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Cellular Location Technology

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Abstract:

This document contains a review of the current status of cellular location technology and near-future developments. Location methods based on cellular system signals (GSM and UMTS), and GPS are presented and evaluated in terms of their applicability for the purposes of CELLO project targets. The location-based applications of CELLO project, i.e. location-aided planning, location-aided handover, and location-aided mobility management, require a location method that gives fast response and accuracy to a fraction of cell radius, causes minimal amount of extra signalling, and has large capacity. These requirements are best met by methods that use standard measurement reports from mobile terminals. Changes to standards may be needed to retrieve the required measurements in GSM and UMTS.

Keyword list:

Location, positioning, GSM, UMTS, GPS

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TERMS AND ACRONYMS

2G	Second generation cellular mobile system (GSM)
3G	Third generation cellular mobile system (UMTS)
3GPP	Third Generation Partnership Project
AOA	Angle of Arrival
BCCH	Broadcast Control Channel
BS	Base Station
BSC	Base Station Controller
BTS	Base Transceiver System
CBC	Cell Broadcast Centre
CDMA	Code Division Multiple Access (UMTS)
CPICH	Common Pilot Channel
DCM	Database Correlation Method
DGPS	Differential GPS
DL	Downlink
E911	Enhanced 911 (wireless Enhanced 911 emergency call service in United States)
E-OTD	Enhanced Observed Time Difference
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Committee
FDD	Frequency Division Duplex
GDOP	Geometrical Dilution of Precision
GMLC	Gateway Mobile Location Centre
GPS	Global Positioning System
GSM	Global System for Mobile communication
HLR	Home Location Register
HMM	Hidden Markov Model
IPDL	Idle Period Downlink
LAH	Location-Aided Handover
LAM	Location-Aided Mobility Management
LAP	Location-Aided Planning
LCS	Location Services
LIF	Location Interoperability Forum
LMU	Location Measurement Unit

LOS	Line of Sight
MGIS	Mobile Geographical Information System
MLC	Mobile Location Centre
MS	Mobile Station (Mobile phone)
MSC	Mobile Switching Centre
NLOS	Non-Line of Sight
OTDOA	Observed Time Difference of Arrival
PCF	Position Calculation Function
QoS	Quality of Service
RTD	Real Time Difference
RTT	Round Trip Time
SA	Selective Availability
SACCH	Slow Associated Control Channel
SFN	System Frame Number
SIM	Subscriber Identification Module
SMLC	Serving Mobile Location Centre
SMS	Short Message Service
SPS	Standard Positioning Service
SRNC	Serving Radio Network Controller
TA	Timing Advance
TA-IPDL	Time Aligned-IPDL
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TDOA	Time Difference of Arrival
TOA	Time of Arrival
TS	Technical Specification
TSG	Technical Specification Group
UMTS	Universal Mobile Telecommunication System (CDMA)
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VLR	Visitor Location Register
VMSC	Visited Mobile Switching Centre

EXECUTIVE SUMMARY

This document contains a review of the current status of cellular location technology and near-future developments. Basic location techniques based on cellular system signals (GSM and UMTS), and satellite systems are presented. Cellular location techniques include methods based on cell identification, signal strength, angle-of-arrival, time delay, correlation with database and signal pattern recognition. An overview of Global Positioning System is given along with description of differential and assisted GPS positioning methods. Some trial systems and commercial products, based on different techniques, are described in order to give a general view on what is being developed and what is already available on the market. In urban environment the best accuracy can be achieved by time delay and correlation based techniques.

GSM and UMTS standardisation on location methods and services is covered. Different location methods are evaluated based on the requirements set by CELLO applications. It is concluded that the most applicable location methods are based on standard measurement reports that are continuously transmitted from the mobile station back to the network during a connection. Such methods in GSM are e.g. the signal strength method and database correlation method. To ensure the support for CELLO applications in GSM and UMTS, contribution to standardisation bodies may be needed.

CELLULAR LOCATION TECHNOLOGY

1 INTRODUCTION

There is increasing interest towards location technologies and location based mobile services. One of the driving forces is the obligation set by the FCC (Federal Communications Committee) in the United States to provide enhanced 911 (E911) wireless services. According to the obligation, cellular systems will be able to locate a cellular phone in connection of an emergency, with certain schedules and accuracy requirements [11]. Also the European Commission has plans to implement a similar obligation, but probably without accuracy specifications. Another driving force is the wealth of foreseen location-based services. By summer 2001, some location-based services have already been introduced by GSM operators in Europe. Available location methods include cell identification and methods based on signal strength measurements. Also first GSM handsets with integrated GPS navigator are available on the market.

There are two basic approaches for locating the mobile phone. The phone can either be located with the help of the cellular system's signals or the phone can be integrated with a GPS receiver, which takes care of the location function. Implementing location methods requires some modifications, either software or hardware or both, to the cellular phone and/or the network. These modifications create various amounts of costs and new signalling to the network. Also the achievable accuracy of location methods varies. The requirements set by the applications determine which location method is the best or most cost-effective.

The location-based applications of CELLO project are location-aided planning (LAP), location-aided handover (LAH) and location-aided mobility management (LAM). They aim at performance enhancements in the cellular network by collecting location-dependent performance data (LAP) or by using the location of mobile users in real-time (LAH and LAM). The requirements for the location method to support these applications are demanding. Accuracy to a fraction of cell size is clearly needed. High capacity of the location system is a requirement, since a large number of users (preferably all!) with on-going call or data connection has to be located. LAH and LAM also need fast response, but for LAP this is not critical. The purpose of this document is to present the location methods that are available or being developed and to evaluate their applicability for LAP, LAH and LAM.

The different location techniques using cellular system's signals are described in Chapter 2. Chapter 3 contains an overview of Global Positioning System and its use as a stand-alone or network-assisted cellular location method. Some of the commercial products and reported location trials are reviewed in Chapter 4. A brief overview of the standardisation activities and their influence on CELLO project is given in Chapter 5. Different location methods are compared, in view of CELLO requirements, in Chapter 6.

2 CELLULAR LOCATION METHODS

Cellular location methods use the signals of the cellular system to find the location of a mobile station. Since cellular systems were not originally designed for positioning, the implementation of different location methods may require new equipment to make the necessary measurements for location determination and new signalling to transfer the measurement results to the location determination unit. Before presenting the cellular location methods and their implementation aspects, some concepts that will be used to classify different methods based on the role of the mobile station (MS) and the network or on the location measurement principle are defined.

Based on the functions of the MS and the network, implementation of a location method belongs to one of the following categories:

- Network-based
- Mobile-based
- Mobile-assisted

In network-based implementation one or several base stations (BSs) make the necessary measurements and send the measurement results to a location centre where the position is calculated. Network-based implementation does not require any changes to existing handsets, which is a significant advantage compared to mobile-based or most mobile-assisted solutions. However, the MS must be in active mode to enable location measurements and thus positioning in idle mode is impossible.

In mobile-based implementation the MS makes measurements and position determination. This allows positioning in idle mode by measuring control channels which are continuously transmitted. Some assisting information, e.g. BS coordinates, might be needed from the network to enable location determination in the MS. Mobile-based implementation does not support legacy handsets

The third category, mobile-assisted implementation, includes solutions where the MS makes measurements and sends the results to a location centre in the network for further processing. Thus, the computational burden is transferred to a location centre where powerful processors are available. However, signalling delay and signalling load increase compared to a mobile-based solution, especially if the location result is needed at MS. Although mobile-assisted solutions typically do not support legacy handsets, it is possible to use the measurement reports (see section 2.8.2) that are continuously sent by GSM handsets to the network in active mode. Techniques that use these measurement reports, e.g. signal strength measurements, are often classified as network-based since they do not require any changes to existing handsets. Nevertheless, it is the MS that makes the measurements and therefore these techniques will be called mobile-assisted in the following.

The requirements set by different applications may favour different kinds of implementations. For example, emergency call location requires high reliability and it is highly desirable to locate these calls from legacy phones as well as new phones. Applications that use continuous tracking, e.g. route directions, require high accuracy and fast location with a fixed update rate. Since the location result is needed at MS in this case, these requirements are best met with a mobile-based solution. Some applications, e.g. traffic monitoring and location-aided network planning (LAP), require mass location capability at network. These requirements can only be met by network-based or mobile-assisted implementations.

Another classification is based on the measurement principle [35]. The measurement principle of each method belongs to one of three categories:

- Multilateral
- Unilateral
- Bilateral

In multilateral techniques, several BSs make simultaneous (or almost simultaneous) measurements. Multilateral measurement principle leads to network-based implementation. Unilateral means that the MS measures signals sent by several BSs and thus leads to mobile-based or mobile-assisted implementation. For bilateral techniques multiple measurements are not needed: either MS measures signal from a single BS or one BS measures signal from MS. This does not exclude any of the three implementation categories. Since multilateral techniques require co-ordination of simultaneous measurements at multiple sites, unilateral techniques are generally better for capacity and signalling load. Bilateral techniques are optimal for rural coverage since only one BS is involved.

2.1 Cell Identification

The simplest method for locating a mobile phone is based on cell identification. Since this is an inherent feature of all cellular systems, minimal changes to existing systems are needed. The cell ID only has to be associated with location, i.e. the coordinates of the BSs must be known (see Figure 1). This is a bilateral location principle that can be implemented as a network-based or mobile-based technique. In mobile-based implementation, the network would have to continuously transmit the coordinates on a control channel.

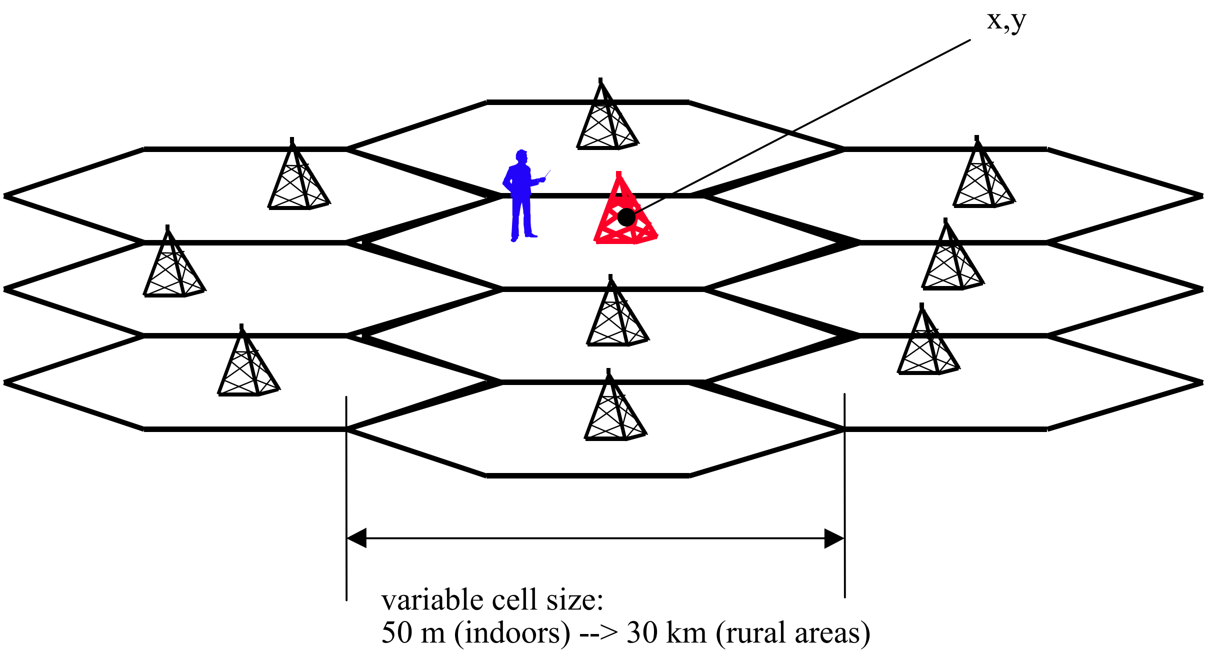

Figure 1. Positioning based on cell identification.

Another advantage of this method is that no calculations are needed to obtain location information. Thus, cell ID based location is fast and suitable for applications requiring high capacity. The drawback is that accuracy is directly dependent on cell radius, which can be very large especially in rural areas. In dense urban areas location accuracy is considerably better due to the small cell radius of micro- and picocells. Nevertheless, this method is not accurate enough for the purposes of CELLO project, since LAP, LAH and LAM all require sub-cell position accuracy. Accuracy can be improved using information of cell coverage area (e.g. sector cells) and timing advance (TA) in GSM or round trip time (RTT) in UMTS. Even with these enhancements the accuracy is probably too low for CELLO applications.

2.2 Signal strength

Using signal strength measurements from the control channels of several BSs, the distances between the MS and the BSs can be estimated. Assuming two-dimensional geometry, an omnidirectional BS antenna, and free-space propagation conditions, signal level contours around BSs are circles. If signal levels from three different BSs are known, the location of the MS can be determined as the unique intersection point of the three circles. However, practical propagation conditions especially in urban areas are far from free-space propagation. Therefore, an environment-dependent propagation model for the dependence of received signal level on BS-MS distance should be used. In urban areas the received signal level generally decreases more rapidly with distance than in open areas.

Multipath fading and shadowing poses a problem for distance estimation based on signal level. The instantaneous, narrowband signal level may vary by as much as 30-40 dB over a distance of only a fraction of the wavelength. Random variations of this order of magnitude cause very large errors in distance estimates. However, fast fading can be smoothed out by averaging the signal strength over time and frequency band. Time-averaging only has a minor effect, due to the motion in the surrounding environment, if the MS is stationary. Contrary to fast fading, the random variations caused by shadowing can not be compensated. Thus, the variations in antenna orientation and local shadowing conditions around the MS (indoors, inside a vehicle etc.) are seen as random errors in distance estimates and consequently in position estimate. Location accuracy also depends on the accuracy of the propagation model and the number of available measurements.

