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Global Positioning in Harsh Environments

Master's Thesis in Computer Systems Engineering

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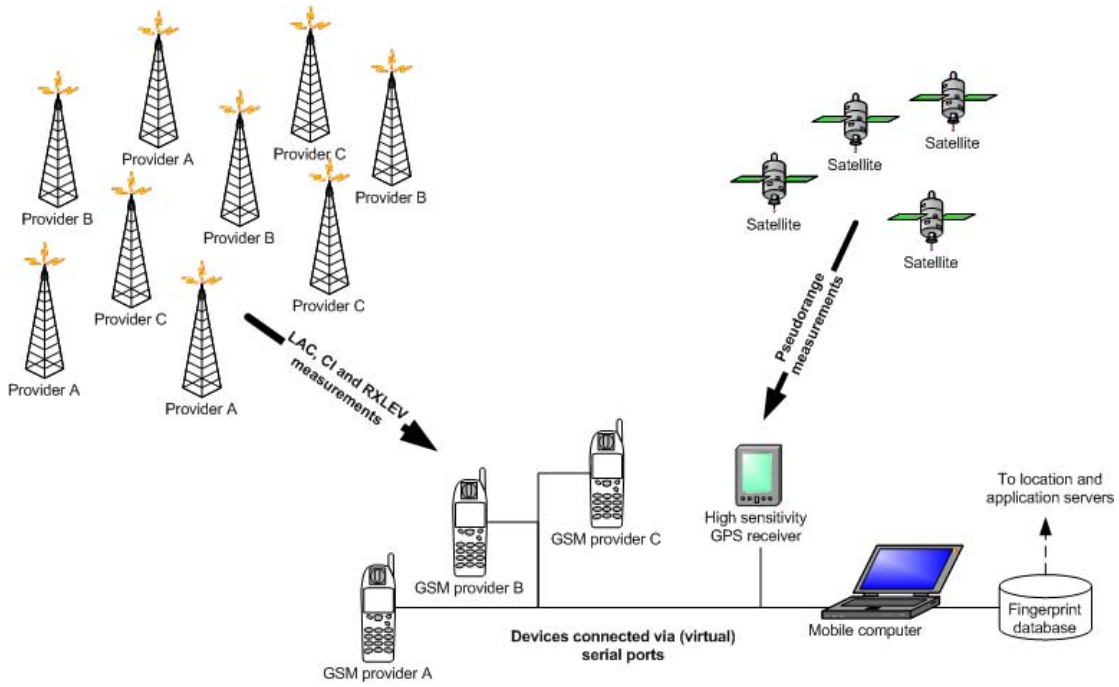

School of Information Science, Computer and Electrical Engineering
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Description of cover page picture: Technical structure of the innovative approach for measuring GSM cell fingerprints developed within this thesis.

Preface

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4. Keyword:	Database comparison
5. Keyword:	Database correlation

Abstract

As global location systems offer only restricted availability, they are not suitable for a world-wide tracking application without extensions. This thesis contains a goods-tracking solution, which can be considered globally working in contrast to formerly developed technologies. For the creation of an innovative approach, an evaluation of the previous efforts has to be made.
As a result of this assessment, a newly developed solution is presented in this thesis that uses the Global Positioning System (GPS) in connection with the database correlation method involving Global System for Mobile Communications (GSM) fingerprints. The database entries are generated automatically by measuring numerous GSM parameters such as Cell Identity and signal strength involving handsets of several different providers and the real reference position obtained via a high sensitivity GPS receiver.

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Abbreviations

3G	…	Third Generation
3GPP	…	Third Generation Partnership Project
4G	…	Fourth Generation
A-GPS	…	Assisted GPS
AOA	…	Angle of Arrival
BCC	…	Base Station Colour Code
BCCH	…	Broadcast Control Channel
BS	…	Base Station
BSC	…	Base Station Controller
BTS	…	Base Transceiver Station, GSM equivalent to BS
C/A	…	Coarse Acquisition
CDMA	…	Code Division Multiple Access
CI	…	Cell Identity
CI+TA	…	Positioning Method Based on CI and TA
CI+TA+RXLEV	…	Positioning Method Based on CI, TA and RXLEV
CR	…	Carriage Return
CRC	…	Cyclic Redundancy Check
DGNSS	…	Differential GNSS
DoD	…	Department of Defense
DOP	…	Dilution of Precision
DS-CDMA	…	Direct Sequence - CDMA
DTD	…	Document Type Definition
E-OTD	…	Enhanced Observed Time Difference
EF	…	Elementary File
EGNOS	…	European Geostationary Navigation Overlay Service
ELIS	…	Emergency Location Immediate Service
ELRS	…	Emergency Location Reporting Service
ESA	…	European Space Agency
ETSI	…	European Telecommunications Standards Institute
FCC	…	Federal Communications Commission
FEC	…	Forward Error Correction
GCC	…	Galileo Control Centre
GDOP	…	Geometric DOP
GMPC	…	Gateway Mobile Positioning Centre
GNSS	…	Global Navigation Satellite System
GPRS	…	General Packet Radio System
GPS	…	Global Positioning System
GRI	…	Group Repetition Interval
GSM	…	Global System for Mobile Communications
GTD	…	Geometric Time Difference
GTS	…	GSM Technical Specification
HDOP	…	Horizontal DOP
HP	…	High Precision
IP	…	Internet Protocol
IPDL	…	Idle Period on the Downlink
ITS	…	Intelligent Transportation System
LCS	…	Location Service
LMU	…	Location Measurement Unit

LOP	…	Line of Position
LOS	…	Line of Sight
LS	…	Location Server
MCS	…	Master Control Station
MEO	…	Medium Earth Orbit
MLC	…	Mobile Location Centre
MLP	…	Mobile Location Protocol
MPP	…	Mobile Positioning Protocol
MPS	…	Mobile Positioning System
MS	…	Mobile Station
MSC	…	Mobile Switching Centre
NCC	…	Network Colour Code
NMEA	…	National Marine Electronics Association
NMR	…	Network Measurement Result
OTD	…	Observed Time Difference
OTDOA	…	Observed Time Difference of Arrival
PDOP	…	Positional DOP
PDU	…	Protocol Data Unit
PSK	…	Phase Shift Keying
PRN	…	Pseudorandom Noise
RNC	…	Radio Network Controller
RSCP	…	Received Signal Code Power
RTCM	…	Radio Technical Commission for Marine Services
RTD	…	Real Time Difference
RTT	…	Round Trip Time
RXLEV	…	Received Signal Strength
SA	…	Selective Availability
SGSN	…	Serving GPRS Support Node
SIM	…	Subscriber Identity Module
SIM AT	…	SIM Application Toolkit
SLIS	…	Standard Location Immediate Service
SLRS	…	Standard Location Reporting Service
SMG	…	Special Mobile Group
SMS	…	Short Message Service
SP	…	Standard Precision
SS	…	Supplementary Service
SSL	…	Secure Socket Layer
TA	…	Timing Advance
TDOA	…	Time Difference of Arrival
TDOP	…	Time DOP
TOA	…	Time of Arrival
TLRS	…	Triggered Location Report Service
TTTF	…	Time-to-first-fix
UMTS	…	Universal Mobile Telecommunications System
USSD	…	Unstructured Supplementary Service Data
UTC	…	Coordinated Universal Time
UTSFM	…	Urban Three-state Fade Model
VDOP	…	Vertical DOP
WGS	…	World Geodetic System

Contents

1 Introduction

Currently, Global Positioning System (GPS) signals are not accessible in certain environments like urban regions or indoors, which raises two unresolved questions considering a world-wide goods tracking solution.

The first challenge is to make GPS usable in urban canyons between skyscrapers, where GPS signals are negatively influenced by multipath effects and the shading caused by high buildings. Secondly, the comparably weak GPS signal is attenuated by walls so that the system is not usable indoors. Hence, either the signal must be brought into the building or GPS is to be combined with a local positioning method using stronger signals that can penetrate the walls.

In order to be able to formulate concepts and possible applications to overcome the problems mentioned above, the commonly used technology of GPS has to be investigated first. After that, the benefits and disadvantages of existing positioning systems versus GPS must be examined and critically viewed. Then, several existing solutions for the stated positioning problem should be elucidated and evaluated based on several criteria such as accuracy, world-wide availability and requirements necessitated due to a possible application scenario. In fact, this consistent evaluation is the primary goal of the project in question. Finally, an innovative approach, which has to be verified by a meaningful demonstration, can be derived from the results of the performed evaluation.

Technical facts of the Global Positioning System (GPS), which is currently the most important positioning technology, are presented in the first chapter and a brief illustration of several technological alternatives to GPS is given in section two. Thereafter, a description and a profound evaluation of former approaches to overcome the aforesaid positioning problems are examined in the next part of the thesis. Chapter four contains the technical description and the motivation for the conception of the innovative method created within this project. Finally, the conclusion provides a summary of the practical implementation of the new approach as well as a future outlook elucidating possible further developments of the project outcomes.

1.1 Global Positioning System

Developed for military use by the United States Department of Defense (DoD), the Global Positioning System (GPS) has achieved great importance also in the field of civil application. Examples in this context are intelligent traffic management and navigation services, tracing of goods, localisation of mobile phones in case of emergency calls and so on. Another important, but often less noticed application is time synchronisation via time signals broadcasted by satellites.

1.1.1 The System Architecture

The architecture of GPS is divided into three different sections. The first one is made up by the navigation satellites. GPS involves a constellation of 24 satellites, which are at semi synchronous altitude of about 11.000 nautical miles or about 20.000 km, respectively. These satellites are moving on six different orbital planes, each including four satellites. The corresponding orbital period is twelve hours. In relation to the equator, these planes are inclined at 55°. Figure 1, taken from [GARM05] roughly illustrates the disposition of the GPS satellites.

Figure 1: GPS Satellite Constellation, [GARM05] © Garmin Corp. 2005.

