-OTD method seems to be quite similar to simulations performed by different vendors of location technology. The accuracy of the E-OTD method is quite good, which makes it a promising location method.

The location accuracy increases when performing E-OTD with four or more BTSs, as opposite to performing E-OTD with only three BTSs. The difference in the location estimate when more than four, or just four BTSs involved, are minimal.

It could be difficult to implement E-OTD in the rural area we have tested in. The simulation results show that 74.6% of the measurements only have one or none neighbouring cells to the serving cell. The E-OTD method requires three or more BTSs to be performed. This is not a problem in the urban area were the density of BTSs is high. In the urban area we have tested in, only 2.9% have only one or none neighbouring cell.

To compensate for the BTS clock drift in an unsynchronised GSM network, LMUs must be deployed. The requirement for an E-OTD implementation to work is that every BTS must be visible for at least one LMU. The density of LMUs required found in our simulations was: 1:5 in the urban area and 1:4 in the rural area.

8.2 Future work

As mentioned in the report, the simulation model is designed in a way that it is easy to add new parameters to the model. A more complex channel model could be added at a later stage. This would make the model more realistic. If measuring on a test GSM system on a later stage, including LMUs, the measured RTD value can easily be added to the simulation model.

Parameters from an evaluation project on the CGI+TA method was used in this master thesis. As this thesis have evaluated the E-OTD method, it remains to evaluate the A-GPS method as this is the three main location technologies we think will be used by the GSM operators. An evaluation of combining these methods should also be performed. This on the basis of costs and which location services and requirements the operator wants to implement.

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Abbreviations

3GPP	Third Generation Partnership Project
A-GPS	Assisted Global Positioning System
ALI	Automatic Location Information
AOA	Angle of Arrival
ARFC	Absolute Radio Frequency Channel
BCCH	Broadcast Control Channel
BSC	Base Station Controller
BSIC	Base station identity code
BSS	Base Station Subsystem
BTS	Base Transceiver Station
CAMEL	Customised Applications for Mobile Enhanced Logic
CBC	Cell Broadcast Centre
CGALIES	Co-ordination Group on Access to Location Information by Emergency Services
CGI	Cell Global Identity
E-112	Enhanced 112
E-911	Enhanced 911
ECR	Enhanced Call Routing
E-OTD	Enhanced Observed Time Difference
E-OTD-C	Enhanced Observed Time Difference Circular
EU	European Union
FCC	Federal Communications Commission
GMLC	Gateway Mobile Location Centre
GMSC	Gateway Mobile Services Switching Centre
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile telecommunications
gsmSCF	GSM Service Control Function
GTD	Geometric Time Difference
HLR	Home Location Register
IEEE	Institute of Electrical and Electronics Engineers
LCS	Location Service
LMU	Location Measurement Unit
LOCUS	LOcation of Cellular Users for Emergency Services project
LOS	Line of Sight
MLC	Mobile Location Centre
MPC	Mobile Positioning Centre
MS	Mobile Station
MSC	Mobile Services Switching Centre
NLOS	None Line of Sight

NSS	Network SubSystem
OTD	Observed Time Difference
PCS	Personal Communications Services
PLMN	Public Land Mobile Network
PPM	Parts Per Million
PSAP	Public Safety Answering Point
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RTD	Real Time Difference
RXLEV	Received Signal Level
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
SMLC	Serving Mobile Location Centre
SMR	Specialized Mobile Radio
SMS	Short Message Service
SMSC	Short Message Service Centre
STK	SIM ToolKit
TA	Timing Advance
TEMS	Test Equipment for Mobile Systems
TOA	Time of Arrival
UL-TOA	Uplink Time of Arrival
UMTS	Universal Mobile Telecommunications System
UTM	Universal Transverse Mercator
VLR	Visitor Location Register
WAP	Wireless Application Protocol
WGS	World Geodetic System

Appendix A. Mapping RXLEV to signal strength (-dBm)

Table 13. Mapping RXLEV to signal strength (-dBm)