Signal strength method is unilateral and can be implemented as mobile-assisted or mobile-based method. Mobile-based implementation requires that BS coordinates are transmitted to the MS. Signal strength method is easy to implement in GSM, based on measurement reports (see Table 1, p. 15) that are continuously transmitted from the MS back to the network in active mode. Therefore, it does not require any changes to existing phones, and is often called a network-based method although it is the MS that performs the measurements. An alternative implementation is to modify the MSs to enable sending measurement reports in idle mode also. GSM phones with this capability are already available. Signal strength is an easy and low-cost method to enhance the accuracy of pure cell ID based location (see also Section 4.1). However, it is questionable whether the accuracy is adequate for CELLO applications.

In UMTS DL the BSs send the common pilot channel (CPICH) with constant power of 33 dBm (10% of the max power). CPICH is unique in each cell and always present in the air. Before any other transmission each MS monitors the CPICH. Thus, each MS is able to measure the power levels of the nearest BSs common pilot channels. In UMTS, signal strength measurements may be slightly more reliable due to the wider bandwidth, which allows better smoothing of fast fading. On the other hand, the hearability problem prevents measurements of as many neighbouring BSs as it is possible in GSM.

2.3 Angle of Arrival

Signal angle of arrival (AOA) information, measured at the BS using an antenna array, can be used for positioning. Assuming two-dimensional geometry, angle of arrival measurement at two BSs is sufficient for unique location. This is illustrated in Figure 2, where the user location is determined as the point of intersection of two lines drawn from the BSs. It is seen that AOA technique requires line of sight between the MS and the BSs for accurate results. Also, the uncertainty in AOA measurement causes a position uncertainty that increases with

MS-BS distance. Achieved accuracy depends on the number of available measurements, geometry of BSs around the MS and multipath propagation also.

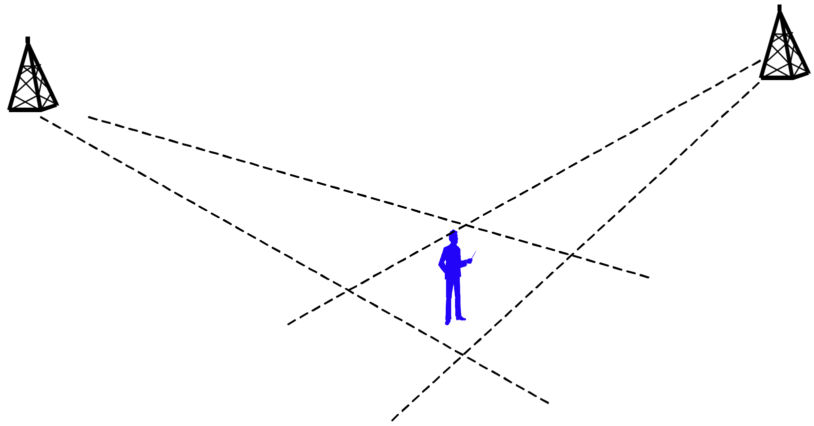

Figure 2. Positioning with angle of arrival measurements.

Since AOA method needs line-of-sight propagation conditions to obtain correct location estimates, it is clearly not the method of choice in dense urban areas where line of sight to two BSs is seldom present. In [32], an rms location error of approximately 300 m with two BSs and 200 m with three BSs in an urban environment was observed. However, the AOA technique could be used in rural and suburban areas where the attainable accuracy is better and it is an advantage to be able to locate a MS which can only be measured by two BSs.

A major barrier to implement AOA method in existing 2G networks is the need for an antenna array at each BS. It would be very expensive to build an overlay of AOA sensors to existing cellular network. However, since it is a network-based method and supports legacy handsets, it is developed by several companies as an E911 solution. In 3G systems AOA measurements may become available without separate hardware if adaptive BS antennas (arrays) are widely deployed.

In addition to financial issues, AOA method may have a capacity problem. Multilateral measurement principle (measurement at several BSs) requires the co-ordination of almost simultaneous measurements at several BS sites, and it is difficult to serve a large number of users.

2.4 Uplink time (difference) of arrival

Signal time of arrival (TOA) measurements, performed either at the BSs or at the MS, can be used for positioning. If the BSs and the MS are fully synchronised, TOA measurements are directly related to the BS-MS distances and three measurements are needed for unique 2D location. However, if the network is not synchronised, such as GSM and UMTS FDD networks, TOA measurements can only be used in differential manner. Even in this case, a common time reference for the BSs is needed. Two TOA measurements then define a hyperbola, and four measurements are needed for unambiguous 2D location.

If the measurements are performed at BSs, it is a network-based multilateral technique. This technique has two drawbacks compared to downlink method: it is only possible to perform the measurements in dedicated mode and there may be capacity problems due to the multilateral measurement principle. The advantage is that due to the network-based implementation, uplink TOA supports legacy phones. It was taken into GSM standardisation as a candidate E911 solution [21]. In GSM implementation of uplink TOA technique, a common time reference, e.g. GPS receiver, is needed at each BS site. The location of an MS with call on is accomplished by forcing the MS to request a handover to several neighbouring BSs. The MS then sends access bursts at full power, and TOA measurements are made from these bursts.

2.5 Downlink observed time differences

In the downlink time difference techniques, the MS observes time differences of signals from several BSs. These signals are typically control channel signals and therefore the MS can perform the measurements in idle mode as well as in dedicated mode. The clock differences of the BSs can be solved by having a reference receiver at known location continuously measuring the observed time differences. This is much simpler and more economical than synchronising the BS transmissions.

The accuracy of all time difference based techniques (uplink as well as downlink) depend on several factors. The accuracy of an individual time difference measurement depends on signal bandwidth and multipath channel. This is illustrated in Figure 3 with an error margin for each time difference measurement. In an urban area the error margin is typically larger, since heavy multipath makes it more difficult to detect the time of arrival of the first echo. If there is no line of sight between the MS and the BSs involved, the location estimates will be biased away from the BSs with no line of sight to the MS (see Figure 3). This is a problem especially in urban areas. In open areas the geometry of the BS configuration around the MS may introduce an additional error, which is described by geometrical dilution of precision (GDOP). A favourable geometry is a uniform distribution of BSs around the MS. Also the number of available measurements has an effect on accuracy: generally it is better to have as many measurements as possible.

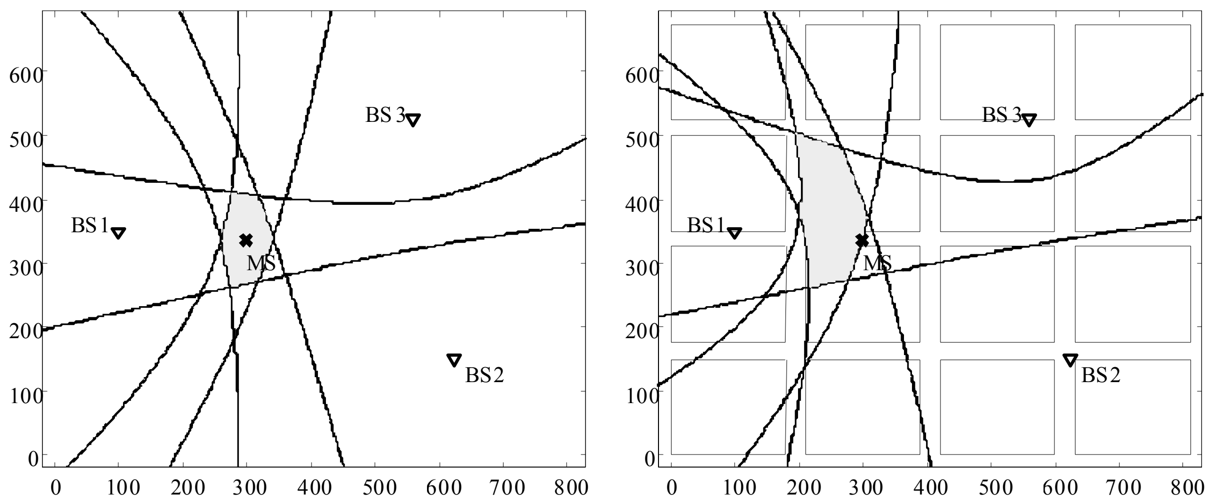

Figure 3. Positioning based on time difference measurements in open (left) and urban environment (right).

UMTS bandwidth is 5 MHz and it operates at a high chip rate 3.84 Mcps/s, which contributes to the better resolution in timing measurements compared to GSM. The timing resolution in UMTS with one sample per chip is ~0.26 μs which corresponds to the propagation distance of ~78 m. In GSM (bit rate 270.8 kBits/s) the bit duration is 3.69 μs and the corresponding propagation distance is ~1100 m. Thus, the finite timing advance (TA) allows to represent absolute distances with a resolution of 554 m. Oversampling of four times the chip rate is often used in the receiver [33]. For UMTS and GSM that means sampling with a rate of 4·3.84Mcps and 4·270.8kBit/s respectively. Thus the timing resolutions are improved to values ~65 ns in UMTS and ~923 ns in GSM corresponding to propagation distances ~19,5 m and ~277 m respectively. In timing techniques for obtaining the needed accuracy level of the MS position estimates, oversampling will be quite mandatory. With advanced technology, it should be possible to achieve higher sampling rates. Thus, the sampling resolution in UMTS will also affect the timing accuracy in measurements. However, the bandwidth of the signal will ultimately determine the time delay measurement accuracy and increasing sampling rate can bring only limited improvement

The downlink observed time difference techniques are unilateral mobile-assisted or mobile-based methods. In mobile-assisted implementation, the MS sends the results of time difference measurements to a location centre, where the location is calculated based on these measurements and measurements from the reference receiver. In mobile-based implementation, the coordinates of the BSs as well as the measurement results from the reference receivers are transmitted to the MS. In GSM and UMTS standardisation, these techniques are called Enhanced Observed Time Differences (E-OTD) and Observed Time Difference of Arrival (OTDOA), respectively. These techniques will be described in more detail in the following subsections.

2.5.1 Enhanced Observed Time Differences (E-OTD)

In GSM, the time difference measurements are called observed time differences (OTDs). Unlike timing advances, OTD measurements observing several BSs are made by the MS without forcing handover, which makes them more attractive for location. However, the resolution at which OTD measurements are reported is only 554 m and the required synchronisation of the BSs is not guaranteed. These problems have been solved in the enhanced OTD (E-OTD) technique.

An experimental E-OTD network architecture is depicted in Figure 4. A handset with modified software is able to report accurate OTD estimates by using sophisticated signal processing algorithms, for example multipath rejection, for finding the earliest arriving signal component. These OTD measurements are then sent via short message service (SMS) to a mobile location centre (MLC) which performs the location calculations. The synchronisation of the BSs is achieved by installing similar receivers as the MS in known locations, typically at the BS sites, to measure the timing differences between BSs. These real time differences (RTDs) are also sent to the MLC via SMS. Disadvantages of this technique are the need for software modifications to the handsets and the need for additional receivers. In operational use, the information transfer will take place using specific signalling messages instead of SMS.

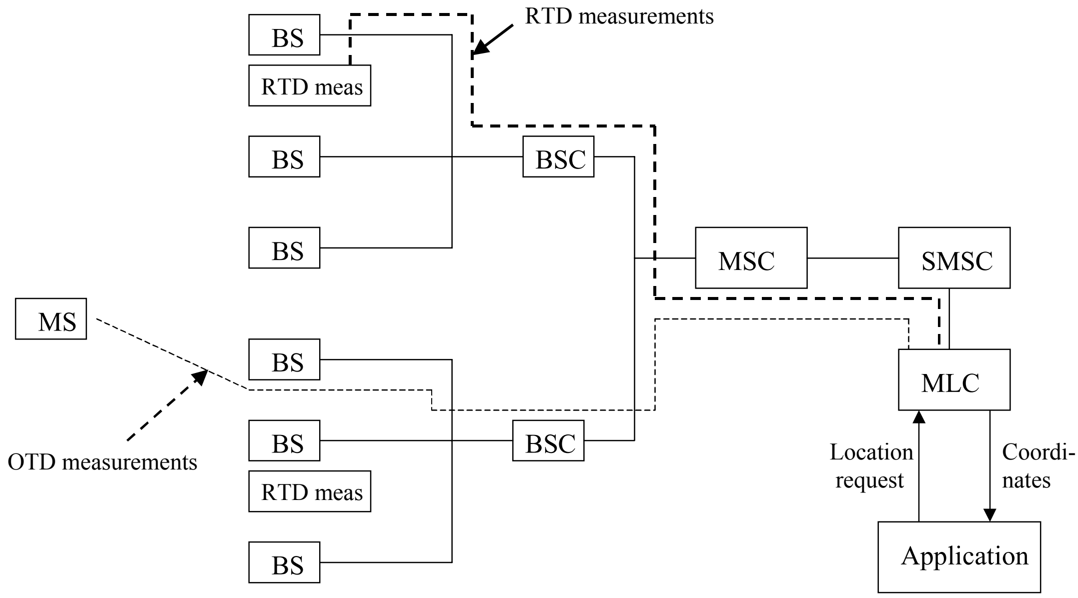

Figure 4. Network architecture for E-OTD concept.

2.5.2 Observed Time Difference of Arrival (OTDOA)

The OTDOA method in UMTS is based on measuring the difference in time of arrival of the downlink signals received at the MS. The OTDOA can be operated in two modes, MS-assisted and MS-based, depending on where the position calculation is carried out. The MS-assisted mode, in which the Serving Radio Network Controller (SRNC) carries out the position calculation, is mandatory and available in all UMTS mobile terminals. The MS-based mode availability depends on MS position calculation capabilities and the operator, as information about the BS positions and relative time differences (RTDs) have to be sent to the MS.