The constellation shown above assures that at least four satellites are visible 24 hours a day all over the world. This is important since GPS requires a minimum of four satellites for accurate three-dimensional positioning. In fact, the number of visible satellites is often higher and can reach an amount of up to ten. An important fact to mention is that positioning requires very exact timing accuracy. This is why all early GPS satellites were equipped with Cesium and Rubidium atomic clocks. Newer generations of GPS satellites rely on the Rubidium standard.

The accuracy of these clocks is within a few nanoseconds of global coordinated world time (UTC).

The second section of GPS, which is situated on earth, is used for the control of the satellites. Within in this section of GPS, one can find a master control station (MCS) located at Schriever Air Force Base, Colorado Springs, CO, USA and five monitor stations distributed over the world. Data recorded by the monitor stations are processed at the master control station. After doing the corresponding calculations, correction messages are sent to the satellites. The purpose of these corrections is to maintain perfect accuracy as far as orbital location and the system-time of the satellites are concerned.

The third and last section of GPS simply refers to the big field of GPS users. Within this section, the communication is only one-directional from the satellites to the GPS receivers. Possible errors have to be corrected by the GPS end-devices or via Differential GPS (DGPS), which is explained in subsection 1.1.4.

1.1.2 The Signal Structure

A GPS receiver is able to calculate its position upon receiving navigation messages, which are packed into two pseudorandom noise (PRN) code sequences. The Coarse Acquisition (C/A) code is a 1023 bits long sequence being repeated every millisecond. Furthermore, this code is clocked with 1.023 MHz. The second code sequence (Y-code), which is repeated every week, is encrypted and 6 trillion bits long. Its clock rate is 10.23 MHz. By processing navigation messages, receivers obtain information about the position of the individual satellites and the system time. The C/A-code has great importance for civil use since it is unencrypted and thus available to all GPS receivers. Moreover, a high repetition rate guarantees a short reacquisition time. Each satellite is sending its messages via two different frequencies, which are called L-band frequencies. L1 can be found at 1.575,42 MHz and L2 is placed at 1.227,60 MHz. These frequencies were chosen in order to be able to compensate for atmospheric phenomena. For example, the two different frequencies can be utilised to determine and cancel out ionospheric effects. The fact that all satellites are sending at the same frequencies requires a Code Division Multiple Access (CDMA) interface. This is done by a set of Gold codes, which means that each satellite transmits a unique code that is not interfering with the codes of other satellites. The carriers are phase shift key (PSK) modulated by the use of the C/A and the Y-code, which results in two spread-spectrum signals having a bandwidth of 2.046 MHz and 20,46 MHz. One important aspect in this concern is the fact that spread-

spectrum techniques allow GPS to work at very low signal strengths, which means that GPS signals are received at a range between -160 and -166 dBW.
In the current implementation, only the L1 band contains both, the Y-code and the civil C/A-code. Within modernisation initiatives, a new, more robust civil signal will be added to the L2 band. In addition, a third frequency band operating at 1.176,45 MHz is planned to be introduced by the end of 2005.

1.1.3 The Positioning Technique

GPS utilises the principle of time difference of arrival (TDOA), which indicates that a 3D-position can be calculated by knowing the distances to any three points in space. The distances are quantified by measuring the propagation time of the GPS signal received from several satellites. In other words, by looking at the C/A code, a receiver knows when the signal was sent and then it has to compare that time with the receiver internal clock. By multiplying the resulting time interval with the speed of light, the distance to the satellite can be calculated. The obtained distance is called pseudorange because of the fact that there is always a small timing offset between the satellite clock and the receiver clock. This timing offset can be determined by involving a fourth satellite. Thus, an accurate three-dimensional positioning requires the signal availability from four different satellites. It has to be mentioned that even very small timing offsets can cause large positioning errors due to the fact that the high value of speed of light is involved in the calculations. As stated in [COOP94], the equation of the noiseless pseudorange to a single satellite is

$$\psi = \sqrt{(X_S - X_R)^2 + (Y_S - Y_R)^2 + (Z_S - Z_R)^2} + c \cdot \delta t$$

where index S depicts the satellite coordinates and R represents the coordinates of the GPS receiver. As mentioned above, c stands for the speed of light and δt symbolises the clock offset at the receiver. Looking at the above formula, it is obvious that involving four GPS satellites is necessary for accurate positioning since the equation contains four unknown values. To sum up, one can state that these four unknown values are the coordinates of the GPS receiver and the timing offset between the involved satellites and the GPS receiver. Due to the fact that all satellites are synchronised to each other, this timing offset is constant for every satellite.
GPS is based on the World Geodetic System (WGS-84), which is an earth-centered earth-fixed format founded by a geocentric equipotential ellipsoid. As stated in [HOFM97; p. 31], the WGS-84 ellipsoid is defined by the parameters semimajor axis of the ellipsoid, zonal coefficient of second degree, angular velocity of the earth and the earth's gravitational

constant. A detailed explanation of the coordinate systems usable for all Global Navigation Satellite Systems (GNSSs) can be found in [HOFM97, pp. 29-36].
Kalman filtering is used in order to process the obtained pseudoranges at the receiver. Further details about this rather sophisticated method can be found in [COOP94].

1.1.4 Errors Affecting the Accuracy

Some error sources of GPS have to be taken into consideration. First of all, there are ephemeris errors, which means that satellite signals transmitted from an altitude of about 20.000 km are often affected by forces like solar winds and earth gravitational pull [COOP94]. Normally, the inaccuracy caused by ephemeris errors is between 15 and 20 meters.
Propagation errors are provoked by the fact that a GPS signal has to propagate through different layers of the earth's atmosphere. For instance, the ionosphere adds an inaccuracy of about 20 meters to the pseudoranges. Furthermore, there is an additional error caused by the GPS signal propagating through the troposphere. Different weather conditions make it impossible to predict this error, which is between three and four meters.
Another important error source was the Selective Availability (SA). This error was introduced by the DoD in order to make the GPS positioning inaccurate for civil use while preserving the best positioning performance only for military use. However, SA was deactivated on 1st May 2000. A method originally introduced to overcome the inaccuracy caused by SA is Differential GPS (DGPS), which involves stationary GPS receivers situated at known positions. The fact that the positions of such stationary receivers are known reduces the number of unknown variables within the GPS calculation. The additional knowledge can be utilised to get important information about the current GPS timing error. Transmitting the resulting correction data to moving GPS receivers via radio waves is an efficient way to improve the positioning accuracy of these GPS receivers.
A further important aspect influencing the precision of the obtained GPS position is the geometry of the satellites involved in the pseudorange measurements. A parameter to quantify the quality of this geometry is the Dilution of Precision (DOP) factor. It should be mentioned that this geometry changes as the satellites are moving along their orbital planes, which means that the DOP values vary over time. No measurement values are necessary for the calculation of DOP values, which can be performed by the use of knowledge about the satellite constellation. Low values of DOP indicate high positioning accuracy. A commonly used threshold value in this context is five, which denotes that positions calculated under a DOP

less or equal five are considered to be accurate. Different categories of DOP are generally defined as follows.

PDOP	Positional DOP	Accuracy referring to position
TDOP	Time DOP	Accuracy referring to time
GDOP	Geometric DOP	Accuracy referring to position and time
HDOP	Horizontal DOP	Accuracy referring to two-dimensional positioning
VDOP	Vertical DOP	Accuracy referring to height

Table 1: Different Categories of Dilution of Precision.

Further details about DOP and its determinism can be found in [HOFM97; pp. 273-277].

1.2 Significance of GPS Receivers

When considering GPS signal availability in harsh environments like urban areas, the performance of the GPS receiver itself also has to be properly investigated. In an early research presented by Melgard et al. [MELG94], different GPS receivers were evaluated in residential and downtown areas of Calgary. Melgard et al. showed that a GPS receiver equipped with a narrow correlator provides best results. The narrow correlator, introduced in 1991, can be seen as the first method to compensate for multipath effects at the GPS receivers, which is also called multipath mitigating. Another important performance characteristic of a GPS receiver is a low signal reacquisition delay. Consequently, the receiver should be able to recalculate its current position as fast as possible after periods of blocked GPS signals, which can occur due to obstacles like high buildings in an urban canyon. The fact that the signal availability between different types of GPS receivers can vary by an amount of up to 60% indicates the importance of a GPS receiver performance analysis when using it in a critical surrounding.

More recent research works carried out in [MACG02] also pointed out the importance of choosing a well-performing GPS receiver in harsh environments. MacGougan et al. described the performance of a twelve-channel L1 receiver produced by SiRF Technology Inc. This high sensitivity receiver was specially designed to work in demanding environments like urban canyons and indoors.

An important ability of GPS receivers is multipath mitigating, as already mentioned above. By diffraction and reflection, the GPS signal is prone to multipath effects in urban environments. Several algorithms of multipath mitigating are presented and evaluated by Mike Braasch in [BRAA01a]. Multipath effects add a considerable inaccuracy to the pseudorange measurements, which can be expressed by a multipath error envelope. As shown

in [BRAA01a], there is a direct relationship between this error envelope and the discriminator function used at the receiver. That is why a first concept to overcome multipath effects is to shape the discriminator function, which is often done by a narrow correlator or by a combination of two discriminators, which are obtained employing two different narrow correlators. Such a combination is called strobe correlator. The second concept is to shape the correlation function, which should be as narrow as possible. The main drawback of algorithms using this concept is a certain loss of signal power, which could be critical in difficult environments. As stated by Braasch, there are no significant performance improvements for multipath signals with a very short delay. According to Braasch, such improvements can only be reached by designing the GPS antenna properly. A very detailed explanation of multipath effects, mitigating methods as well as narrow and strobe correlators can be found in [BRAA01a], [BRAA01b] and [MACA00].