RXLEV	RANGE
0	Less than -110 dBm + SCALE
1	-110 dBm to -109 dBm + SCALE
2	-109 dBm to -108 dBm + SCALE
3	-108 dBm to -107 dBm + SCALE
4	-107 dBm to -106 dBm + SCALE
5	-106 dBm to -105 dBm + SCALE
6	-105 dBm to -104 dBm + SCALE
7	-104 dBm to -103 dBm + SCALE
8	-103 dBm to -102 dBm + SCALE
9	-102 dBm to -101 dBm + SCALE
10	-101 dBm to -100 dBm + SCALE
11	-100 dBm to -99 dBm + SCALE
12	-99 dBm to -98 dBm + SCALE
13	-98 dBm to -97 dBm + SCALE
14	-97 dBm to -96 dBm + SCALE
15	-96 dBm to -95 dBm + SCALE
16	-95 dBm to -94 dBm + SCALE
17	-94 dBm to -93 dBm + SCALE
18	-93 dBm to -92 dBm + SCALE
19	-92 dBm to -91 dBm + SCALE
20	-91 dBm to -90 dBm + SCALE
21	-90 dBm to -89 dBm + SCALE
22	-89 dBm to -88 dBm + SCALE
23	-88 dBm to -87 dBm + SCALE
24	-87 dBm to -86 dBm + SCALE
25	-86 dBm to -85 dBm + SCALE
26	-85 dBm to -84 dBm + SCALE
27	-84 dBm to -83 dBm + SCALE
28	-83 dBm to -82 dBm + SCALE
29	-82 dBm to -81 dBm + SCALE
30	-81 dBm to -80 dBm + SCALE
31	-80 dBm to -79 dBm + SCALE
32	-79 dBm to -78 dBm + SCALE
33	-78 dBm to -77 dBm + SCALE
34	-77 dBm to -76 dBm + SCALE
35	-76 dBm to -75 dBm + SCALE
36	-75 dBm to -74 dBm + SCALE
37	-74 dBm to -73 dBm + SCALE
38	-73 dBm to -72 dBm + SCALE
39	-72 dBm to -71 dBm + SCALE
40	-71 dBm to -70 dBm + SCALE
41	-70 dBm to -69 dBm + SCALE
42	-69 dBm to -68 dBm + SCALE
43	-68 dBm to -67 dBm + SCALE
44	-67 dBm to -66 dBm + SCALE
45	-66 dBm to -65 dBm + SCALE
46	-65 dBm to -64 dBm + SCALE
47	-64 dBm to -63 dBm + SCALE
48	-63 dBm to -62 dBm + SCALE
49	-62 dBm to -61 dBm + SCALE
50	-61 dBm to -60 dBm + SCALE
51	-60 dBm to -59 dBm + SCALE
52	-59 dBm to -58 dBm + SCALE
53	-58 dBm to -57 dBm + SCALE
54	-57 dBm to -56 dBm + SCALE
55	-56 dBm to -55 dBm + SCALE
56	-55 dBm to -54 dBm + SCALE
57	-54 dBm to -53 dBm + SCALE
58	-53 dBm to -52 dBm + SCALE
59	-52 dBm to -51 dBm + SCALE
60	-51 dBm to -50 dBm + SCALE
61	-50 dBm to -49 dBm + SCALE
62	-49 dBm to -48 dBm + SCALE
63	Greater than -48 dBm + SCALE

Appendix B. Measurement Equipment

Measurement equipment used by Telenor R&D during the measurement campaign summer 2001:

- TEMS-MS: Ericsson SH 888
- GPS: Northstar model 8700
- RDS receiver: Seatex DFM-200
- PC with TEMS software, version 98.0.2
- Antennas for GSM900/1800, GPS and RDS

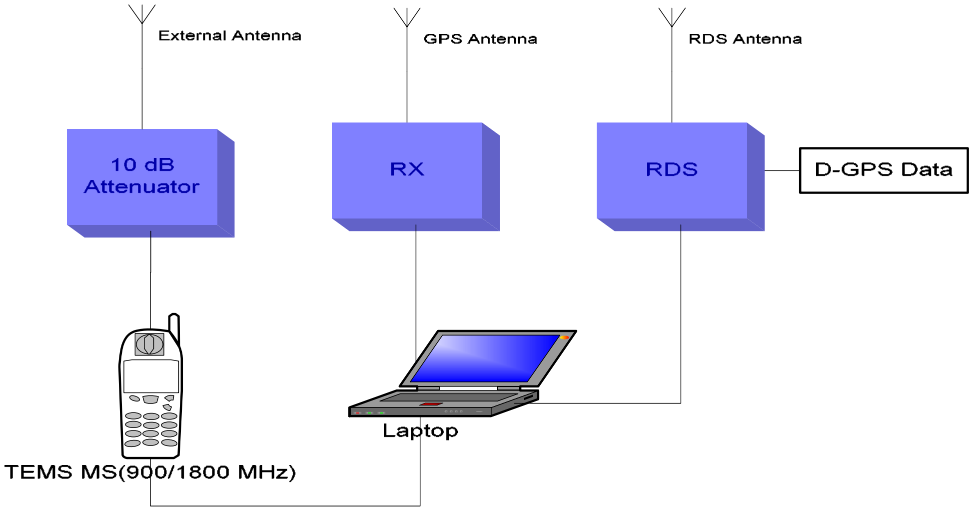

Figure 19. TEMS measuring equipment.