In UTRA TDD mode the BSs are synchronised, but in the UTRA FDD mode the BSs transmit asynchronously, so the relative time difference (RTD) of the actual transmissions of the downlink signals is also needed for the position estimate calculation of the MS. For carrying out these RTD measurements, additional network elements, Location Measurement Units (LMUs), are required. The other way for obtaining the RTD values is by synchronising the BSs, which gives a constant RTD. The BS synchronisation has to be very accurate, as 10 ns uncertainty corresponds to 3 m error in the position estimate. In addition, drift and jitter in synchronisation timing have to be controlled. This needed level of synchronisation accuracy is not easy to achieve and currently it is only technically feasible through satellite based time-transfer technique [6].

Power control is used in UMTS to prevent the near-far problem occurring in CDMA-based systems. On that account the mobile in the downlink direction cannot hear other BSs when it is near to its serving BS and the needed hearability from three BSs may not be attainable. In rural and hilly areas where the density of BSs is small, hearability is a major problem. One possible solution to the hearability problem in OTDOA is the downlink idle periods.

Idle Period Downlink (IPDL)

The OTDOA-IPDL method is based on the same measurements as the basic OTDOA. In order to improve the hearability of neighbouring BSs, the serving BS provides idle periods in continuous or burst mode. In continuous mode, the idle periods are active all time and one idle period is placed in every DL frame (10 ms). In the burst mode, the idle periods are arranged in bursts and an idle period spacing is under the operator's selection, e.g. 1 IPDL every 10 frames (100 ms). The idle periods are short and arranged in a pseudo random way. With longer idle periods, the achievable accuracy would be better because of longer integration time at the MS, but the system capacity would be reduced. During these periods the serving BS completely ceases its transmission and the MS is scheduled to make the needed OTDOA measurements (SFN-SFN) from the neighbour BSs now hearable. By supporting the IPDL, the OTDOA performance in MS will improve, as there will be less interference present during idle periods. Idle periods in the downlink are standardised for the OTDOA-IPDL method, however the support of the idle periods is optional for the MSs.

Time Aligned-Idle Period Downlink (TA-IPDL)

Time Aligned-IPDL method is a modification of the standard IPDL. In TA-IPDL the idle periods are intentionally time aligned approximately 30μs across the BSs. Time alignment creates a common idle period, during which each BS will either cease transmission entirely, typically ~70% of the time, or transmit the common pilot, typically ~30% of the time [22]. During the common idle period, the MSs are scheduled to make the needed OTDOA measurements. In simulations, in [22][36], the interference level is noticed to be lower for TA-IPDL than for IPDL. Due to lower interference, TDOA estimation is more accurate, more BSs will be hearable to MS and multipath rejection is more effective. TA-IPDL reduces the handset complexity, but additional signalling is needed as well as added complexity in the network. In [36], it has also been noticed that increasing the number of measured BSs without making LOS state estimations before location estimation, the accuracy is reduced. This is due to increased probability of using NLOS measurements, which degrade the location estimation accuracy.

2.6 Hybrid methods

Hybrid location techniques combine several of the methods described above to provide positioning estimates with better accuracy, reliability and coverage, including indoor, outdoor, urban and rural areas. The hybrid techniques are not standardised and all the needed signalling in the network may not be available. The drawbacks of hybrid systems are usually greater processing requirements and increased network costs. Usually using a hybrid i.e. involving two techniques, the cost will be as high as using two separate solutions.

2.6.1 Angle of Arrival + Round Trip Time (AOA+RTT)

A potential UMTS location technique especially in rural and suburban areas where a LOS connection between the MS and the serving BS is often present, is AOA-RTT hybrid in which even one BS is enough for location estimation. It is a bilateral network-based method that avoids the hearability problem since a single BS, equipped with an antenna array, can make the necessary measurements.

The location estimate accuracy of this technique is limited by the beamwidth of the antenna array and RTT resolution. As with AOA method, the location error will increase with BS-MS distance.

2.6.2 OTDOA + AOA

In UMTS, the OTDOA measurements will be available in every MS and deployment of antenna arrays will enable the AOA measurements without extra costs. The performance of both OTDOA and AOA techniques is decreased due to NLOS conditions. Even though the errors in AOA measurements due to NLOS conditions are correlated to the errors affecting the timing measurements involving the serving BS, they should be useful to the location estimation. In [37], the UMTS system using TA-IPDL has been simulated and the results show an improvement of 20%-60% in location error performance when using the available AOA data in rural, suburban and urban car scenarios.

Using the OTDOA-AOA hybrid the MS positioning may be made possible even in highly NLOS conditions or by measuring only two BSs. The accuracy of the hybrid is better than OTDOA or AOA alone and the coverage increases if two BSs are enough for location. Also, it avoids problems with high GDOP, e.g. in a highway scenario where the BSs are aligned with the highway. In this case, pure AOA positioning would suffer from dilution of precision.

2.7 Database correlation

2.7.1 Generic location method

Database Correlation Method (DCM) [19] is a generic location method that can be applied to any cellular network. The key idea is to store the signal information seen by a MS, from the whole coverage area of the location system, in a database that is used by a location server. The database should contain signal information samples, called fingerprints, with a resolution comparable to the accuracy that can be achieved with the method, and this resolution may vary in different environments. Depending on the particular cellular system, the signal fingerprints could include signal strength, signal time delay, or even channel impulse response. Any location-dependent signal information that can be measured by the MS is useful for the DCM technique. Also, it is possible to use measurements performed by the network as well as by the MS. When the MS needs to be located, the necessary measurements are performed and transmitted to the location server. The location server then calculates the MS location by comparing the transmitted fingerprint and the fingerprints of the database. The architecture of a DCM location system is illustrated in Figure 5. It is highlighted that DCM can be implemented in any wireless system, the MS only needs to be able to transmit a location-dependent fingerprint to the location server. This fingerprint may consist of signals measured from GSM, UMTS and/or GPS. The location server must be powerful enough to process all location requests in a reasonable time. In a large-scale implementation, this may require distributed processing.

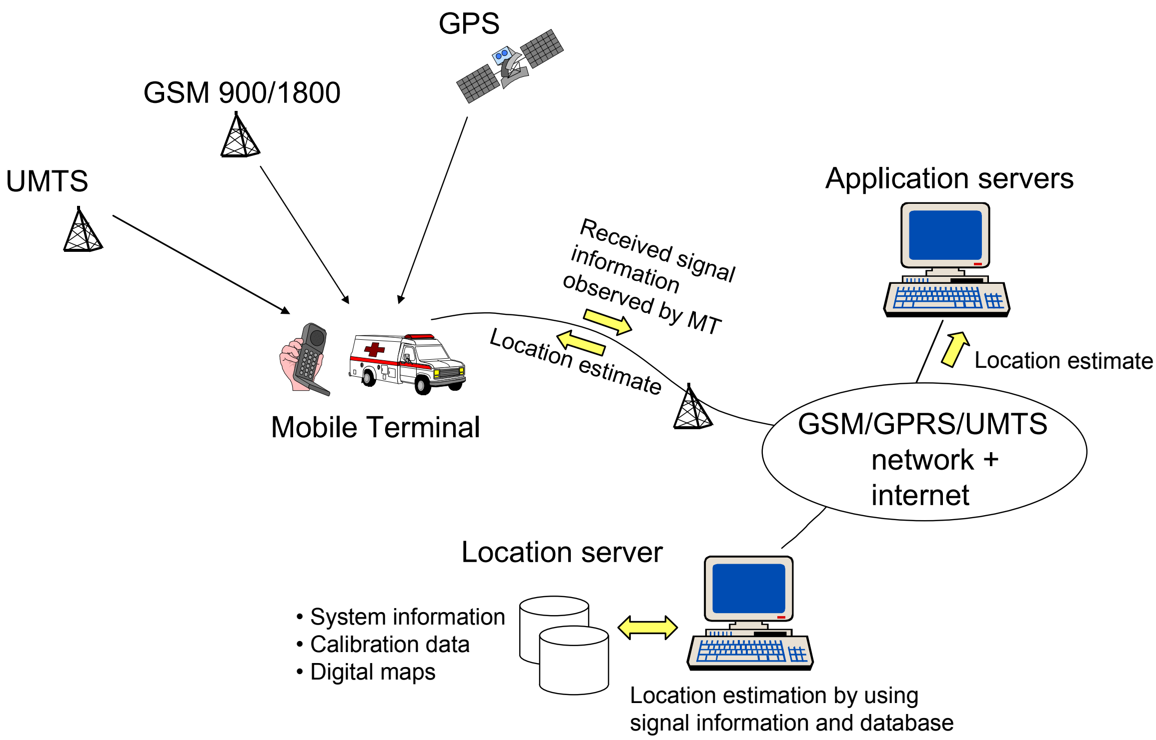

Figure 5. Architecture of a DCM-based location system.

The major effort in applying DCM is the creation and maintenance of the database. The signal fingerprints for the database can be collected either by measurements or by a computational network planning tool. Measurements are more laborious but produce more accurate fingerprint data. Also a combination of measured and computed fingerprints can be used. The compensation for the effort to build the database is an optimal location accuracy in environments where the assumption of line-of-sight propagation is not valid, e.g. in dense urban and indoor environments. The only assumption is that the database contains up-to-date data. However, minor changes in the network or propagation environment, e.g. new buildings, will only be seen as lowered location accuracy if the database is not updated. Also, it should be noted that similar information that is contained in the DCM database is also needed in network planning. Therefore, the creation and maintenance of the database also support network planning.

2.7.2 Application to GSM

The essential location-dependent parameters defined in GSM standard are Location Area Code (LAC), serving cell ID, timing advance (TA), and the measured signal strength of the serving cell and its neighbours. In dedicated mode (call on) all these parameters are known both at the MS and the network (signal strength measurements from up to 6 neighbour cells are reported from the MS back to the network). However, in idle mode only the LAC is known at the network. The MS, on the other hand, continuously makes signal strength measurements and also knows the cell ID of the strongest cell. Thus, in order to locate an idle-mode MS using these parameters, the MS must be able to transmit the available parameters to the location server. GSM handsets with the capability to send these measurements through SMS are already available.

LAC, cell ID, and TA, which is known with a resolution of 554 m in dedicated mode only, can be used for rough positioning only. Signal strength measurements must be used if more accurate location is needed. The idea of using previously measured signal strength contours in location determination was first presented in [12], where it was emphasised that instead of instantaneous signal strength, the median of samples collected over a sufficiently long period should be used to avoid the effects of fast fading. In GSM, signal strength values in idle mode are averages over a period of at least 5 seconds, which is sufficient to smooth out fast fading if the MS is in slow motion. Even if the MS is stationary, the 200 kHz bandwidth of GSM assures that signal strength samples from adjacent locations vary considerably less than in the case of a single-frequency carrier wave. In a fixed position, variations on the order of 10 dB are common, but over 20 dB variations can be seen if a strong signal path, e.g. a line-of-sight path, is suddenly obstructed. Therefore, the algorithm that uses signal strength values for positioning should not be too sensitive to such variations.

The algorithm used in [19] for finding the best match between the fingerprint to be located and the fingerprints of the database was simple: the difference between two fingerprints was calculated as

$$d(k) = \sum_i (f_i - g_i(k))^2 + p(k)$$

where f_i is the signal strength of the request fingerprint on the ith Broadcast Control Channel, $g_i(k)$ is the signal strength of kth database fingerprint on the same channel, and the summation is taken over channels that are found in both fingerprints. Each channel that is found in only one of the fingerprints contributes to the penalty term $p(k)$. The coordinates of the database fingerprint that minimises this difference are returned as the location result. It should be noted that the database search can be limited, based on LAC and cell ID, to a relatively small area.

2.8 Localisation in 2/3 G systems based on signal pattern recognition

There are currently several positioning techniques available, which require significant modifications of network components, including mobile terminals. Another issue that seems to be rather critical is the additional signalling overhead, which is combined with an on-demand localisation of subscribers. Therefore, positioning methods that will be based on the existing network data would be preferred in the future. In this section a pattern recognition method will be presented, a technique, which exploits the measurement reports, performed by the mobile station and compares them with pre-trained area-models. In the following subsection the mathematical background of this method and the algorithm itself is presented.

2.8.1 Hidden Markov Models

Signal models can be classified in deterministic and statistical ones. Deterministic models exploit specific properties of the signals, e.g. the signal is a sine wave or a sum of exponentials. The statistical models characterise only the statistical properties of the signal. Such statistical models include Gaussian processes, Poisson processes, Markov processes, Hidden Markov processes and other. The meaning of the statistical model is that the signal can be characterised as a parametric random process and that the parameters of the stochastic process can be determined in a precise, well-defined manner.

A discrete Markov process is characterised by a finite or infinite number of states. A modelled system can be seen as being in one of these states and changing between the states at equally spaced discrete times, according to the state transition probability associated with each state.

In the case of a first-order Markov chain, the state transition probability does not depend on the history of the process, but only on the current state.

The measured data during a call can be received and analysed at several network interfaces, e.g. A_{bis} interface. In a further step, the measurements can be compared with saved street models, which are stored in repositories. The step of street modelling is one of the most basic steps for this positioning technique. The prediction field strength of the street elements has to be modelled in that way that all signal pattern information is saved. Hidden Markov Models have been used in the past for speech recognition, as well as for other applications that are based on pattern comparison and detection. In the case of positioning in GSM, the uplink and downlink signal characteristics can be saved in a Hidden Markov Model (HMM), which will be trained with predicted data [28].

2.8.2 Training the Models

Training of models encodes observation sequences, in this case the prediction data for the considered street element, in such a way that any other observation sequence having many characteristics similar to the given, it should be able to identify it. The training is performed by means of the Segmential K-means Algorithm. This algorithm is based on the maximum state optimised likelihood criterion. At the beginning, clusters are randomly created and every vector (observation symbol from the training sequences) is assigned to the above clusters, from which its Euclidean distance is minimum. The initial choice of clustering vectors does not decide the final HMM, but can decide the number of iterations required for the HMM training.