To sum up, one can state that one solution to achieve localisation in critical environments like urban and residential areas consists of two steps. Firstly, the concrete performance of different GPS receivers and their algorithms have to be investigated. Secondly, methods to switch to other localisation techniques in periods where no GPS signals can be received have to be found. The benefit of using well-performing GPS receivers could be a less global and thus less cost-intensive enhancement of the localisation estimation in case of GPS-blind spots in urban canyons.

1.3 GPS Signal Fading in Urban Environments

In order to quantify the problems when using GPS in urban areas, the GPS signal fading was investigated by Klukas et al. in [KLUK03]. This is important since knowing the corresponding dependencies makes it possible to find suitable simulation models for future research. Klukas et al. collected and examined GPS signal fading data in the downtown area of Vancouver and Calgary, Canada. These data were then associated with the Urban Three-state Fade Model (UTSFM) developed by Karasawa et al. [KARA95] and further improved by Akturan and Vogel [AKTU97], who replaced the Rayleigh distribution used for the blocked state of the UTSFM by the Loo distribution in order to get a model more suitable for urban areas.

Klukas et al. measured the fade differences between a mobile and a reference GPS receiver. Several fade histograms for different satellite elevation angles were produced by using these data. With the help of the least-square criterion and the dependencies of the UTSFM as done in [KLUK03, p. 247], the corresponding fade diagrams were also produced theoretically.

Finally, the fade histograms obtained by measurements in Vancouver and Calgary were compared to the histograms obtained by applying the UTSFM, which showed that there are sufficient similarities among the several histograms to be able to state that a generic UTSFM for large cities can be found.

Furthermore, the results explained above were matched up to measurements recorded in the centre of Tokyo. Klukas et al. confirmed that it should be possible to find a UTSFM valid for large cities in general.

The research discussed above is related to the problems of this thesis, since finding a generic model for GPS signal fading in downtown areas is essential for the development of consistent simulation models.

2 Technological Alternatives to GPS

In general, there are two globally used positioning systems, namely Galileo and GLONASS, which are conceptually comparable to GPS. Furthermore, a radio frequency-based positioning system termed Loran-C, as well as a combination of this technology with GPS are discussed.

2.1 Galileo

Galileo, a joint initiative between the European Commission and the European Space Agency (ESA), is a satellite navigation system similar to GPS developed in order to create a European non-GPS dependent satellite-based positioning system. One of the primary concerns of this project is to develop the system with the final goal of civilian control.

Started in 2001, Galileo is still in the development phase. During this period, EGNOS (European Geostationary Navigation Overlay Service) satisfies enhanced positioning needs by processing GPS or GLONASS signals resulting in an advanced accuracy of about five meters. EGNOS consists of three geostationary satellites and a complex network of ground stations. The system has reached operational status in the middle of 2004. More detailed information on EGNOS can be found in [ESA04].

The first experimental satellite of Galileo will be launched in the second semester of 2005 and four operational satellites will be launched in 2005 and 2006. The full operational capability of the system shall be achieved by 2008. The final system will contain 30 Medium Earth Orbit (MEO) satellites in a height of 23.626 km above the earth.

The general system consists of three main component groups. Firstly, the global components are represented by the satellites, already mentioned above, which will comprise a navigation payload and a search and rescue (SAR) transponder. The ground segments are responsible for distributing integrity information and controlling the constellation of the satellites. In order to compute this integrity information and to synchronise the time signal at the ground stations with the satellites, two redundant Galileo Control Centres (GCCs) will be set up.

Secondly, there are regional components, which determine the integrity of information for a certain area. The regional EGNOS module is in charge of ensuring data integrity and differential correction of GPS and GLONASS data and also provides authorisation capabilities.

Finally, the local elements of the architecture are needed to receive additional services like improved positioning data or additional navigation signals and commercial data such as corrections or maps.

The main system architecture is depicted in Figure 2. More information about the components can be found in [BENE01].

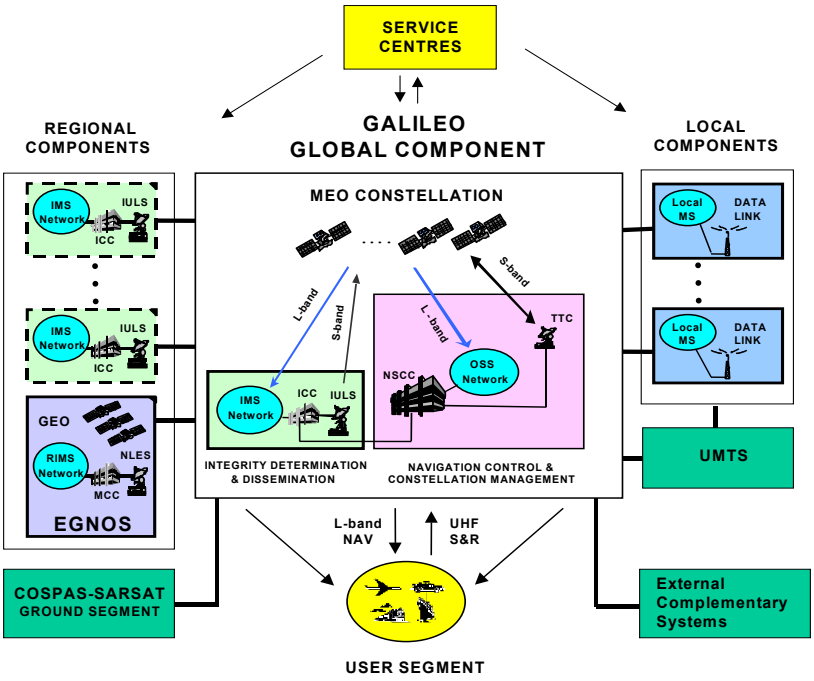

Figure 2: Galileo System Architecture, with permission of Javier Benedicto, [BENE04], © ESA Navigation Department.

As Galileo provides four navigation services and the SAR service, several frequency bands are necessary. Ten navigation signals will be available in three frequency ranges from 1.164 to 1.215 MHz, from 1.260 to 1.300 MHz and from 1.559 to 1.592 MHz. Six of the broadcasted signals will be accessible to all users and two pairs of signals will be encrypted ranging codes. One of them will offer Commercial Services and the other will only be accessible to authorised users of the Public Regulated Service.

More information about the Galileo signal and the service definition can be retrieved from [EUCO03] and [ISSL03].

2.2 GLONASS

GLONASS can be considered the Russian counterpart to the American GPS. The general function of the two systems is widely similar. This also results from the main design objective to be compatible and interoperable with each other and other globally used positioning systems such as Galileo.

GLONASS was developed very quickly resulting in a full operational capability with 24 satellites in 1995. However, the satellite constellation was degraded until 1998 because of lacking federal budget funding. Currently, eight GLONASS satellites are positioned in three orbital planes at a height of 19.100 km. At the moment, Russia is striving for rebuilding the

satellite infrastructure with the main goal of a final, full deployment in 2008. This setup will allow the satellites to transmit two civilian signals. Firstly, this is the standard precision (SP) navigation signal that has a principal frequency of 1.602 MHz, which is slightly changed to uniquely identify each satellite. The SP signal is accessible to all GLONASS users in a continuous and world-wide manner, whereby positioning accuracy is about 70 meters and the maximum velocity amounts to 15 meters per second at 99.7% of the time. Secondly, a high precision signal (HP) is transmitted simultaneously, but no information on this signal could be obtained.

Besides the satellites, the system architecture contains the ground-based control segment, which comprises the GLONASS system control centre, several command tracking stations, the central system synchroniser as well as a navigation and signal monitoring system. Finally, the user segment includes user receivers, local and regional differential subsystems as well as management and control systems.

At the moment, several enhancement objectives are connected to the current efforts to build up a fully deployed satellite network. At first, more robust navigation as well as higher accuracy, availability and integrity should be provided to civil users. Then, the military use of GLONASS should be made more robust against interference and provide an improved ability to deny hostile use of the system. Furthermore, expenses for constellation maintenance and ground operation should be lowered. Generally speaking, GLONASS shall be modernised during the next decades by enhanced satellite capabilities with a preliminary goal of transmission of three civilian signals in 2012.

2.3 Loran-C

Loran-C is a regional positioning system, which was originally developed as a radio navigation service for U.S. costal waters. Unlike global positioning mechanisms, Loran-C is not based on satellite navigation, but on ground wave propagation.

This positioning system uses a carrier frequency of 100 kHz. The topology, which is called a chain, comprises a master and two to five slaves. A baseline, which is a line drawn from the master to each slave, has a typical length of 1.200 to 1.900 km. The coverage of a chain can be obtained by considering the power emitted by each sender, the geometry, which is the setup of the chain, and the distance between the chain components.

The communication within a chain proceeds as follows. Firstly, the master transmits a burst of eight pulses plus one pulse in order to be uniquely identified. Then, the slaves transmit the

same 8-pulse sequence, whereby there is a precise predetermined time span between the different broadcasts. Figure 3 illustrates this communication process.

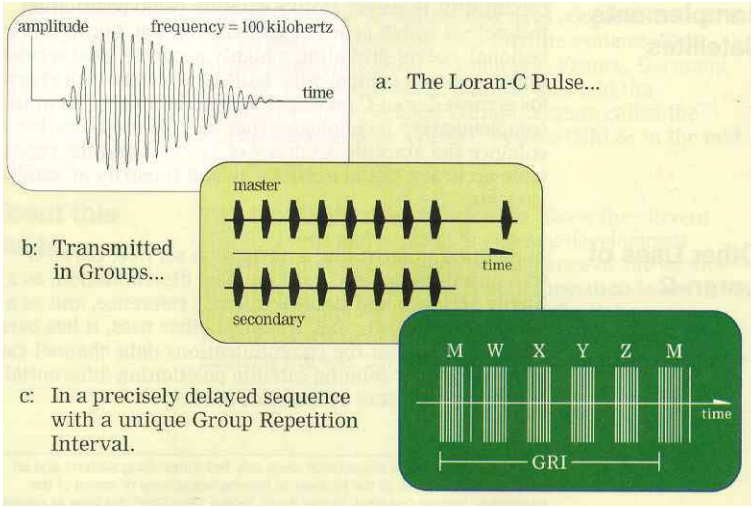

Figure 3: Loran-C Pulse Sequence, with permission of Tron-Erik Tomtum, Northwest European Loran-C System, Coordinating Agency Office, [PROC01].