Appendix C. Example of a hyperbola plot

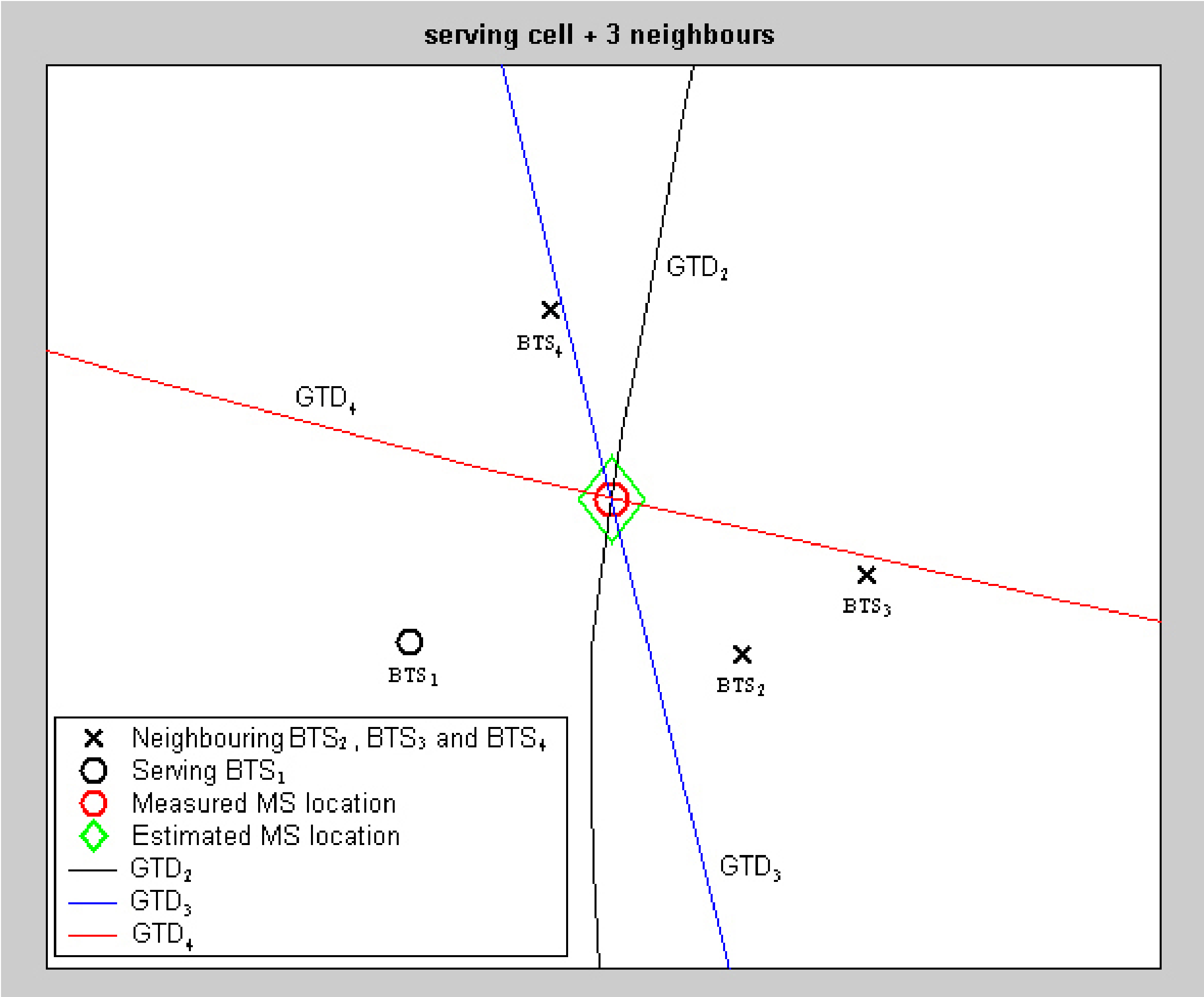

Figure 20. Example of a hyperbola plot with four BTSs involved