On the next step the segmentation of the training sequences has to be optimised, until the final model represents the training sequences. This step can be made by means of Viterbi algorithm. The Viterbi algorithm finds the optimum state sequence in terms of the maximum likelihood. The state sequence is a sequence of states (clusters) where each observation vector is assigned. With other words the problem is to find an I that will maximise $P(O,I|\lambda)$. The inductive Viterbi algorithm keeps the best possible state sequence for each of the N states as the intermediate state for the desired observation sequence $O=O_1, O_2, O_3, \ldots, O_T$. In this way the best path for each N states will be found for the desired observation sequence.

In the case of Pattern-Recognition-Localisation, the observation sequences is a set of RXLEVs which results if we assume that a mobile terminal is moving on a street with a specific velocity and transmits measurement reports to the network. The training sequences are generated if several random speeds are used, according to a pre-defined normal distribution of speed for the specific street element. The more training sequences are used, the better the modelling will be.

The network planning is based on prediction data. Planning tools simulating the actual behaviour of a mobile radio network in geographical space, with all its technical details. With the aid of these data the propagation models consider different attenuation along the propagation path of radio waves. In Figure 6, a typical presentation of the field strength of a BTS is presented [16].

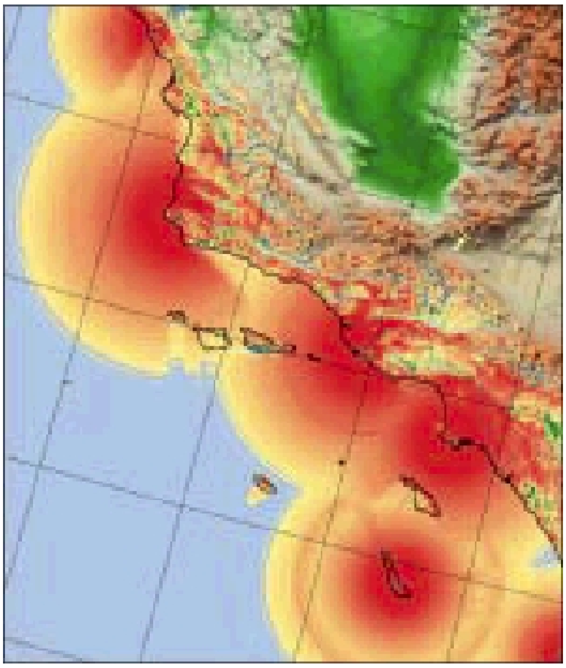

Figure 6. Area field-strength prediction

During a call the mobile terminal makes several measurements. These measurements are transmitted to the network over the SACH channel. The mobile station (MS) measures the level and quality of the downlink-burst during the connection and the level of the neighbour cells. The radio level is in the interval -110dBm and -48dBm.

The signal quality is measured according to the Bit Error Ratio (BER) before the channel coding. There are 8 discrete RXQUAL-values that describe the quality of the connection. The required precision is between 75% (RXQUAL 1) and 95% (RXQUAL 5-7). For RXQUAL 0 the bit error rate is less than 0,2%. Another important measurement is the Timing Advance (TA). Based on TA, the absolute distance between mobile station and BTS can be estimated. This value results from the measured Round Trip Propagation Delay. This value indicates the number of bits that the mobile station has to consider by starting the transmission earlier, in order to be synchronised with the TDMA-frame. To calculate the distance that a TA value presents, the propagation time of 1 bit has to be considered. The place where the subscriber is located according to the TA is a ring circle with radius around 554m [38].

The data that the mobile station transmits are: RXLEV and RXQUAL of the traffic channel, BCCH-RXLEV from up to 6 neighbour cells with information about BSIC and frequency of each BCCH. The time between two measurements is 4.615ms (TDMA-frame). If the subscriber is moving with a velocity of 100km/h, this time corresponds a line of around 13cm. Oriented to the duration of a SACCH-block (480ms), there are 100 measurements that are averaged and transferred over the measurement reports to the network. The measurement protocol is transmitted over the SACCH, that appear every 120mr and with an interleaving of a *Block Recurrence Time* of 480ms last. In Table 1, information from a measurement report is presented.

Table 1. Measurement report.

m.r.	RXLEV UL	RXLEV DL	RXQUAL _UL	QXQUAL _DL	TA	BS_R ED	MS_ RED	BSIC	BCCH	RXLEV-NC1	…
1	24	36	0	0	4	0	10	35	5	22	
2	22	31	0	0	4	0	10	35	5	23	
3	24	40	0	0	4	0	10	35	5	26	
4	26	35	0	0	4	0	10	35	5	25	
5	25	36	0	0	4	0	10	35	5	24	
6	24	36	0	0	4	0	10	35	5	29	
7	25	37	0	0	4	0	10	35	5	36	
8	23	34	0	0	4	0	10	35	5	40	
9	19	33	0	2	4	0	10	35	5	42	
10	23	36	0	1	4	0	10	35	5	43	
11	22	35	0	1	4	0	10	35	5	42	
12	26	39	0	0	4	0	10	35	5	42	
13	22	38	0	0	4	0	10	35	5	42	
33	22	27	0	1	4	0	10	35	5	38	
34	18	26	0	1	4	0	10	35	5	36	
35	19	26	0	2	4	0	10	35	5	36	

From this information, important fields are: #m.r. ; RXLEV_UL; RXLEV_DL; TA. This data can be used to extract new (real) observation sequences and compare them with the pre-trained models.

The area around the base station was sampled in timing advance zones and the streets, belonging to each TA-zone were modelled. Furthermore the created models are saved in repositories, according to the TA-identificator.

The next step is to analyse the measured reported data. The reported uplink level has to be presented and new (real) observation sequences have to extracted. The uplink level diagrams have to be segmented according to TA. In case of an identification of constant uplink level, the parts of the uplink level have to be excluded, due to the fact that models are trained with multiple constant velocity observation sequence. After the extraction of the observation sequences, the final step was the comparison with the stored models of the same TA-repository. After the comparison a sequence of possible models is resulted and according to the most probable path (Viterbi algorithm) an estimation of the driven route can be made.

Several parameters and variables that have to be justified for each position estimation. The length of the generated sequences as well as the number of model states have to be adjusted Since each model represents the level-pattern of a street segment and not of a sequence of coordinates, the number of states must describe characteristic parts of the pattern progression and not the level in equal spaced time intervals. In Figure 7, the segmentation of the roads in street elements is shown. Each red circle indicated a Timing Advance Zone, i.e. a zone with a constant TA value. The pre-trained street models are stored in the repository with the index of TA-x, where x the identificator of a street model in the actual TA-zone. During the position estimation procedure, the observation sequences exported from the measurement reports are compared with these street segments, resulting in a sequence of diagrams, e.g. TA1:m;d;e;f;g;h;I;j;k;l;o;p;TA2:x….. . Due to several reasons it is possible, that the estimated sequence contains mistakes, but implementing a tracing algorithm, which calculates the most probable path it is possible to correct these mistakes, resulting in the mobile station's route. For instance, a sequence, TA1:b;c;d;o;f;g is wrong, and the state 'o' has to be replaced by state 'e'.

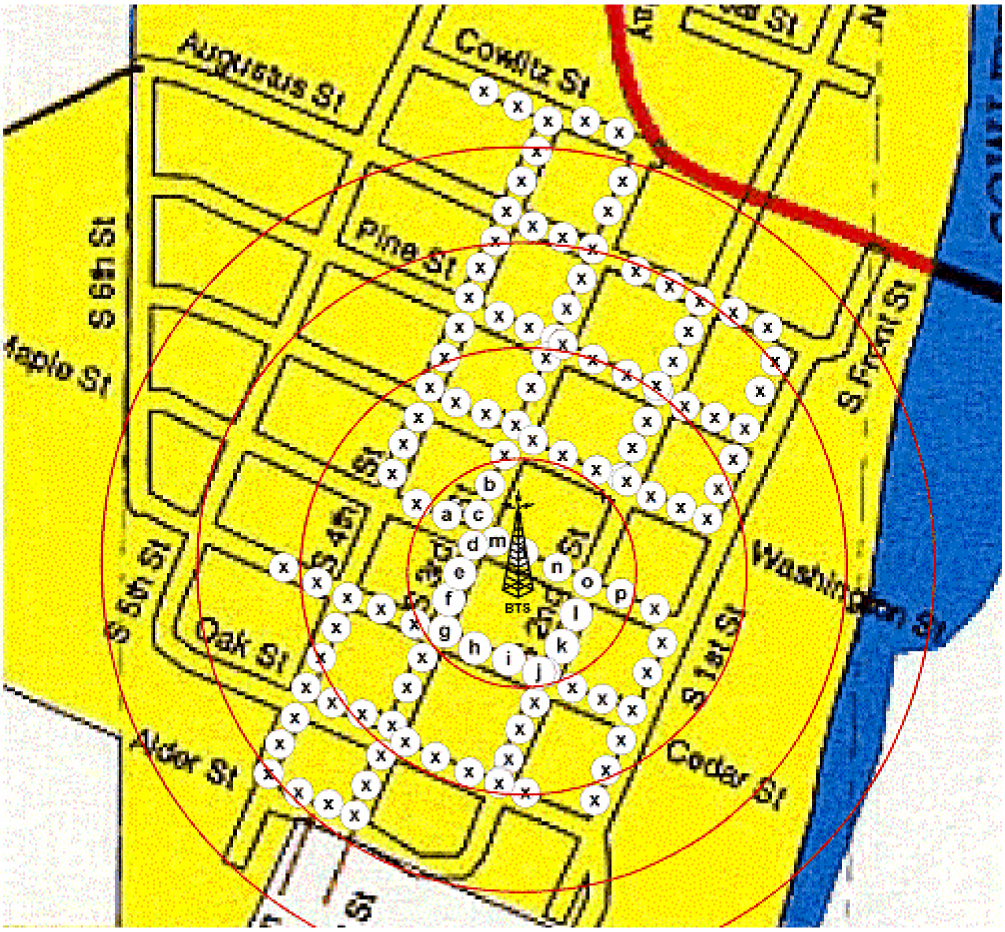

Figure 7. Segmentation of street in elements and assignment of a HMM for each street-segment for a further comparison with the measured data.

2.8.3 Conclusions

The described method has several advantages and disadvantages compared to other positioning mechanisms. The accuracy depends on the street elements. Therefore, if the planning tool can give information about coverage with a high resolution, it is possible to achieve localisation precision of less than 100m. On the other hand there is an accuracy limit, by which the precision cannot be lower. There is no signalling overhead, but the positioning can be done only if a call has been set up. According to ETSI there are some thoughts of initiating "silent calls" for an on-demand user tracing. The pattern recognition technique does not require additional signalling, which is important, since cellular networks are already congested from call set-up procedures, SMS, handover and location updates. The positioning can be done by means of several power computers, distributed to network MSC's or at a centralised place, where the measurement reports are collected, according to the network.

3 HANDSET-BASED GPS LOCATION OF MOBILE TERMINALS

For the last 5 years the FCC Report and Order has been the main driver for the adoption of Location Services by Mobile operators. The FCC clearly requires that wireless carriers be able to locate any caller requesting emergency assistance throughout its network. This requirement would appear to eliminate handset-based solutions, such as GPS, from consideration, as it would not be to integrate GPS or other location system components to all phones operating on a network by October 2001. In December 1997, however, FCC issued a supplementary notice (Memorandum and Opinion) showing that it would endorse a gradual deployment of the location capability, especially if the proposal would help achieve higher levels of accuracy, and performance guarantees. The memorandum concludes that FCC will consider allowing the addition of GPS to new phones to meet Phase II requirements, recognising that most subscribers would be likely to replace their existing phones with GPS-equipped handsets over a two- to three-year period.

3.1 GPS Overview

GPS is a Satellite Navigation System funded by and controlled by the US Department of Defense (DoD). Despite the large base of millions of civil users of the system world-wide, the system was designed for and is operated by the US military personnel. GPS provides specially coded satellite signals that may be only processed by a GPS receiver, enabling the receiver to compute position, velocity and time.

The basic measurement performed by a GPS receiver is the time required for a signal to propagate from one point in space to another. Because in the general case, the speed that RF signals travel is known with relative accuracy this time measurement can easily be converted to distance -range from the RF source. If the range from the receiver to four satellites is calculated, the receiver can accurately determine his position anywhere on earth. Four (4) GPS satellite signals are thus used to compute positions in three dimensions and the unknown time offset in the receiver clock. The system allows the military users to make use of an enriched signal set, achieving a much better guaranteed accuracy than civilian receivers may achieve.

The system's operation relies primarily on the GPS satellites. A number of 24 LEO-SV (Low Earth Orbit - Satellite Vehicles) are positioned in such orbits as to cover almost all of the earth surface, while at any time 4 to 6 are on stand-by in orbit to replace malfunctioning. They complete one full rotation about the Earth every 12 hours.

The users of the system take advantage of special purpose GPS receivers to convert the signals into position, velocity estimates, while the receiver may be also used as a highly accurate timing source. GPS receivers are used for navigation, positioning, time dissemination, and other research. Civil users worldwide use the Standard Positioning Service (SPS) without charge or restrictions.

According to the 1999 Federal Radionavigation Plan the predictable accuracy for GPS amounts to 100m (for 95% of the measured samples) horizontal accuracy and 340nsec timing accuracy (95%). These figures are however out-of-date since following May 2000. In that date, the main error source affecting the system, the "Selective Availability" - i.e. the intentional degradation of the system accuracy, was turned off by the US DoD. Figures and experience since that day show a ten-fold decrease in Expected Position Errors.