This procedure is then repeated periodically, where the reoccurrence of the master transmission is called the Group Repetition Interval (GRI). Each chain has a different GRI, which can range from 40 to 100 ms, and can thus be easily identified by the receiver.

As already mentioned above, a carrier frequency of 100 kHz is employed in Loran-C. This low frequency, which corresponds to a wavelength of about three kilometers, was chosen in order to take advantage of the ground wave propagation properties. In contrast to satellite positioning systems, which use frequencies at above 1 GHz, the signal of the Loran-C system can not be easily stopped in difficult environments like urban areas. Nevertheless, the pulse shape can be distorted within the signal by the presence of delayed sky waves. To compensate for this contamination, a certain zero crossing in the pulses (cf. Figure 3a) is applied to obtain the exact phase of the signal.

In order to eliminate the influence of noise and interference, a certain phase coding for the master and the slaves is employed that also allows a straightforward distinction between the master and the slave signal. The code sequences, which are repeated every second GRI, are shown in Table 2. The + and – signs represent a phase shift of 0 and π radians, respectively.

	Master	**Slave**
First GRI Period	++--+-+- +	+++++--+
Second GRI Period	+--+++++ -	+-+-++--

Table 2: Loran-C Phase Coding.

The basic positioning principle of Loran-C is to measure the time differences of arrival (TDOAs) of the signals transmitted by the master and the slaves. Via the direct connection between the distance *d*, the propagation speed of electromagnetic waves *c* and the arrival time *t*, the distance can easily be calculated by the following formula.

$$d = c \cdot t$$

The whole measurement system of Loran-C is called hyperbolic because the locus of two points having the same distance to a certain master-slave pair is represented by a hyperbolic line of position (LOP). This means that a hyperbola represents all points where the TDOA is constant. To obtain the position of the receiver, simply two or more LOPs have to be intersected. Figure 4 illustrates this process.

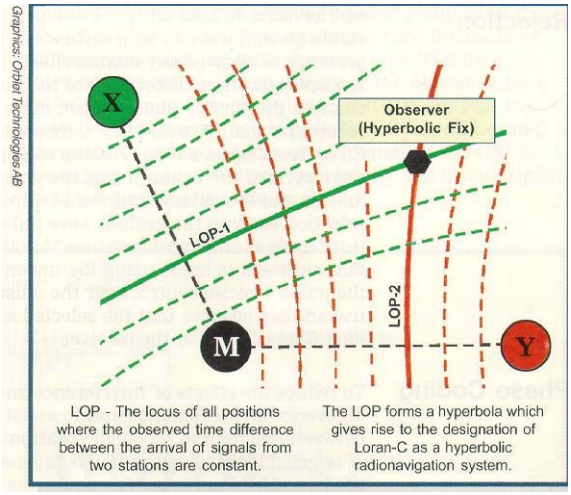

Figure 4: Time Difference Measurement, with permission of Tron-Erik Tomtum, Northwest European Loran-C System, Coordinating Agency Office, [KVAE04].

A more detailed description of the components, the operation and the system accuracy can be found in [KVAE04] and [NIMA95].

2.4 Eurofix

Eurofix is a navigation project based on the upgrade of Loran-C or Chayka stations, which combines these technologies with Differential GNSS (DGNSS). More information about Chayka, the Russian equivalent to the Loran-C system, can be found in [KUEG99] and [UNIT04]. Eurofix was designed in order to provide an accuracy of five meters at an average availability of 99,9996%. The whole system can be combined with GPS unscrupulously because the basic technologies of Loran-C and GPS are highly dissimilar and thus do not interfere.

The main purpose of the Eurofix system is to transmit DGNSS corrections from a ground station to the receiver, as shown in Figure 5.

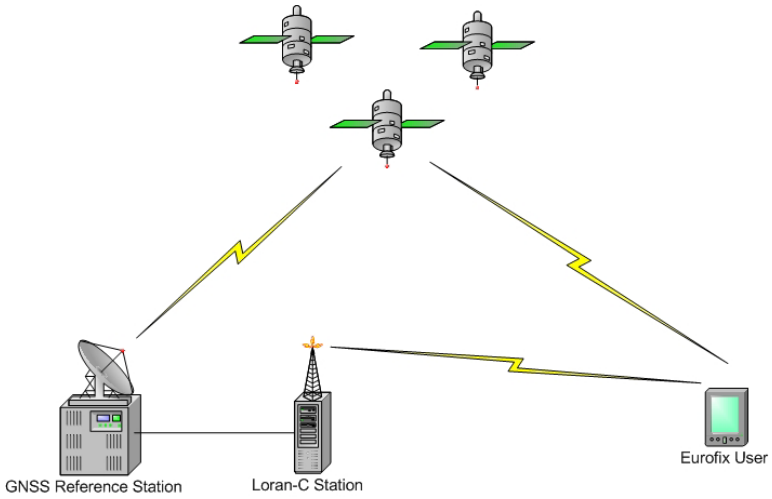

Figure 5: Eurofix System Setup.

The shown combination results in an improved navigation reliability. Apart from the fact that Loran-C and the DGNSS systems can operate in common, whereby the standard operational modes of the two systems are preserved, the system also provides a back-up function. This means that navigation - naturally at lower accuracy - is still possible if one of the systems fails.

Technically viewed, Eurofix is an 8-channel long-range low-bandwidth broadcast system that uses Loran-C signals as the carrier [TUDE99]. The main idea of this concept is to slightly shift the arrival times of Loran-C pulses without impairing the performance of the latter navigation method. Firstly, this is achieved by employing a balanced type of modulation, which means that there have to be as many advanced pulses as delayed ones, which are shifted. This method is called a 3-level pulse position modulation because each pulse can have three states that include the two mentioned before and moreover, it can be on time with no shift. Furthermore, the so-called blinking service must be preserved, which results in the non-availability of the two first pulses of each GRI for modulation. Lastly, the modulation index, which represents the ratio of the frequency deviation of a modulated signal to the frequency of a sinusoidal modulating signal, has to be kept small in order to avoid a significant loss in tracking the signal power.

In order to protect the transmitted signal from disturbances like cross-rate interference or atmospheric noise, Forward Error Correcting (FEC) codes are employed. These codes are able to correct casual errors to improve the data link availability as well as to validate the decoded data to ensure data integrity. The signal is protected by employing a Reed-Solomon code [DRUR00] followed by a 14-bit Cyclic Redundancy Check (CRC) over 56 bits or seven GRIs of information.

As a matter of fact, Eurofix is currently used to transmit DGNSS corrections, integrity messages and also short messages. Thus, the broadcasted signal has to be compatible with GNSS receivers. Therefore, the messages are sent in the Radio Technical Commission for Marine Services (RTCM) message format. Due to the rather low data rate of the Loran-C system, the DGNSS corrections are transmitted asynchronously, meaning that every message contains a correction for only one satellite in order to preserve short processing times. An important fact is that the DGNSS reference station is set up directly at the Loran-C transmitter site.

Eurofix is planned to enable a Europe-wide availability for precise and reliable navigation, which will be achieved in several steps. Presently, four stations are installed in Europe, where dynamic and static field tests are carried out.

3 Evaluation of Former Approaches

In this chapter, earlier approaches to overcome the positioning problems mentioned above and important concepts behind their use in connection with GPS are discussed and evaluated considering following criteria:

- **Accuracy**: precision of the calculated position
- **Availability**: world-wide disposability
- **Impact (Handset)**: necessary modifications concerning the mobile unit
- **Impact (Network**): required modifications in the underlying network
- **Needed Information**: cooperation demand; relation between available and necessary information provided by the operator (e.g. GSM)
- **Operating Compatibility**: functional compatibility with a wide range of underlying networks based on different technologies
- **Roaming Support**: ability of the system to function in other networks besides the home network
- **Technology-specific**: optional field, which describes aspects that only concern the currently examined method

The scale for the evaluation comprises four grades: excellent, good, moderate and poor.

3.1 Assisted GPS

Shaojun Feng and Choi Look Law [SHAO02] presented an approach, which uses GSM to support the integrity and accuracy of GPS. They focused on aspects valid for intelligent transportation systems (ITS). At first, the positioning method of dead reckoning was presented, by which a vehicle measures the distance to a reference object. This can be done by the use of different sensors (speed, distance, etc.) located at the vehicle. For obtaining accurate positioning, dead reckoning is often combined with GPS.

As already mentioned, Assisted GPS (A-GPS) is achieved by involving GSM communication, which is often available on board of vehicles. The basic system structure of A-GPS is illustrated in Figure 6.

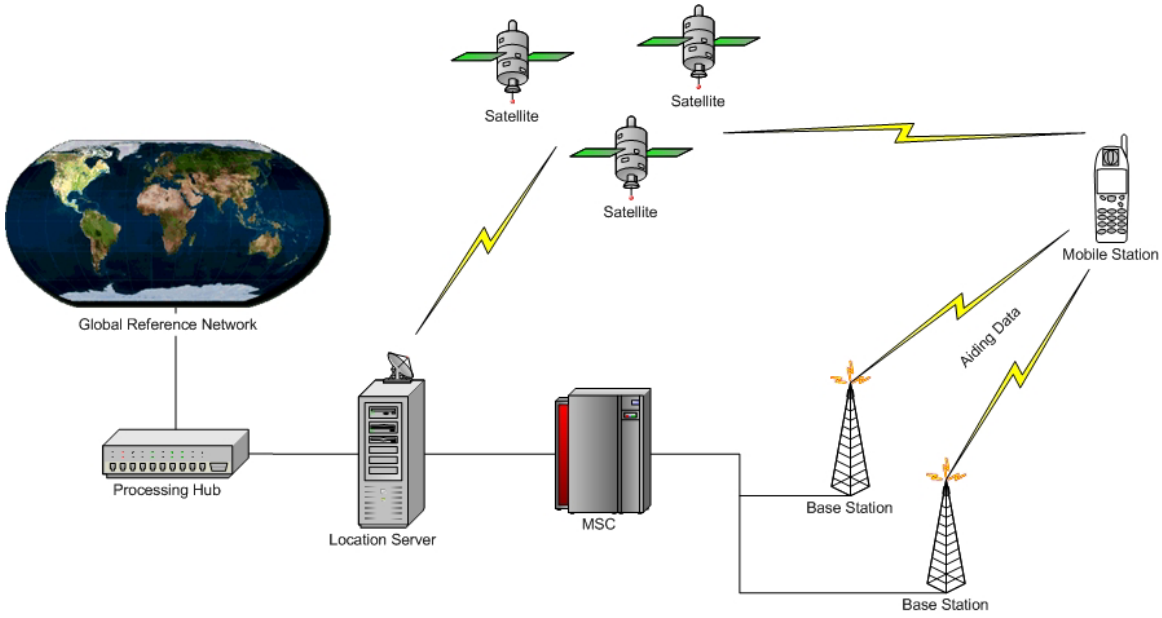

Figure 6: A-GPS System Structure.

The system consists of a location server (LS), a processing hub, a mobile station (MS) or a User Equipment (UE) with a GSM or a UMTS link. As it can be seen from Figure 6, the processing hub serves as connection to the global reference network. To make the system work properly, the MS and UE need to contain a built-in GPS receiver.

The key functionality of A-GPS is to provide the GPS receiver with additional positioning and GPS information via the GSM/UMTS link that is particularly helpful in areas of minor GPS signal availability. As mentioned in subsection 1.2, a short signal reacquisition time is essential in urban environments. The movements of the GPS satellites and the GPS receiver add a Doppler shift to the L1 frequency of 1.575,42 MHz, which means that a GPS receiver has to search over a frequency interval greater than ±4.2 kHz to find the satellite's GPS signals in the worst case. This interval and hence the signal reacquisition time can be reduced by a Doppler shift prediction transmitted via the GSM/UMTS channel, where the monitoring of satellites and frequency shift prediction are carried out by the location server mentioned above.

As described in [SNAP03], there are two different operational modes of A-GPS: the first is the MS/UE-assisted mode, where the mobile unit only calculates pseudoranges from satellite signals and sends the information back to the A-GPS LS, which then computes the position. The second is the MS/UE-based mode, in which the receiver itself calculates the position, which requires more assistance data and thus uses more network capacity and it has the remarkable disadvantage that an A-GPS circuitry is necessary in the handset. Furthermore, precise timing requirements have to be met to operate this system in a reliable way, which can

be achieved by a location server providing assistance timing data or by a synchronised network.

The location server method requires a global reference network of GPS receivers, which has already been implemented by several providers like Global Locate or SnapTrack. This network is responsible for continuously tracking the GPS satellites as well as sending the retrieved information to two redundant reference hubs, which then calculate the long-term orbits and are therefore capable to predict the satellites' clocks several days ahead. This timing data is then forwarded to the LSs, which can distribute the information in various formats. Currently, most implementations employ communication via SMS, which results in the considerable disadvantage that the sent data can only amount up to 140 bytes per SMS message. Consequently, the data has to be compressed and even then, three or four SMS messages have to be sent for transmitting one set of assistance data. In future applications, GPRS or UMTS could also be employed because of their high data rates of maximally 171,2 kbps and 384 kbps, respectively, which would eliminate the need for data compression and thus save time and computational resources. Nonetheless, UMTS does not seem to be too promising as plans exist in several countries to skip third generation (3G) applications and directly switch to fourth generation (4G) because of transition and license cost reasons.

The second mentioned method for establishing the relationship between GPS time and MS time uses a synchronised network, where the relationship can be established by the use of Location Measurement Units (LMUs) that causes additional costs because of the need of LMUs around the cellular network and additive signalling. Thus, the timing relationship can also be achieved without the use of LMUs by retrieving the time of the GPS data set via the handset.

The concluding statement concerning A-GPS is that it has enhanced functionality compared to GPS as the Time-to-first-fix (TTTF) is reduced from the maximum of two minutes to a few seconds and as it increases receiver sensitivity, which means that the handset can also perform positioning calculations although only a rather weak signal is provided. Furthermore, A-GPS has many advantages in comparison to other positioning techniques as far as the impact on the cellular network, roaming support, accuracy and compatibility with existing underlying networks are concerned, but it also suffers from the noteworthy inconvenience that existing handsets cannot be employed.

Table 3 shows a summarised version of the evaluation of A-GPS.

Criterion	Specification	Evaluation
Accuracy	Typically 5-50m	Excellent
Availability	Highly increased receiver sensibility	Excellent
Impact (Handset)	Special A-GPS circuitry required	Good
Impact (Network)	Reference Network necessary; no modifications in cellular network needed	Good
Needed Information	No cooperation necessary	Excellent
Operating Compatibility	Operates on GSM, GPRS and UMTS networks	Excellent
Roaming Support	A-GPS LS support in the roamed network required	Good
Technology-specific	Considerable decrease of TTFF	Excellent

Table 3: Evaluation Summary of A-GPS.

3.2 Indoor GPS

After having evaluated A-GPS, a very promising approach to enhance this system has to be described. The Indoor GPS system implemented by Global Locate Inc. combines A-GPS with parallel correlation in order to increase the maximum dwell time in each frequency bin for the GPS receiver.

In [DIGG02], van Diggelen states that the idea of developing such a system can be found in the required processing gain of 20 to 30 dB, which enables GPS signal acquisition indoors and in other harsh environments. Hence, the need for parallel correlation arises. In conventional GPS receivers, two correlators, which sequentially search the frequency bins, are employed. This chronological search method results in a short dwell time for each frequency, which again requires a strong signal that makes a receiver start-up only possible outdoors with a clear view of the sky. By employing A-GPS combined with parallel correlation, the dwell time for each frequency is increased in two ways, which directly raises the processing gain. The principle of parallel correlation is depicted in Figure 7.

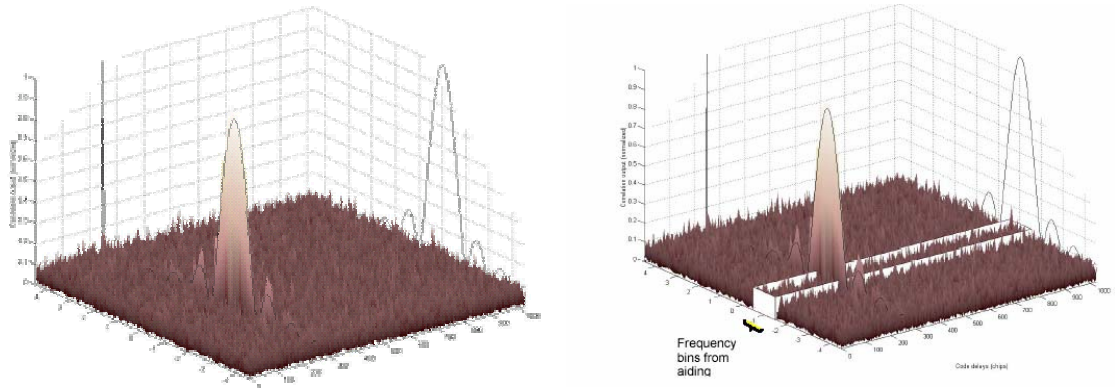

Figure 7: Reduction of Searched Frequency Bins by Parallel Correlation, with permission of Frank van Diggelen, Global Locate Inc., [DIGG01].

To implement Indoor GPS, two chips have to be added to a common cell phone: the first is the GL-HSRF, a high-sensitivity tuner chip, and the second is the GL-16000 chip, which is able to search the frequency bands in parallel. [DIGG02]

Finally, several tests in harsh environments like in urban areas, inside a moving steel trunk, in a parking lot or inside a shopping mall have been carried out. All the tests resulted in a remarkably satisfying reliability of the system. The carrying out and the outcomes of the tests can be found in [DIGG02] and in terms of a video presentation on the Global Locate homepage at [GLOB04].

A further similar approach, whose product presentation is given in [SIRF04], has been performed by SiRF Technology Inc., which uses massive parallel correlation together with GPS and A-GPS, respectively. Table 4 shows a technical comparison of the two technologies.

Characteristics	Global Locate Inc.	SiRF Technology Inc.
Name of Product	Hammerhead	SiRF starIII
Number of Correlators	>20.000 hardware correlators	>200.000 software correlators
Correlation Method	Massive parallel correlation	"Fast and deep GPS signal search capabilities"
Utilizable Signal Level	-158dBm	-159dBm
Time-to-first-fix	250ms	~1s
Unaided Mode Support	No information available	Yes

Table 4: Comparison Global Locate Inc. with SiRF Technology Inc.

As it can be seen from Table 4, the approach done by SiRF Technology Inc. uses more correlators in parallel, whereby the TTFF is shorter using the technology developed by Global Locate Inc.

To sum up, it can be stated that the Indoor GPS approach implemented by Global Locate Inc. as well as the technology developed by SiRF Technology Inc. seem to be very promising, but it has to be considered that their reliability has not been proven in practice yet, as the systems will only come onto the market during 2005. Table 5 summarises the evaluation of the Indoor GPS technology.

Criterion	Specification	Evaluation
Accuracy	Down to a few meters	Excellent
Availability	Available also in most harsh environments, where weak GPS signals are disposable	Excellent
Impact (Handset)	Two chips to be built in	Moderate
Impact (Network)	No modifications necessary	Excellent
Needed Information	No information needed	Excellent
Operating Compatibility	A-GPS operates on GSM, GPRS and UMTS networks	Excellent
Roaming Support	A-GPS LS support in the roamed network required	Good
Technology-specific	Only subjective results available via tests performed by the manufacturer	---

Table 5: Evaluation Summary of Indoor GPS.