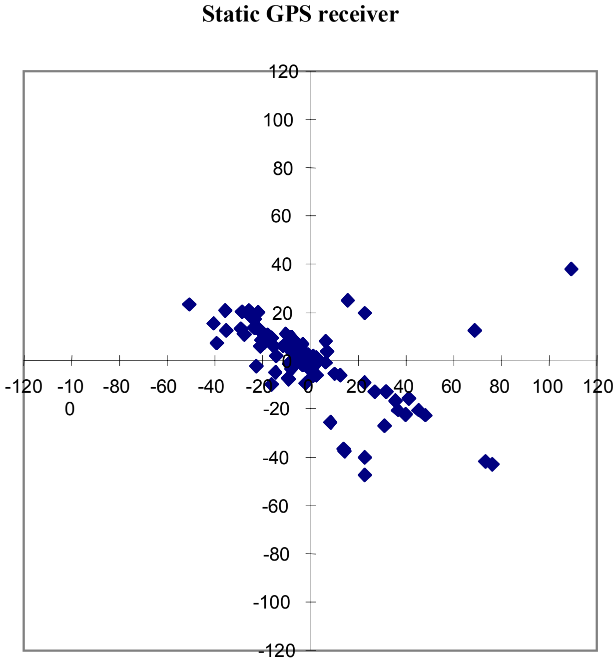

Figure 8. GPS Estimates over a 24h period for Static Receiver (SA Activated - prior to May 2000).

Although indispensable as the fundamental navigation system for use by the marine community and recently by the aviation world, the system is not as well adapted for urban use as the system will need to have direct visibility (Line-of-Sight conditions) with the satellites used for the position calculation. This requirement immediately excludes the use within buildings or even in dense urban roads. Measurements in a typical route in the suburbs of Athens (the peripheral ring road) show the obvious low availability of visible satellites. It is remarkable that although the type of environment remains the same throughout the measuring period, there are cases that the number of received satellites will drop to as low as 3, allowing only 2D positioning.

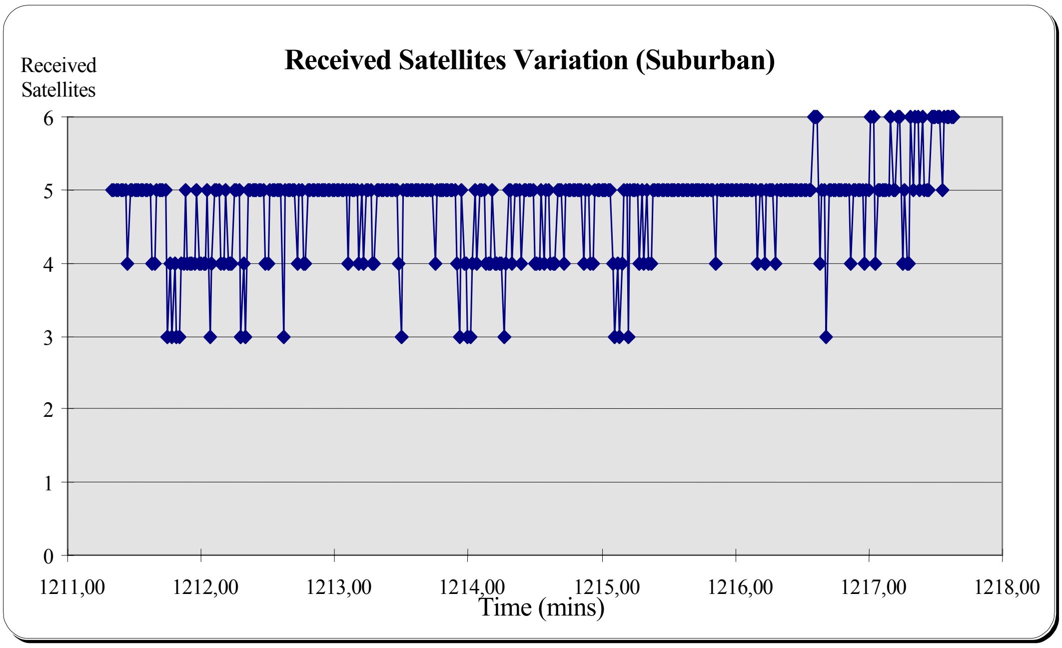

Figure 9 - GPS satellite visibility, sub-urban environment

Further enhancements to the plain civilian positioning service are the techniques known as Differential GPS and Assisted GPS which we examine in the following. These techniques promise to effectively improve system performance parameters such as accuracy, time-to-first-fix and coverage especially in the case where the system will be used in dense urban environments to provide location information and location-based services.

3.2 DGPS

The idea behind differential positioning techniques is to correct systematic bias errors at one location based on measured bias errors at a known position. In the case of DGPS a reference receiver, or DGPS Base Station (not to be confused with a GSM BS - although the two may be co-located), computes corrections for each satellite signal received. The DGPS Base Station then transmits the corrections to the co-observing receivers.

Because individual pseudo-ranges must be corrected prior to the formation of a navigation solution, DGPS implementations require software in the reference receiver that can track all SVs in view and form individual pseudo-range corrections for each SV. These corrections are passed to the remote, or rover, receiver (i.e. the handheld) which must be capable of applying these individual pseudo-range corrections to each SV used in the navigation solution.

DGPS removes common-mode errors, those errors common to both the reference and remote receivers (unlike multi-path or receiver noise). The following table summarises the main error sources, 95% estimates (2drms) of these errors and how these affect the overall estimate calculated by GPS with SA activated (as was the typical case before May 2000), without SA and in the case of differential GPS. The total horizontal error is also provided for comparison with the DGPS providing by far the most accurate estimate.

Table 2: Factors of inaccuracies in the horizontal position (Horizontal Dilution of Precision = 2)

Error Source	GPS Error 2drms (m)	GPS After May 2000 2drms (m)	DGPS Error 2drms (m)
Satellite Clock	3	3	-
Orbit Imprecision	2.7	2.7	-
Ionosphere	8.2	8.2	0.8
Troposphere	1.8	1.8	0.4
Selective Availability	30	-	-
Multi-path	1.5	1.5	1.5
Subtotal RMS	31.5	9.5	1.75
Total Horizontal RMS error (= Subtotal * HDOP)	63	19	3.5

Differential position accuracy of a meter or even sub-meter level are possible with DGPS based on civilian (SPS) signals. Improvement in User Estimated Position Error (UEPE) is immense as may be seen in the next figures.

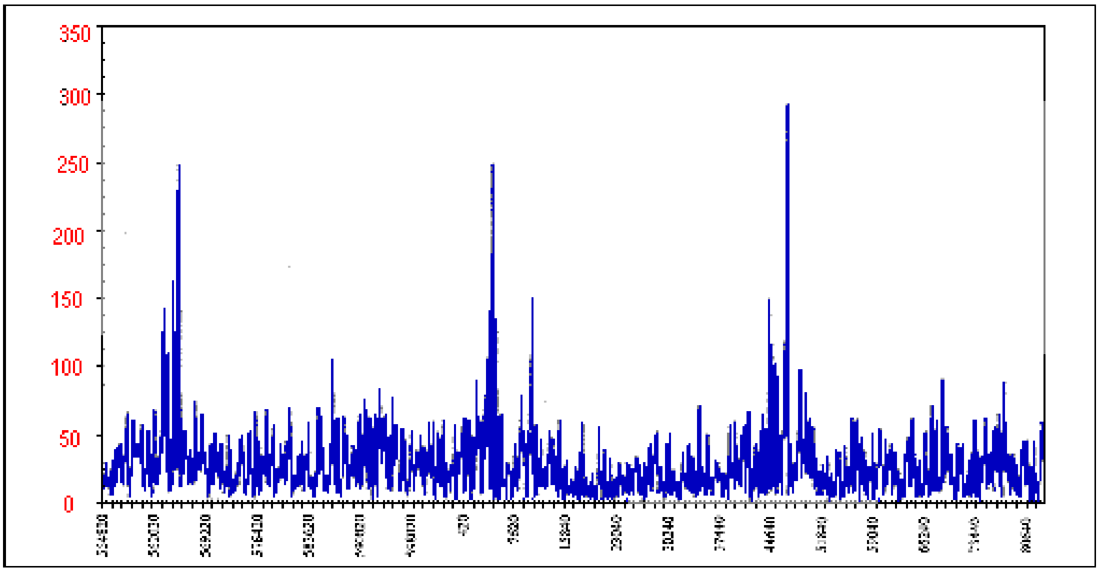

Figure 10 - GPS Positioning error over a 24h period (SA Activated - 10min. samples) - ***Trimble Electronics***

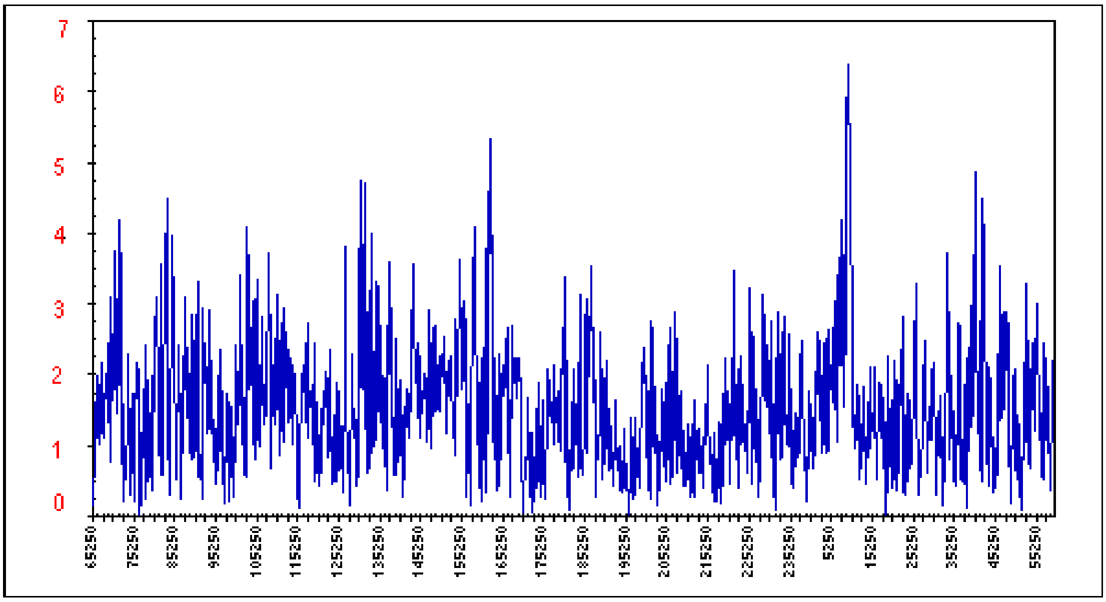

Figure 11 - Differential GPS Positioning error over a 24h period (SA Activated - 10min. samples) - *Trimble Electronics*

For the purpose of locating a cellular terminal the reference station may be considered to be located at the BTS or even at the BSC/MSC, remaining within 100km from the served terminals. This condition guarantees that both the reference and the remote receiver are identically affected by bias errors. DGPS corrections are mostly transmitted in a standard format specified by the Radio Technical Commission Marine (RTCM) Special Committee SC-104 ver. 2, in 1990.

3.3 Assisted GPS

Assisted GPS methods aim to assist the handset in estimating its own position using GPS (and thus are categorised as handset-based / network-assisted). Such technologies - already market available - make it possible to receive GPS satellite data even at signal levels below known thresholds, allowing in some cases the estimation of users' positions even when user is indoors. Most methods require a additional circuitry in wireless phones and special purpose server. The handset passes GPS pseudorange measurements to the server, which estimates the caller's location. A variation of this method automatically updates the - embedded in the terminal - GPS receiver, with up-to-the-hour ephemeris information.

3.4 Other Satellite-positioning systems

The Russian analogue of GPS is termed as "GLONASS". The system is also of high accuracy however the service provided is not as trustworthy since the system may be turned on and off without warning. Furthermore GLONASS is prone to satellites' malfunctioning while low financing seems to prohibit regular satellite replacements.

ESA is on its way however with its own European Constellation - termed as GALILEO. GALILEO is to achieve Initial Operation Capability after 2006, some 20 years after the GPS IOC. GPS, GALILEO and possibly GLONASS are to form the long awaited integrated worldwide navigation system GNSS-2.

3.5 Industry Support to handset-based systems

The industry, i.e. suppliers of handsets and infrastructure equipment, seem to be investigating long-term caller location solutions that include the addition of GPS to the handset. Assisted GPS is regarded a favourable solution where communication with a server will be involved. The suppliers generally favour GPS as an element of the long-term solution based on the view that aided-GPS will support a higher level of accuracy than stand-alone network-based systems. Most believe that the higher accuracy will be needed to support a wide range of commercial location-based services. However, a number of major carriers continue to express a preference for a network-based solution.

The reasons behind the reluctance in the full adoption of GPS as the exclusive positioning methods include the following realistic observations:

1. GPS is only one system and not a combination of systems (although DGPS may claim to be one viable evolution from the basic single system) and thus may fail to provide a position estimate should the conditions not allow it (loss of signal).

2. It may (for many different reasons) provide a totally false and in some cases misleading position estimate while it also is extremely prone to interference from intentional or unintentional RF sources.

3. The system may cease to operate unexpectedly (as has already happened on September 22, 1994, when thousands of receivers stopped providing a position fix when the US Department of Defense decided to upgrade the satellite software. This happened without any previous warning - and no one may legally blame any authority as the system operation is not guaranteed in any case.

These problems however should not hide the fact that GPS (and in the future GNSS-2) is by far the most complete and accurate positioning system and will definitively be the primary component for adoption by mobile equipment suppliers.

4 PRODUCTS AND TRIALS

Some location trial systems and products, based on different techniques will be described in this Chapter. It is not possible to give an exhaustive list of all activities in this field since a large number of companies are trying to enter the market. Instead, the aim is to give a general view on what is commercially available and what is being developed.