3.3 GSM Localisation

Since the United States Federal Communications Commission (FCC) E-911 directed that 67% of all mobile phones initiating emergency calls have to be located within an accuracy of 50 meters and 95% of the mobile phones within an accuracy of 150 meters by October 2001, increasing interest in the subject of localisation techniques within the GSM network can be found. Similar requirements are about to be formulated by the E-112 initiative of the European Commission. It has to be mentioned that not only GSM positioning is considered in this context, but also the use of the GNSS as a separate solution for GSM handsets and a combination of GSM and GNSS positioning are taken into account.

There are a number of different localisation techniques applicable within radio networks. The most trivial one is the use of cell identification and simply requires knowledge about the exact position of the base station, which is serving the handset, and the base station's cell this handset is using. One of the main drawbacks of this approach is that its accuracy depends on the cell size, which can be large in less populated areas. Moreover this positioning method necessitates provider cooperation in order to get information about the base stations' coordinates.

A further possibility to find the position of a GSM handset is by measuring the signal strength followed by applying suitable algorithms to calculate the distance between one or more base stations and the handset.

3.3.1 Cell-Information Based Positioning

Since GSM is a cellular wireless network, information about the cell, in which a handset is currently served, can be used for its positioning, but its drawback is that the accuracy of this method strongly depends on the size of the cell. In order to allow higher positioning accuracy, this localisation technique can be enhanced by involving parameters such as Timing Advance (TA) and received signal strength (RXLEV), which are integrated in the present GSM specification. The result of all positioning methods is a confidence region, where the mobile handset is located with a certain confidence coefficient.

3.3.1.1 Pure Cell-ID

This kind of localisation is the simplest way of estimating the position of a mobile phone. Since each base station (BTS) serves only a limited area, information about the location of this base station is sufficient to estimate the approximate position of a mobile handset. Within the GSM standard, the identity of a base station is easily obtainable via the parameter Cell Identity (CI), which is also available at the handset.

If the base station is equipped with an omni-directional antenna, the confidence region of the handset is simply expressed referring to the coordinates of the serving base station, which requires a database containing the coordinates of all the possible base stations and their cell identities. In the case of having sector cells, the antenna azimuth can also be taken into consideration to further limit the estimated area. The principle of Cell-ID is depicted in Figure 8.

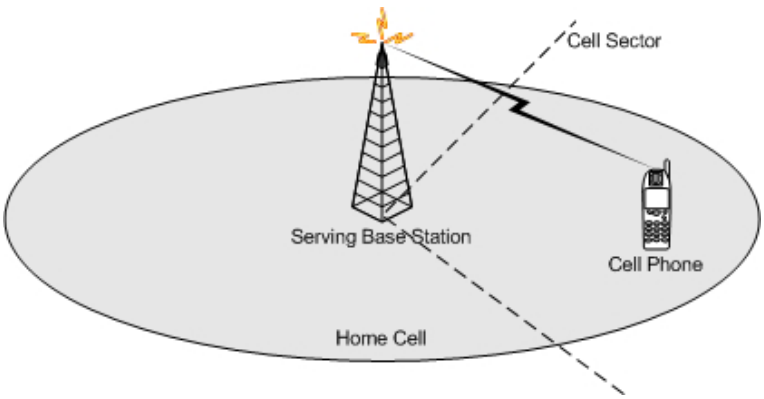

Figure 8: Localisation Using Cell Identity.

As illustrated in Figure 8, the cell phone is located in its home cell (grey-shadowed area). Knowing the coordinates of the serving base station allows estimating the area where the cell phone may be located. Further restrictions are made by information about cell sectors, whereby it has to be mentioned that this procedure does not work for base stations with omni-directional antennas.

The main advantage of location estimation based on the parameter CI is its simplicity in implementation, since it is already included in the current GSM standard and thus supported by present GSM infrastructure all over the world. Moreover, no time consuming calculations are necessary for performing the location estimation and Cell-ID is also applicable in cellular networks of the third generation, namely in UMTS and CDMA2000 networks.

A significant contrast to these benefits is that the accuracy of Cell-ID directly depends on the size of GSM cells, which may be rather large particularly in rural areas (approximately five to 20 km). Nevertheless, Cell-ID can be an alternative in densely populated urban areas, where micro- and picocells providing relatively small (approximately 500m) cell radii are often used. This is particularly valid if GSM localisation is used as a complement to GPS, which tends to have performance problems in such environments. Table 6 gives an overview about the performance characteristics of Cell-ID and an evaluation based on the fulfilment of the project requirements.

Criterion	Specification	Résumé
Accuracy	Depending on cell size, rural area: 5 to 20 km and densely populated urban area: up to 500m	Poor
Availability	Available in all GSM networks	Excellent
Impact (Handset)	No changes required	Excellent
Impact (Network)	No changes required	Excellent
Needed Information	Coordinates and CIs of serving base stations	Moderate
Operating Compatibility	Compatible to 3G cellular networks	Excellent
Roaming Support	Available in GSM networks worldwide	Excellent

Table 6: Evaluation Summary of Cell-ID.

3.3.1.2 Cell-ID and Timing Advance

As visible from Table 6, the main drawback of Cell-ID is its poor accuracy. One possibility to improve this accuracy is to involve the parameter Timing Advance (TA), which, like the CI, is integrated in the present GSM specification. Originally introduced to avoid overlapping bursts among several base stations, this integer number, which ranges from 0 to 63, can also be employed to estimate the distance between a mobile handset and the serving base station

[SPIR01]. If the distance between the handset and the serving base station is large, a high value will be assigned to TA and vice versa. Hence, TA is proportional to the distance of the handset. As already mentioned, a higher positioning accuracy is possible by combining the knowledge obtainable via TA with the Cell-ID method. Nevertheless the position resolution obtainable by involving the TA value is only about 554 meters and rather poor (see subsection 3.3.5.1). The resulting confidence area is either a ring or a ring segment when information about the cell sector is also used. Figure 9 clarifies the principle of GSM positioning by employing a combination of CI and TA.

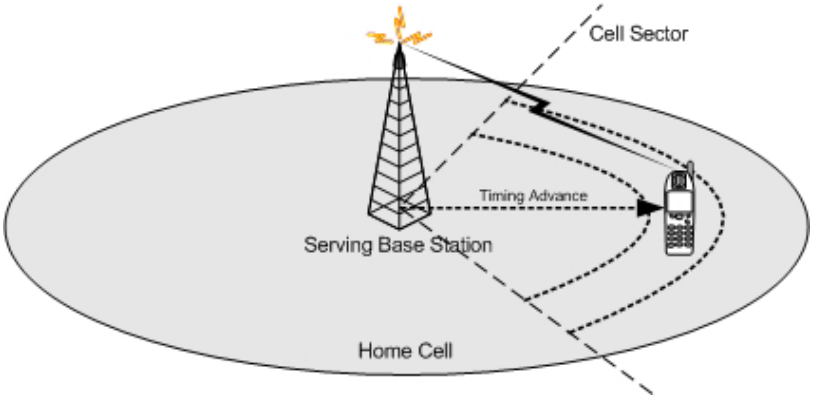

Figure 9: Positioning Based on Cell Identity and Timing Advance.

Figure 9 shows that the confidence area that is obtainable by the principle of Cell-ID combined with TA (dotted ring segment), without information about the cell sector the confidence area would be an entire ring within the home cell.

The performance characteristics of Cell-ID and TA are comparable with those provided by pure Cell-ID with the exception that it yields better accuracy. Like Cell-ID, TA is also included in the GSM standard with the restriction that the TA is only known within in the GSM network if the mobile handset is in active mode. If a cell phone is in idle mode, the parameter TA will not be transmitted to the network and thus only available at the handset. There are two possibilities to overcome this problem. The more straight-forward one is to employ a mobile phone that is capable to transmit the TA value also in idle mode. This can be realised by exchanging data via SMS or GPRS, which implies that software modifications at the handset are necessary. Transmitting the value of TA via SMS is for instance implemented in *Benefon Oyj's* cell phone named *Benefon ESC!* [BENE05].

A more sophisticated possibility to obtain the TA value also in a handset's idle mode is the forced handover method employed in Nokia's positioning solution called *mPosition*. Forced handover means that a mobile station (MS) is forced to attempt a handover from the serving

base station to a neighbour base station, which has the effect that the latter BTS measures the TA to the mobile handset and then rejects the handover. Thus, the TA values at two different base stations are known in the network and can be used for positioning purposes, by repeating this procedure more TA values can be obtained. The main advantage of the forced handover is the fact that it is supported by all legacy phones. Figure 10 shows the principle of employing Cell-ID combined with TA values from more than one base station for location estimation.

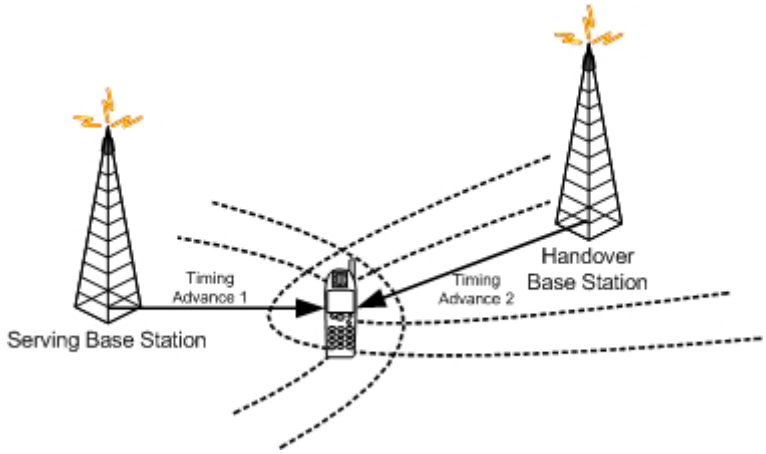

Figure 10: Principle of Forced Handover.