4.1 Radiolinja

On the 10^{th} anniversary of the first GSM call Finland-based Radiolinja and Nokia Networks, Infrastructure arm of Nokia, started piloting a co-developed mobile positioning system in Radiolinja Estonia. The first official GSM call in the world was made in the network of Radiolinja in Finland on March 27^{th} 1991. The now piloted new positioning system gives improved accuracy for all existing GSM phones. Applications access positioning information from the network over a proposal for standard Applications Programming Interface (API) defined by the Location Interoperability Forum (LIF).

The Nokia mCatch mobile positioning system, developed in co-operation between Radiolinja and Nokia, is being piloted in the network of Radiolinja Estonia. In addition to the commonly used Cell Identity and Timing Advance parameters, the system utilises received signal strength (RX) levels for calculating the position of a mobile phone. Radiolinja contributes RX Algorithms for Nokia mCatch.

The new positioning method offers several advantages the foremost being the improved accuracy. Also important is the possibility to position all existing GSM handsets both in idle and active mode without modification either to the handset or to the SIM card. Radiolinja and Nokia Networks jointly promote this technology for wide implementation in the mobile industry.

In addition to new positioning technology, the pilot also demonstrates the functionality of a proposal for standard API, developed and proposed to the industry by the LIF, towards the applications. The standard interface between the mobile network and the location based services is viewed as a critical factor for ensuring the timely development of new innovative services.

The accuracies achieved in Estonia mCatch trial in urban and suburban environments are shown in Table 3 and Table 4, respectively. It is seen that using signal levels in addition to cell ID and timing advance gives clearly more accurate results in the urban environment. However, in the suburban environment using signal levels gives no enhancement on CI+TA positioning.

Table 3. Positioning accuracy [m] in urban environment (76009 samples).

Method	50%	67%	80%	90%	95%	99%
CI	240	328	393	519	603	766
CI+TA	207	283	343	475	554	780
CI+TA+RXLEV	158	207	264	339	429	621

Table 4. Positioning accuracy [m] in suburban environment (102269 samples).

Method	50%	67%	80%	90%	95%	99%
CI	482	639	834	1085	1345	1969
CI+TA	319	415	516	666	844	1144
CI+TA+RXLEV	307	448	593	790	917	1121

4.2 KSI

The location concept TeleSentinel is based on the AOA technique [34]. The angle of arrival is measured at specific sensors, typically co-located with the BSs of the cellular system. The measured AOAs from at least two sensor stations are sent to the control station for location determination. The location sensors also read the contents of the control channel of the call in order to find the telephone number of the mobile station. This is forwarded to the central station together with the AOA data. The estimated coordinates and the mobile telephone number are stored in the database to be accessed by the location users. In the system design especially the E911 service has been considered. The system does not require any modification for the handset.

The first trials were carried out by using the AMPS system, but a later version was tested in digital TDMA (IS-136) system [34]. The field trial was deployed in the Annandale area of Northern Virginia just outside Washington DC. Four sensor sites, covering a 2 km by 2 km area, were used in the trial. Each sensor site had three omnidirectional antenna elements. In this trial, the achieved accuracy was quite good: 50 % of location errors were within 34 m, 67 % within 45 m, 90 % within 89 m, and 99.9 % within 282 m.

KSI was later acquired by TruePosition [15] which now develops a TDOA + AOA hybrid location system. According to TruePosition, their commercially available technology complies with the FCC Phase II requirements and works with multiple air interfaces (AMPS, CDMA, GSM, TDMA).

4.3 Cambridge Positioning Systems

The Cursor™ location system is under development by the British company Cambridge Positioning Systems (CPS) [13]. It is a standards-compliant high accuracy mobile location technology using the E-OTD (Enhanced Observed Time Difference) method. The used technique is essentially the E-OTD described in Section 2.5.1 and the system architecture is essentially the same as depicted in Figure 4. The required synchronisation between the base stations is obtained observing their signals by a specific receiver (Location Measurement Unit, LMU) at a fixed location, typically co-located with one base station. Approximately one LMU is required for each four BSs. The location calculation is carried out at the Serving Mobile Location Centre (SMLC) to where the delay observations of the mobile unit and the LMUs are sent by using the SMS service of the GSM.

The handsets in CURSOR system are GSM phones including some software modifications. According to CPS, the whole measurements, reporting and processing period is no more than a few seconds. CPS has reported the following accuracies from trials [20]:

- Cambridge (UK), suburban 5 km^2 trial area: 50 m accuracy 67 % of the time
- Houston (US), suburban areas: 75 m accuracy 67 % of the time
- Hong Kong, dense urban area (Golden Bowl region): 125 m accuracy 67 % of the time

From these results, it can be concluded that E-OTD can achieve quite high accuracy, but NLOS and heavy multipath propagation in city centres cause accuracy degradation.

4.4 VTT

VTT has performed a location trial using database correlation method in two environments: a densely built urban environment (the centre of Helsinki, Finland) and a suburban environment (the campus area of Otaniemi in Espoo, Finland) [19]. The trial area was approximately 3 km^2 in urban and 1.4 km^2 in suburban environment. In both cases, measurements were performed with a standard GSM phone, which was attached to the dashboard inside a car and connected to a laptop PC. Part of the urban measurements was performed on foot. In all measurements, the phone was in idle mode. The street grid of the trial area was covered once in order to create the database, by collecting on the average two measured fingerprints per second. Reference coordinates for the measured fingerprints were obtained by mouse-clicking marker points on the laptop PC each time the car stopped, started moving, turned, or passed a street corner. Between the marker points, reference coordinates were calculated assuming that the car moved with constant velocity. It was estimated that the errors in reference coordinates caused by the non-constant velocity and inaccurate marker coordinates should be below 20 meters.

In addition to the measurements forming the database, test routes through the trial area were driven in order to evaluate the location accuracy. In the urban area, three test routes of total length 15 km and in the suburban area one 1.5-km long test route were driven. The lengths of all test routes and the numbers of fingerprints collected are summarised in Table 5.

Table 5. Test route lengths and numbers of collected fingerprints.

test route	length	fingerprints
urban 1	1450 m	389
urban 2	8600 m	3604
urban 3	4550 m	1240
suburban	3500 m	766

The cumulative distributions of location error along the test routes are shown in Figure 12. It is seen that the error distribution in the urban test routes does not vary much, but there is a clear difference between urban and suburban accuracy. There are two factors that cause the higher accuracy in the urban environment: denser network and building shadowing. In an urban microcellular environment, the difference in signal strength values on different sides of a (heavy) building is so large that it exceeds random variations caused by e.g. antenna orientation or body shadowing. The signal propagates along street canyons and, as a consequence, the location error is typically directed along the street.

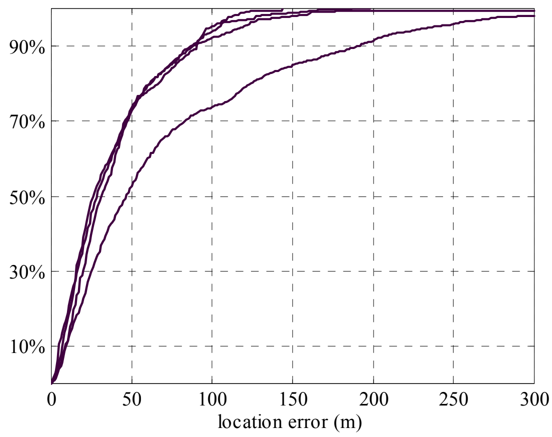

Figure 12. Cumulative location error distribution in urban test routes (solid curves) and suburban test route (dashed curve).

4.5 US Wireless

The RadioCamera^{TM} location concept developed by the US Wireless Corporation is based on location pattern matching, which is similar to the database correlation approach described in Section 2.7. It requires a calibration measurement in order to collect multipath patterns (cf. fingerprints in Section 2.7) from the area to be covered, and a database of the patterns at the location server. However, in this technique the multipath pattern (e.g. signal covariance matrix or angular power distribution) is measured at the base station using an antenna array [39]. It is a bilateral network-based technique that can locate legacy phones using a single BS only.

US Wireless has carried out several trials in order to prove compliance with E911 regulations. In a trial conducted in Billings, Montana [26] a wireless E911 location system covered an area of 25 square miles with light urban, industrial, residential, and suburban/rural environments. Five RadioCamera™ Base Units with six omni-directional antennas were collocated at cell sites. 22 fixed test points and 9 mobile test routes were selected from the coverage area to provide a balanced cross section of the types of environments found in the region. Testing was done for AMPS phones.

The performance of the system was evaluated in terms of location accuracy as a function of the length of the total observation interval. During a call, RadioCamera system estimated the subscribes location every 2.5 to 4 seconds. However, only one of these location estimates was reported per observation interval. The observation interval varied between 1 fix period (approximately 3 seconds) and 15 fix periods (approximately 45 seconds). The reported location estimate was selected based on a location quality measure. Results of the trial are summarised in Table 6.

Table 6. 67th percentile accuracy performance as a function of test environment and length of observation interval.

Environment	Observation Interval	
	single fix only	up to 15 fixes
Light Urban	125.8 m	84.9 m
Industrial	89.2 m	54.7 m
Residential	79.2 m	64.7 m
Suburban/Rural	62.7 m	52.9 m
Combined	85.7 m	62.0 m

4.6 Benefon

Mobile phone manufacturer Benefon has launched the first GPS-enabled cellular phones. GSM phones Benefon Esc! and Track both have an integrated 12 channel GPS receiver. Mobile Phone Telematics Protocol (MPTP), developed by Benefon, is used to send location, tracking and route messages between service centres and MPTP enabled terminals. At the moment telematics protocol is based on SMS. Benefon's phones also have the capability of sending network measurement reports through SMS. Thus, it is possible to implement a hybrid location system using GPS and e.g. cell ID or signal strength methods.

4.7 SnapTrack

In the SnapTrack™ [14] concept, which is a type of assisted GPS solution, the GPS signals are received at fixed stations and the decoded navigation message is transmitted to the location server to be used in the location computation. This way, it is sufficient for the GPS module of the handset to carry out only the pseudo-range measurements to the satellites, without the need to decode the navigation message. Consequently, the pseudorange measurements can be carried out in a short time and with smaller amount of received power. Additional advantage in synchronisation time is gained by transmitting the rough user location and satellite doppler-frequencies to the user via the cellular network. The receiver sends the observed pseudo-ranges to the location server, which then calculates the user location by using also the measured pseudo-ranges of a fixed GPS receiver to obtain an accurate differential GPS solution.

According to information provided by [25] the time required for pseudo-range measurement by the mobile is only a few seconds. The messages between the handset and the location server are quite small, 50-100 bytes. Considerable savings in power consumption can be achieved, as the GPS receiver needs to be turned on only for a short time. Because of the relaxed receive power requirement, the system is claimed to provide locations even inside buildings. Theoretically as much as 25 dB additional fade margin can be achieved according to [25].

SnapTrack has been extensively tested in field trials. Results given in [25] show almost 100% availability in urban canyons and good coverage in indoor locations also. Accuracy at 68%

probability level varied from 4 metres in open outdoor conditions to 84 metres inside a building (4 metres from outside wall). In general, the accuracy ranges from 3 to 100 meters.

5 STANDARDISATION

5.1 GSM standardisation

GSM standardisation activities for Location Services (LCS) cover both the location techniques and the corresponding network infrastructure.

Three approaches for location determination are included in GSM standardisation:

1. Time of Arrival (TOA)
2. Enhanced Observed Time Difference (E-OTD)
3. Assisted GPS (A-GPS)

In addition, the standard supports usage of Cell ID and the Timing Advance in the case that the network and/or the terminals do not have the required functionalities for the more sophisticated methods. The mentioned techniques were already described in Chapter 2. In the following the architecture supporting location is described. The generic LCS logical architecture is shown in Figure 13.

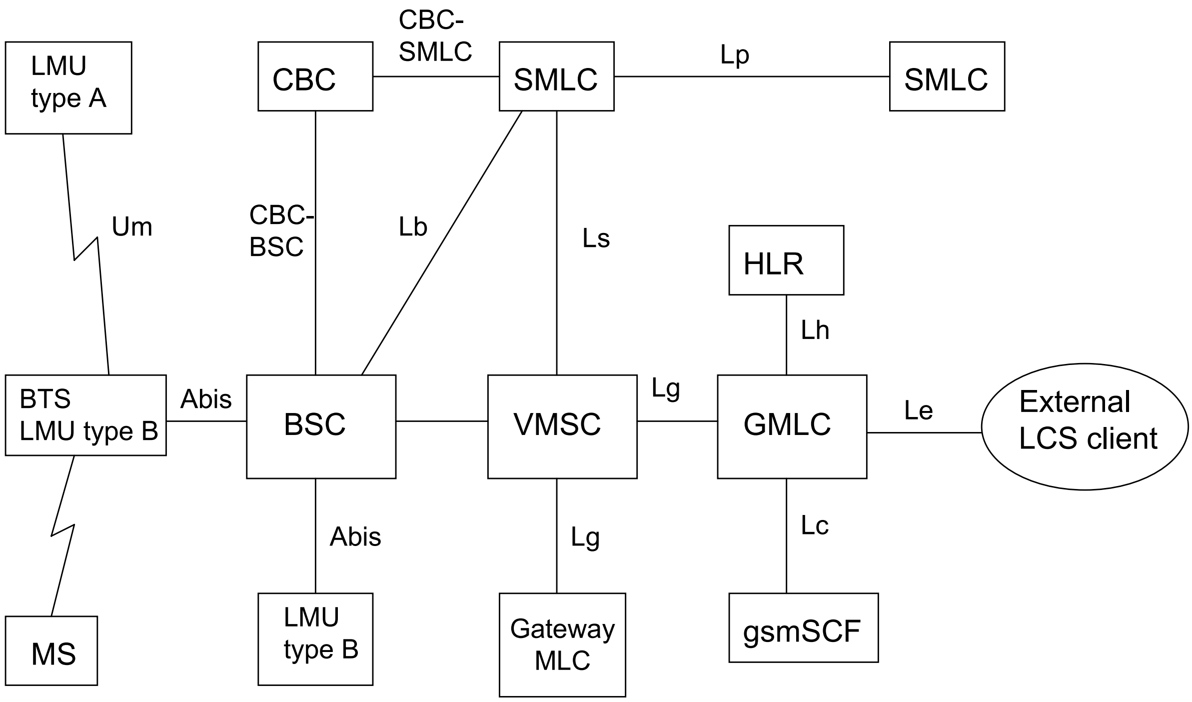

Figure 13. Generic LCS logical architecture [2].