As presented in Figure 10, two ring segments are obtained by the use of two TA measurements. The confidence area can finally be found by intersecting these two segments. Two main drawbacks of measuring the TA values via a forced handover are its rather sophisticated technical implementation and the additional signalling traffic introduced into the network.

Table 7 summarises the performance characteristics obtainable by combining the information CI and TA.

Criterion	Specification	Résumé
Accuracy	Depending on cell size, but better than pure Cell-ID	Poor
Availability	Available in all GSM networks	Excellent
Impact (Handset)	Transmission of TA value also in idle mode is needed for network-based positioning	Good
Impact (Network)	Implementation of forced handover is needed in the case of network-based positioning	Good
Needed Information	Coordinates and CIs of serving base stations and their corresponding TA values	Moderate
Operating Compatibility	Same principle also applicable in 3G networks using the parameter RTT	Good
Roaming Support	Available in GSM networks worldwide	Excellent

Table 7: Evaluation Summary of Cell-ID and Timing Advance.

3.3.1.3 Cell-ID, Timing Advance and Signal Strength

Another possibility to improve the accuracy of the location estimation by taking into account Cell Identity and Timing Advance is referring to the parameter signal strength. According to the GSM specification, a handset measures the signal strength provided by up to six of the strongest neighbour cells. This information, which is exchanged via the messages *MEAS_RES* and MEAS_REP of the GSM protocol stack, is essential for the control of handovers. Data about signal strength can also be used to calculate the position of GSM phones. As a matter of fact, well-developed signal propagation models are needed for this computation so that currently received signal levels can be compared to predetermined propagation models. These models are constructed either to be valid only for a certain geographic area or as a more common cell-model. Due to hard predictable signal fading, multipath effects, lack of LOS-conditions, the employment of directional antennas and their corresponding antenna gain, the finding of suitable propagation models is not a trivial task. Nevertheless, GSM localisation on base of statistical models can be an effective possibility to achieve good positioning accuracy. Further information about former research work carried out in the field of GSM signal propagation models can be found in [WONG00], [ROOS02] and [KUNC04].

Figure 11 depicts the principle of involving Cell-ID, TA and signal levels into the location estimation.

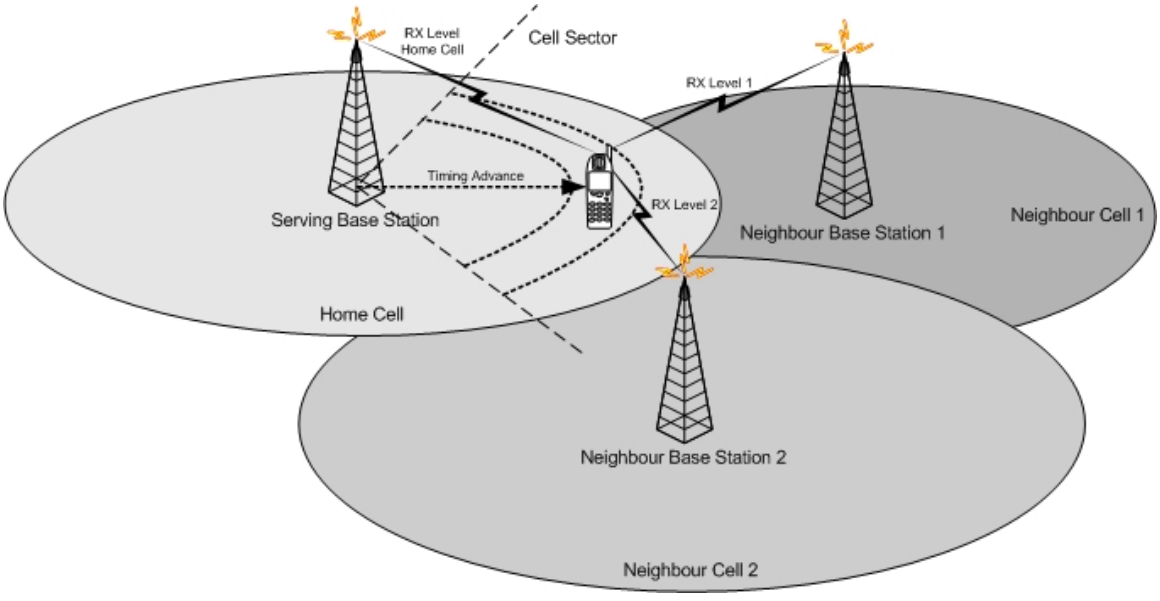

Figure 11: Localisation by referring to Cell Identity, Timing Advance and Signal Strength.

As visible in Figure 11, the mobile handset measures the signal strength of the serving base station and of two neighbour stations. Combined with the information CI and TA, these measurements are used to decrease the confidence area.

One main advantage of involving signal strength into the positioning process is that the relevant measurements are already included in the GSM specification. Hence, changes in the current network are not necessary. Nevertheless, the computation of suitable propagation models and the location estimation itself can be rather demanding for handset-processors and is thus not suitable for mobile based positioning. Thus, the necessary calculations should be performed by any kind of location server with defined communication interfaces to the mobile handset. The method in question is also applicable in 3G networks, where the parameters TA and RXLEV are replaced by the parameters RTT and Received Signal Code Power (RSCP). Table 8 summarises the performance characteristics of GSM positioning based on CI, TA and RXLEV.

Criterion	Specification	Résumé
Accuracy	Depending on cell size and employed propagation model, but better than pure cell-ID and Cell-ID combined with TA	Moderate
Availability	Available in all GSM networks	Excellent
Impact (Handset)	RXLEV and TA available at the handset, but transmission of TA value also in idle mode is needed for network-based positioning	Good
Impact (Network)	No modifications necessary if only TA of home cell is used, eventually forced handover is necessary; computations have to be performed by a location server	Moderate
Needed Information	Coordinates and CIs of serving base stations, their corresponding TA values and suitable propagation models	Moderate
Operating Compatibility	Same principle also applicable in 3G networks using the parameters RTT and RSCP	Good
Roaming Support	Available in GSM networks worldwide	Excellent
Technology-specific	Accuracy depends on the quality of employed propagation models	Moderate

Table 8: Evaluation Summary of Cell-ID combined with TA and RXLEV.

The three cell information-based methods explained above were tested and evaluated in a real-world experiment within a project carried out by the Estonian GSM-provider Radiolinja in cooperation with Nokia, which is described in [SPIR01]. Four laptops, which were situated in a moving car, were used to perform GSM location estimation. The location computation was performed by a location server, which was connected via a GSM connection with the equipment placed in the car. At each time, a GSM location request was sent from the laptops to the location server, the exact GPS positions were also saved in order to obtain reference points for later comparison and evaluation, respectively. The tests were carried out in the city centre of Tallinn, Estonia and in a suburban area of the same region. Table 9 illustrates the corresponding scenario as it is presented in [SPIR01].

Type of Area	Number of Samples	Number of Serving Cells	Number of Neighbour Cells
City Centre	76009	44	76
Suburban Area	102269	46	83

Table 9: Evaluation Summary of Cell-ID combined with TA and RXLEV.

Table 9 shows that 76.009 and 102.269 location measurements were performed in urban and suburban areas, respectively. The corresponding data were recorded in several measurement reports, where one measurement report contains the information about CI, TA and RXLEV of the serving cell as well as the RXLEV values for each of the strongest neighbour cells. As Spirito and Pöykkö stated in [SPIR01], these measurement reports were post-processed according to the three cell information-based location methods described in this section of the thesis. Spirito and Pöykkö showed that GSM localisation based on a combination of CI, TA and RXLEV reached a better accuracy than the other two positioning methods in urban environments. Moreover, there were hardly any performance differences between the positioning using CI and TA (CI+TA) and the localisation estimation involving CI, TA and RXLEV (CI+TA+RXLEV) in suburban environments. Nevertheless, both methods were more accurate than pure Cell-ID in all areas. Another important detail presented in [SPIR01] is the fact that increasing values of TA degrade the accuracy of pure Cell-ID and CI+TA. The degradation of CI+TA+RLEV's accuracy is significantly smaller than that of the other two methods. Furthermore, the accuracy of the location estimation was improving with an increasing number of neighbour base stations. The results presented by Spirito and Pöykkö suggest that CI+TA+RXLEV can be used in densely populated areas, where its accuracy is relatively high due to small cell sizes in urban areas. This statement is particularly valid considering that GPS positioning shows performance problems in such environments. Thus, CI+TA+RLEV can be used as a backup positioning method providing less accuracy, but higher availability than GPS. Table 10 shows the accuracy in meters achieved within Spirito's and Pöykkö's real world experiment, which was also presented in [CELL01, p.23]. The accuracy is divided into three categories (represented in the third, fourth and fifth column of Table 10), namely 50, 67 and 95 percent, which means that for example the positioning method CI provided an accuracy of at least 603 meters in 95% of all position estimates in urban areas, while CI+TA+RXLEV reached an accuracy of at least 429 meters in 95% of the location estimates in the same type of area. Within this context, accuracy means the location error compared to the saved GPS positions.

Positioning Method	Type of Area	50%	67%	95%
CI	Urban	240 m	328 m	603 m
	Suburban	482 m	639 m	1345 m
CI+TA	Urban	207 m	283 m	554 m
	Suburban	319 m	415 m	844 m
CI+TA+RXLEV	Urban	158 m	207 m	429 m
	Suburban	307 m	448 m	917 m

Table 10: Results of Real World Experiment Carried Out by Radiolinja and Nokia.

As visible in the second, fourth and sixth line of Table 10, CI+TA+RXLEV performed best in urban areas, where it offered the least positioning error for all three categories of accuracy compared to CI and CI+TA. In contrast to that the performance differences of CI+TA and CI+TA+RXLEV were small in suburban environments (see fifth and seventh line).