The location services in GSM are enabled by a number of network elements and other entities referred to as LCS components. The whole system consisting of distributed LCS components is referred to as LCS Server. External LCS client is an entity which interacts with the LCS

Server via the interface Le. LCS clients subscribe to LCS in order to obtain location information of mobile terminals. In most cases the LCS client is external which means that the client is not part of the GSM network. However, for example, in mobile originated location requests the client is internal. The description of LCS server services from LCS client point of view is included in [1].

The external client connects to the LCS server via the GMLC (Gateway Mobile Location Centre). After performing registration authorisation of the client the GMLC forwards the positioning requests the VMSC (Visited Mobile Switching Centre). The VMSC performs a number of essential tasks to find out the location of the mobile, for example:

- Checks the subscription authorisation of the MS to be located
- Retrieves the information of which location method to use based on the MS classmark and the network capabilities
- Initiates required procedures depending on the location method (e.g. put the mobile terminal to dedicated mode to obtain the Cell ID)
- Coordinates the flow of incoming location requests
- Interfaces with functions of SMLC (Serving Mobile Location Centre) in order to get the location estimation of the MS

The SMLC coordinates and carries out the actual positioning function. There are several SMLC’s in the network either connected to the MSC's or the BSC's (Base station controller). SMLC retrieves information required by the location algorithm from LMU's (Location measurement unit). There are two types of LMU's. From functional point of view type A LMU is similar to a mobile terminal. It is located at a known location, typically at a BS site, where it carries out time delay measurements towards base stations. This way it provides reference measurements for the E-OTD method. SMLC communicates with type A LMU through the standard GSM radio interface. Type B LMU carries measurements for the TOA method and is accessed via the Abis interface. In addition to LMU data, SMLC collects the required signal measurement results from uplink and downlink as well as retrieves the geographic coordinates of the BS's. Using all this information the SMLC performs location calculations and converts the co-ordinate estimation to the preferred geodetic reference system. The estimated coordinates of the user are then sent to the LCS client via VMSC and GMLC.

The SMLC may use the services of Cell Broadcast Centre (CBC) in order to broadcast assistance information to several users at the same time. This can be information required for A-GPS positioning or terminal-based E-OTD positioning.

5.2 GSM standardisation support for CELLO applications

The GSM standardisation for location has been mainly targeted towards "end-user" applications and location of emergency calls. This is logical since the companies see high revenues in providing location-based services for customers and because location of emergency calls will be mandatory in the future (at least in the USA). However, "professional" services such as the ones identified in the CELLO project plan may actually be introduced in quite short time frame and they may also turn out to yield good profit for the network owners. In the following, it is considered how the GSM standardisation supports the service requirements of CELLO.

There are some requirements that seem necessary in order to use location methods for operational CELLO applications:

1. The location information should be retrieved from any legacy phone
2. It should be possible to carry out the location procedure without any involvement of the user.
3. The mobile network operator is in charge of calculating and storing the location data.
4. The location determination procedure shall not cause significant load to the network.
5. Together with location information at least the received signal levels from BS's are required as an output.

The first requirement comes from the fact that in order to obtain sufficient amount of information from the network a maximum number of "probes" are needed. It seems clear that for several years from now GPS modules will be included only in special cellular phones. Therefore CELLO applications can not rely only on these techniques although the provided accuracy is best. The E-OTD and TOA techniques will support location of a large number of users. TOA method supports legacy phones directly, while E-OTD requires a software upgrade. However, both techniques require expensive infrastructures to be built, which may provide the operators to begin with other, non-standard, technologies.

The second requirement is evident, since we can not expect that, in general, a user wants to do anything just to help the network operator. The GSM location architecture supports well the possibility of carrying out the location measurement without action by the user.

The third requirement seems necessary in order to ensure that the user's privacy rights are respected. The mobile network operator already has to be a "trusted party", e.g. because of being charge of billing information collection, it is logical that they are also responsible of the collection of the user location data. The storage procedure of the location and signal information has to take care that no personal information is stored. After the personal identity information is removed from the data there should be no restrictions in transferring the location data to third parties when required. The GSM network architecture is defined in the way that the location determination and subsequent usage of the information can be controlled by the operator and in this respect the standard supports well the CELLO applications.

The fourth requirement is clear: since the target of CELLO applications is to improve the performance of the network, it is not acceptable that the applications would significantly increase the network traffic. As each GSM location fix involves quite a lot of signalling, there is a risk that the CELLO applications could have considerable effects on the network. Especially in connection with commercial end-user applications a large amount of signalling for paging and authentication is required. In order to minimise signalling, the location procedure used for CELLO applications should be similar to the one used by GSM emergency services. The emergency call location is carried out only for an active terminal and therefore the additional signalling in the air-interface is minimised. In addition, the actual location function should be based only on the information, which is available in the measurement report of the mobile: the signal levels and timing advance.

The fifth requirement comes from the objective to store signal levels in MGIS (Mobile network Geographic Information System). The current GSM standard does not support sending the signal level information together with the location estimate out from SMLC. CELLO project should try to affect standardisation to include this feature. As a conclusion it can be said that the GSM standard only partly supports CELLO-type applications. The main issues of concern are:

- the support to legacy phones (or a substantial part of phones of users) is limited.
- the standard location techniques are mainly involving quite a lot of signalling (e.g. E-OTD and TOA) and do not support more simple methods based only on MS measurement reports.
- the standard does not support providing signal level information together with the location estimate

It seems that in order to support CELLO applications new features should be added to the GSM standard. The emergency location service is basically similar to what is needed in CELLO applications. Therefore, the new location procedure could be a modified version of the emergency location procedure

5.3 UMTS standardisation

In Europe, the European Telecommunications Standards Institute (ETSI) with its 3G Partnership Project (3GPP) is responsible for the standardisation of the Location Services and the location techniques for UMTS and different positioning solutions are being studied widely by the network operators and research institutes. Currently, there are three 3GPP standardised location techniques supported by the UMTS Terrestrial Radio Access Network (UTRAN): the cell-ID, OTDOA with optional Idle Period DL (IPDL) assistance by the network and the network-assisted GPS (AGPS).

5.3.1 Location Architecture

The general arrangement for implementing MS positioning functionality in UTRAN is presented in Figure 14. The Radio Network Controllers are in charge of the network resources managing the BSs and specific Location Measurement Units (LMUs) in the location process. The Serving RNC works as the Serving Mobile Location Centre and receives the location request from external LCS application or LCS Client Function in the Core Network. SRNC both co-ordinates and controls the overall MS positioning.

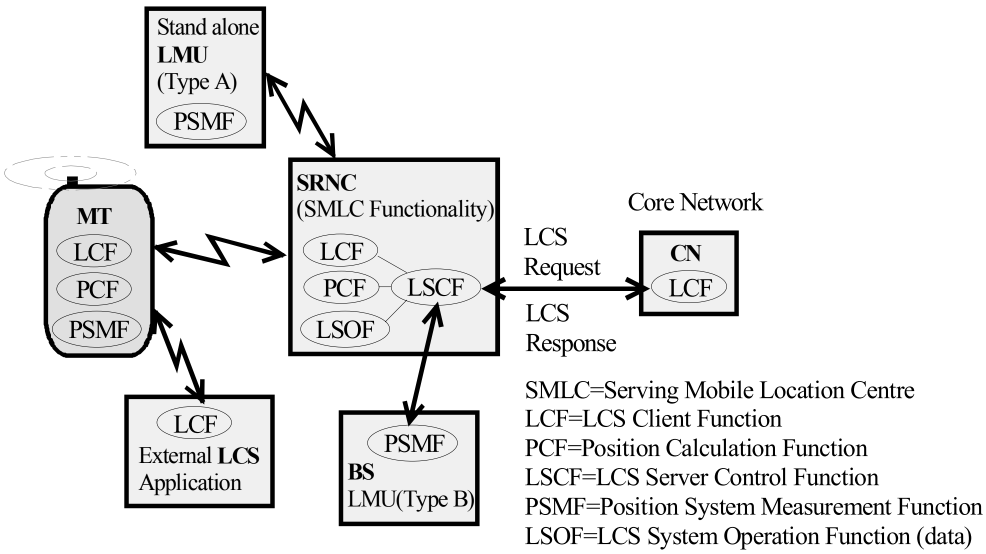

Figure 14. General arrangement of MS positioning in UMTS.

The LCS System Operation Function in SRNC works as a database of the needed information in MS position calculations, e.g. the geographic locations of the BSs, or in other network operations during the location process. The LCS Server Control Function in SRNC requests the needed measurements from the MS, LMU or one or more BS and sends the results to appropriate Position Calculation Function (PCF) in the network. The PCF makes the needed co-ordinate transformations for the MS location estimate. For every location estimate result the PCF estimates the QoS level regarding the achieved accuracy and sends it together with the time-of-day information about the measurement as a part of the reported result. The SRNC can also use the MS location information internally e.g. for location-aided handover [6]. The logical positioning architecture in UMTS does not depend on a single measurement and location technique but it is able to perform with the standard measurements and techniques available and appropriate. The selection of the used technique(s) is the operator's decision.

5.3.2 Location Measurements and Reporting

The most suitable channel for the location measurements in the MS is the primary downlink Common Pilot Channel (CPICH) whose reception level (RSCP) at the MS is used for handover evaluation, downlink and uplink open loop power control and for the pathloss calculations [3]. Every base station sends the Primary CPICH with a fixed data rate of 30 kbps and it is unique for each cell or sector. It is always present on air, under the primary scrambling code with a fixed channelisation code allocation, thus, the CPICH can be measured at any time by the MSs. The transmission power of CPICH is set to 10% of the maximum i.e. 33 dBm, which makes it possible to use readily available measurements at the MS made on CPICH also for location purposes.

The standardised measurements suitable for MS positioning in the UTRA FDD mode are presented in Table 7 [4]. Similar measurements are available also in UTRA TDD mode [5]. Possible MS modes for making the measurements are also presented. In idle mode the MS is not actively processing a call. Connected MS mode involves two cases, in an intra-frequency mode the measurements are made within one carrier frequency and in an inter-frequency mode the carrier frequencies between the measured system and the MS are different e.g. the measurements made from the GSM cells.

Table 7. Standardised measurements by the MS and UTRAN in FDD mode

MS Measurements	Possible MS Modes for Measurements	Possible to use with Location Techniques
RSCP, Received Signal Code Power on CPICH (for TDD cells separate measurement)	Idle & Connected Intra/Inter	Signal strength, DCM
RSSI, Received Signal Strength Indicator on a DL carrier	Idle & Connected Intra/Inter	(Signal strength, DCM)
MS Transmitted power	Connected Intra	As a reference level
SFN-SFN observed time difference on CPICH, Type2 (SFN=System Frame Number), relative time difference between cell i and j	Idle & Connected Intra/Inter	OTDOA, DCM
MS Rx-Tx time difference, for each cell in the active set	Connected Intra	Advantageous for OTDOA and DCM
MS GPS Timing of Cell Frames for LCS	Connected Intra/Inter	AGPS
UTRAN Measurements	Possible to use with Location Techniques	
Transmitted carrier power	(Signal strength and DCM with RSSI)	
Transmitted code power, power on the pilot bits of the DPCCH field	As a reference	
RTT, Round Trip Time (T_{RX}-T_{TX}) at BS	Advantageous for OTDOA , DCM and in hybrids	
UTRAN GPS Timing of Cell Frames for LCS	AGPS	
SFN-SFN observed time difference on CPICH, measured by a LMU	OTDOA, DCM	

In connected mode the MS continuously measures the detected, usually eight, intra-frequency cells and searches for new intra-frequency cells in the monitoring set, which can involve up to 32 intra- or inter-frequency cells [3]. These intra-frequency measurements and reporting of the results are typically made with a 200 ms period if no other measurements have been requested. If needed, a specific measurement, e.g. Rx-Tx time difference, may be requested by the UTRAN. The request involves e.g. the measurement ID, type, reporting quantities and criteria [4] e.g. requirements of periodic or event-triggered reporting. With event-triggered reporting the MS shall not return the measurement result report until the reporting criteria, i.e. the required accuracy level set in [3] for the measurements, is fulfilled. For intra-frequency and MS internal measurements, specific events can be defined to trigger the MT to report the UTRAN.

5.4 CELLO Contribution to standard Bodies

Contribution to standardisation bodies is expected to be one of the major outcomes of project Cello. Such contributions can be in the form of reports or presentations given at the appropriate venues. Location-based services are handled in a variety of different fora. However, Cello has targeted two major venues to address contributions and reports. They are:

- 3GPP
- Location Interoperability Forum (LIF)

Next paragraphs provide an overall description of the activities and contact points framed within these two bodies as well as contact references to address future contributions.

5.4.1 3rd Generation Partnership Project (3GPP)

3GPP (http://www.3gpp.org) is organised according to 5 different Technical Specification Groups as shown in Figure 15.

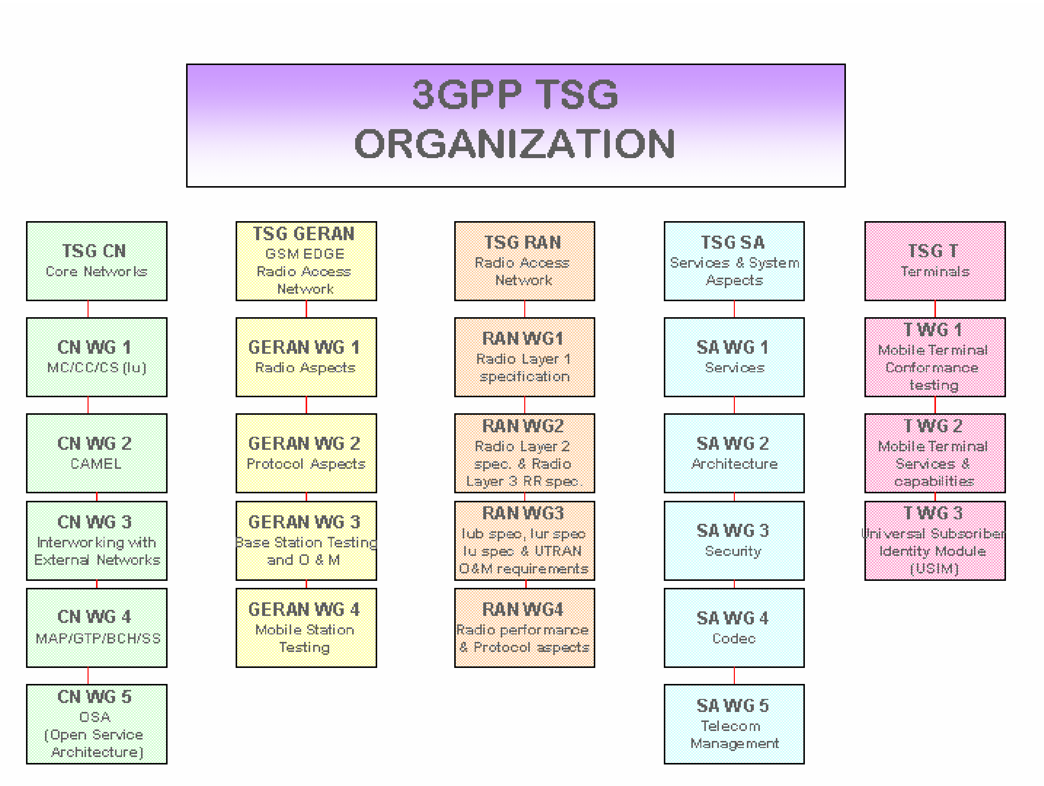

Figure 15. 3GPP structure.

Location issues are handled in different groups and subgroups. TSG-RAN (Radio Access Network) is responsible for identifying suitable location algorithms among the different techniques currently available or forecast. TSG-SA considers location-based services both from the users' and network operators' perspective.

A major Technical Specification in this context is represented by 3GPP TS 25.305 V3.4.0 (2000-12) "Stage 2 Functional Specification of UE Positioning in UTRAN". This TS provides the location concepts currently evaluated in 3GPP such as;

- cell ID based method;
- OTDOA method that may be assisted by network configurable idle periods;

- network-assisted GPS methods.

Cello contributions focused on location methods can be addressed to this group and specifically to the enhancement of this TS.

Within TSG-SA (Service Aspects), WG2 "Architecture" is responsible for identifying suitable network architectures to support location-based services. The major TS in this area is 3G TS 23.271 V 1.10.0 (2000-1109) "Functional stage 2 description of LCS". Cello can contribute to this group by providing information on the functional mapping of LCS functionality onto physical network entities.

TSG CN (Core Network) analyses location-based service from the HLR/VLR/MSC point of view. In particular, 3G TS 23.012 V3.3.0 (2000-06) "Location Management Procedures" provides a comprehensive description (with SDL diagrams) of mobility management procedures (Location Update) in 3G systems. The impact of location-aware services is assessed as well and this might be one the major areas where Cello, and more specifically WP5, could contribute.

Table 8. TSG and WG addresses by Cello.

3GPP TSG	TS	Contact	Company
TSG-RAN	25.305	Francois COURAU francois.courau@alcatel.fr	Alcatel
TSG-SA (WG2)	23.271	Niels ANDERSEN NielsPeter_Andersen@Europe30.mot.com	Motorola
TSG-CN	23.012	Stephen Hayes EUSSRH@am1.ericsson.se	Ericsson

5.4.2 Location Interoperability Forum (LIF)

The world's three largest mobile phone manufacturers, Ericsson, Motorola and Nokia, in October 2000 founded the Location Interoperability Forum (LIF) to achieve the goal of offering location-based services worldwide on wireless networks and terminals (http://www.locationforum.org). The forum is dedicated to developing global interoperability between mobile positioning systems. The aim of LIF is to produce a common view on positioning technologies and system solutions to meet the emerging service requirements such as information retrieval and mobile commerce applications. LIF is therefore specifically focused on the user's rather than on the operators' perspective: in other words, this forum aims at identifying technologies and opportunities to provide location-aware services and not to use such data to enhance network management policies. LIF also handles security issues related to users' location data. The first applications based on the LIF recommendations are expected to be available already starting in 2001.

LIF's purpose is to define, develop, and promote through the global standard bodies and specification organisations a common and ubiquitous location services solution. Such a solution will:

- Define a simple and secure access method that allows user appliances and Internet applications to access location information from the wireless networks irrespective of their underlying air interface technologies and positioning methods.
- Promote a family of standards-based location determination methods and their supporting architectures, which are based on Cell-ID and Timing Advance, E-OTD (GSM), AFLT (IS-95), and MS Based Assisted GPS.
- Establish a framework for influencing the global standard bodies and specification organisations to define common methods and procedures for testing and certifying the LIF-recommended access method and positioning technologies.

LIF intent is to have representation from a mix of network operators, equipment manufacturers, and service providers responsible for deploying equipment utilising this solution. Its members will define this solution and submit it to the working standards groups. The members will then support the solution developed in the LIF in the appropriate existing global standard bodies and specification organisations and in the deployment of their systems and services.

It is worthwhile mentioning that LIF is not a standardisation body but rather a forum whose objective is to influence standards to promote the development of location-based services. Cello can therefore aim at contributing to LIF by providing contributions that can be then forwarded to the appropriate standard bodies. Since Motorola is one of the members of the LIF, Motorola Italy and Motorola UK, both active parties in Cello, will take the responsibility for evaluating, together with project control board, the results that are worth being forwarded to the LIF

5.4.3 Proposed Strategy

Cello is now passing the first 6 months from the project start. It is therefore time to start advertising the project within the standards bodies that have been targeted. The work plan proposed to make the international community aware of Cello's results is summarised in the following table.

Table 9. Action items to approach standard bodies

Forum	Action	Owner	Deadline
3GPP	Prepare a standard presentation to describe project approach and expected results.	Project manager	3Q 2001
3GPP	Evaluate 3GPP meeting calendar and identify suitable time where Cello could forward contributions.	Motorola	4Q 2001
LIF	Identify contact person in LIF and negotiate methods to receive and forward contributions.	Motorola	3Q2001

6 COMPARISON OF DIFFERENT TECHNIQUES

The location-based applications of CELLO project are location-aided planning (LAP), location-aided handover (LAH) and location-aided mobility management (LAM). In general, different applications impose varying requirements for the location method. LAP, LAH and

LAM belong to a class of internal applications that are used by the network operators. It is important for these applications that the location data is easily available in the network. Consequently, mobile-based methods, e.g. standalone GPS, are not applicable. High capacity is needed since it would be beneficial to locate all active-mode mobile stations in the network, even in real time in the case of LAH and LAM. Thus, multilateral techniques like angle of arrival and uplink time difference of arrival that require signalling between multiple measurement sites, are not good solutions. Due to the large number of mobile stations to be located, it is essential that the location method does not cause additional signalling on the air interface. Therefore the location method should be a network-based method or it should use standard measurement reports (see e.g. Table 1, p. 15 or Table 7, p. 33). High accuracy, substantially better than cell size, is a requirement for LAP, LAH and LAM. Especially in urban areas the accuracy requirement may turn out to be challenging. However, urban areas are important target areas for these applications.

Some properties of the potential location methods are compared in Table 10. Urban, suburban and rural coverage of each method is estimated based on the number of base stations/satellites that are needed for location fix on one hand, and typically available in each environment on the other hand. Suitability for "mass location" applications is evaluated based on the complexity of the required measurements, signalling, and computations that are needed in the network side. For example, signal strength method in GSM and OTDOA in UMTS work with standard measurement reports and do not require complicated calculations for position solution. Therefore, these methods are well suited for "mass location" applications. On the other hand, E-OTD in GSM is not suitable because legacy phones can not be located using this method. Additional signalling means any data transfer between mobile and base stations that is not included in standardised measurement reports.

Table 10. Comparison of potential location methods.

Method	GSM/ UMTS standard	Urban/suburban/rural coverage	Suitability for "mass location"	Additional signalling
Signal strength	no	good/good/low (3 BSs required)	good	no
Angle of arrival (AOA)	no	good/good/moderate (2 BSs required)	low	no
uplink TOA	GSM	good/good/low (3 BSs required)	low	no
E-OTD	GSM	good/good/low (3 BSs required)	low	yes (OTD measurements)
OTDOA	UMTS	moderate/moderate/low (hearability problem)	good	no
DCM	no	good/good/moderate	moderate+	no
Pattern recognition	no	moderate, relevant in urban areas	moderate+	no
Pattern matching (RadioCamera)	no	good/good/good (1 BS required only)	moderate-	no
A-GPS	UMTS	moderate/good/good	low	yes (pseudorange measurements

Three location methods use standard measurement reports in GSM: signal strength method, DCM and pattern recognition. Signal strength method is the simplest and could offer fast response times and large capacity. However, accuracy may be insufficient (see Section 6.1). DCM and pattern recognition require more complicated calculations and/or a database search, but may offer better accuracy.

Network-based methods like uplink time of arrival (TOA), Angle of arrival (AOA) and pattern matching (RadioCamera of US Wireless, see Section 4.5) can be used to locate legacy phones and the network operator could use these techniques for CELLO applications. However, uplink TOA and AOA are based on multilateral measurement principle (measurements are made at several BSs), which may cause severe capacity problems with applications requiring “mass location”. Moreover, AOA requires antenna arrays at base stations and is not a realistic alternative in existing GSM networks. Pattern matching technique also uses array reception. However, in contrast to AOA, it is able to locate MSs using measurements from one BS only. Therefore it might offer better capacity, although a database search and more complicated calculations are needed to determine the location.

In addition to the above-mentioned methods, possible UMTS solutions include OTDOA and A-GPS methods. Poor hearability of neighbouring BSs near the serving BS is a problem for OTDOA which causes coverage gaps. This problem can be solved with Idle Period Downlink

(IPDL) technique, but all MSs and networks may not support IPDL. A-GPS offers the best accuracy, but is not well suited for CELLO applications since it requires some extra signalling (assistance data) and the response delay may be too large. Also, it is not likely that all UMTS handsets will be equipped with a GPS receiver.

6.1 Location accuracy

Accuracy is an essential performance measure for the CELLO applications. In [31], an accuracy requirement of 50 meters for LAP is stated. This kind of accuracy would probably be sufficient for LAH and LAM also. Table 11 and

Table 12 present reported accuracies from different trials. Since the trials have been made in different places, different networks and environmental conditions, the results are not directly comparable. However, these figures give an indication of what can be achieved. In Radiolinja's trial signal strength (RXL) method gave significant accuracy enhancement over cell ID. However, it is doubtful whether this method is accurate enough for CELLO applications. All the other methods listed seem to offer accuracy that is acceptable for CELLO applications. Angle of arrival (AOA) is not suitable for urban microcellular environments, but has been successfully tested in suburban environments. E-OTD suffers from accuracy degradation in dense urban environment compared to the suburban environment. This holds for OTDOA also, as can be seen from simulation results e.g. in [22]. DCM, on the other hand, performs better in dense urban environment than in open areas.

Table 11. Reported accuracies from location trials in suburban environments.

Company	Method	System	Place	Source	Reported 67% accuracy [m]
Radiolinja	Cell ID	GSM	Estonia	[9]	639
Radiolinja	Cell ID + TA	GSM	Estonia	[9]	415
Radiolinja	RXL	GSM	Estonia	[9]	448
KSI	AOA	IS-136	Annandale, Northern Virginia	[34]	45
CPS	E-OTD	GSM	Cambridge	[20]	50
VTT	DCM	GSM	Espoo, Finland	[19]	74
US Wireless	Matching	AMPS	Montana	[26]	63

Table 12. Reported accuracies from location trials in urban environments.

Company	Method	System	Place	Source	Reported 67% accuracy [m]
Radiolinja	Cell ID	GSM	Estonia	[9]	328
Radiolinja	Cell ID + TA	GSM	Estonia	[9]	283
Radiolinja	RXLEV	GSM	Estonia	[9]	207
CPS	E-OTD	GSM	Hong Kong	[20]	125
VTT	DCM	GSM	Espoo, Finland	[19]	44
US Wireless	Matching	AMPS	Montana	[26]	126

7 CONCLUSIONS

In order to meet the requirements of CELLO applications (e.g. support for all terminals, large capacity and low response delay), the location method should be based on standard measurement reports that are continuously transmitted from the MS back to the network during a connection. Alternatively, a network-based method that uses only one base station, could be used.

Potential methods in GSM are the signal strength method and database correlation method. Signal strength method is easier to implement but DCM would offer better accuracy. In UMTS, some new methods should be considered. Observed Time Difference of Arrival (OTDOA) is a standardised method that is supported by all handsets. Also, network-based techniques that utilise antenna arrays can be used for CELLO applications, especially if adaptive arrays become commonly used in UMTS networks. Methods that require reception at one base station only include the pattern matching technique of US Wireless and a method based on angle of arrival and round trip time measurement.

To ensure the support for CELLO applications in GSM and UMTS, contribution to standardisation bodies is needed. The use of measurement reports for location determination without any additional signalling, and the use of location results together with the measurement reports, should be standardised.

ANNEX A REFERENCES

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