3.3.2 AOA

The positioning method Angle of Arrival (AOA) means measuring the angle of incidence of the mobile station's signals at more than one base station. In case of two-dimensional positioning, two base stations are sufficient for location estimation, but the accuracy of AOA is the higher the more base stations are involved in the measurements. Figure 12 shows the principle of AOA.

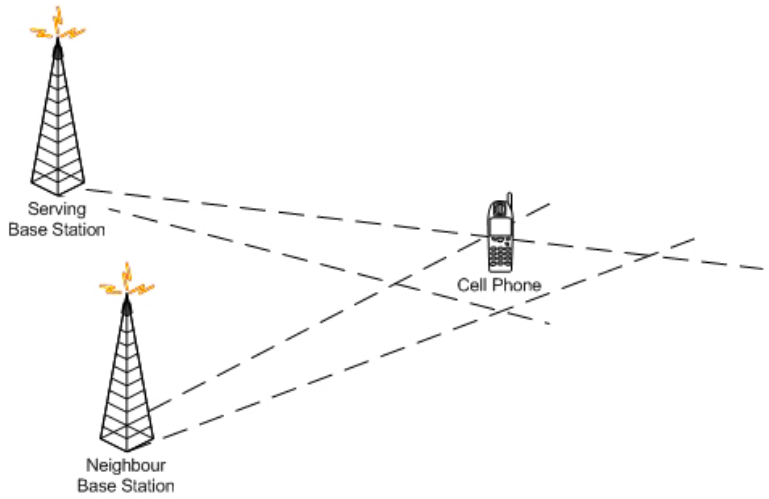

Figure 12: Principle of Positioning Based on Angle of Arrival.

Figure 12 illustrates that AOA measurements result in lines from the MS to the base stations, and that the position of the cell phone can be estimated by intersecting these lines. The accuracy of AOA degrades as the distance between the MS and the involved base stations increases. Using AOA for location estimation is hardly applicable for the purposes of this project, because it has some major disadvantages. First of all, AOA requires line-of-sight

propagation in order to obtain accurate results. This presumption is particularly critical in densely populated area, where LOS cannot be assumed due to shading caused by high buildings. This problem is even graver if one takes into account that LOS to more than one base station is necessary. A further main problem of AOA is that all involved base stations must be equipped with antenna arrays to be able to perform AOA measurements, which is specifically valid for GSM, where BTSs are not equipped with such arrays and realising AOA would introduce very high implementation costs. If AOA should be employed for a high number of mobile stations, capacity problems must also be considered since multiple and simultaneous measurements at several base stations are needed. In contrast to this, an advantage of the AOA positioning method is that all current GSM users can be served without the need of new mobile handsets. Table 11 summarises the performance characteristics of AOA.

Criterion	Specification	Résumé
Accuracy	Depending on the mobile station's distance and the number of involved base stations. Urban area 300 m with two BTSs and 200 m with three BTSs	Moderate
Availability	Not available in GSM networks without modification of the employed BTSs, LOS required	Poor
Impact (Handset)	No changes required	Excellent
Impact (Network)	Antenna arrays required	Poor
Needed Information	Coordinates serving base stations, measurements of the angle of incidence	Moderate
Operating Compatibility	Compatible to 3G cellular networks if antenna arrays are available also in the 3G network	Moderate
Roaming Support	Available only in AOA-capable GSM networks	Poor

Table 11: Evaluation Summary of AOA.

Table 11 shows that AOA is hardly suitable to solve the problems of this project, since it shows poor availability in urban areas where LOS cannot be assumed. Furthermore, the according implementation costs would be too high for a world-wide application.

3.3.3 Time of Arrival

Time of Arrival (TOA) means measuring the time interval, which is needed by a GSM signal to propagate from a BTS to the MS or vice versa. The according measurements can be done either at the MS (downlink TOA) or at the BTS (uplink TOA). TOA is based on the assumption that this time interval is proportional to the distance between a MS and a BTS. Thus, taking into account the measured time interval allows a proper estimation of this distance. In the case of two dimensional positioning, three base stations have to be involved in

the TOA measurements. As a matter of fact, TOA can only be realised in perfectly synchronised networks. Figure 13 shows the principle of TOA in such networks.

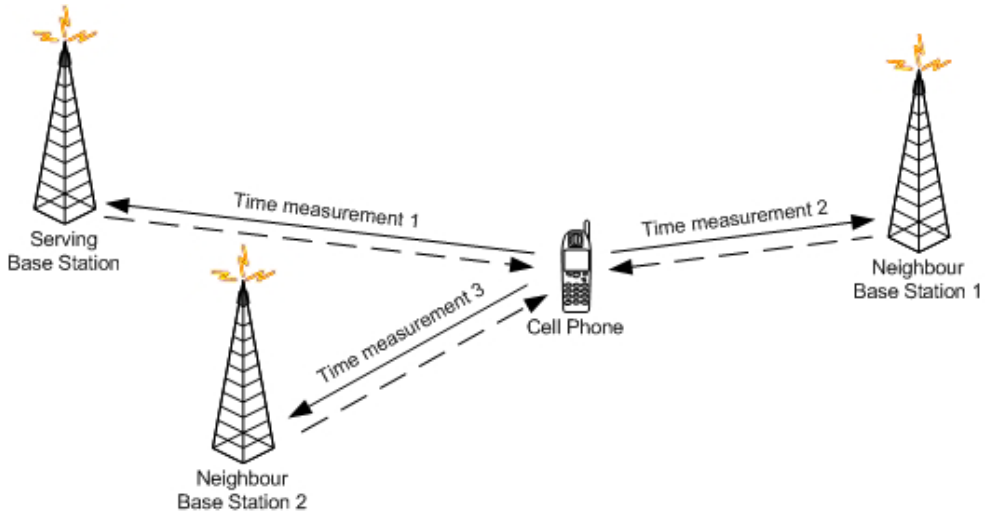

Figure 13: Positioning Principle of TOA.

According to Figure 13, the three time intervals, on which 2D-location estimation is based, are either measured by the handset (dotted arrows) or by the network (solid arrows). As already mentioned, pure TOA only works in synchronised networks. Hence, TOA can only be realised in a differential manner in GSM or 3G networks. This leads directly, without any further evaluation to the location principles based on time differences, which are explained in the next subsection of this thesis.

3.3.4 Uplink Time Difference of Arrival

Uplink Time Difference of Arrival (Uplink TDOA) means that not absolute time values, but differences between the arrival times are measured at several base stations by the network. Hence, a time difference hyperbola, on which a mobile handset can be located, is built referring to one pair of base stations. By intersecting two such hyperbolae (requiring measurements from at least three different base stations) the position of the MS can be estimated. Since TDOA requires very precise timing, a common time-reference is needed. In practice, TDOA may be realised by employing GSM base stations, which are equipped with a Location Measurement Unit (LMU). Every LMU can measure the propagation time of the handset's signal and refers it to a time reference such as the one provided by GPS.

Once a location request is sent from an application server to the network via the Mobile Location Centre (MLC), the serving base station controller forces the handset to perform a handover, which was already explained in subsection 3.3.1.2 of this paper. The forced handover results in a mobile handset transmitting up to seventy access burst at full power in a

known frequency and timeslot combination [LOPE99]. While forcing a handover, the Base Station Controller (BSC) also provides information about the access bursts to a suitable number of LMUs. Thus, these LMUs are able to process the received bursts using knowledge about the GSM training sequences and to measure the time of arrival in relation to GPS time. Next, the resulting measurement values are sent back to the MLC, which processes the corresponding values and finally sends the handset's coordinates to the application server. The communication between the BSC, the LMUs and the MLC occurs via the GSM infrastructure. Figure 14 shows the principle of Uplink TDOA and important parts of the required infrastructure.

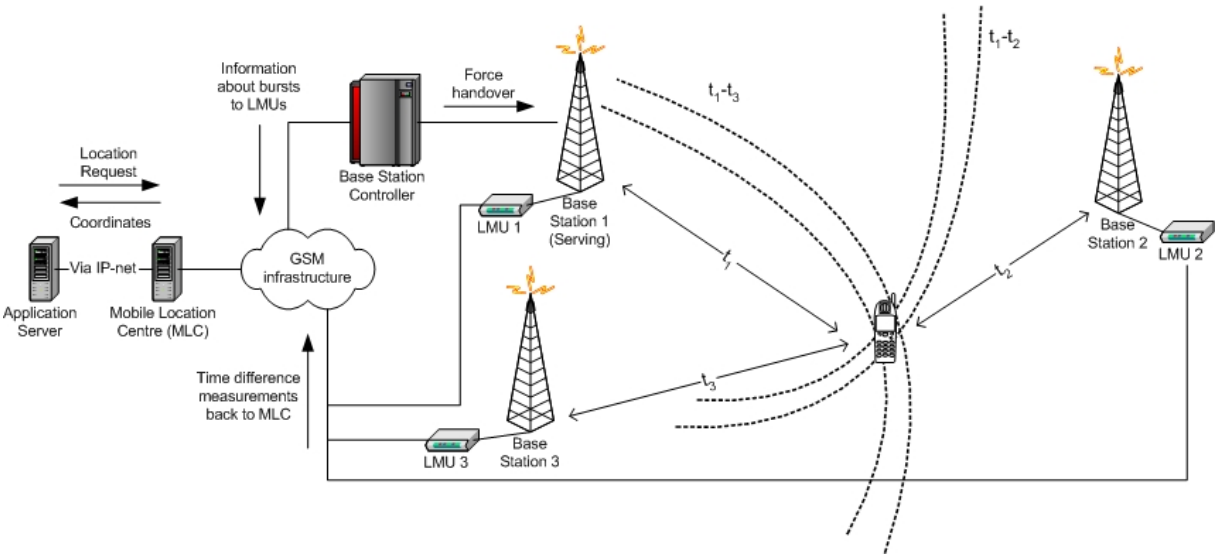

Figure 14: Principle of Uplink Time Difference of Arrival.

As depicted in Figure 14, the time difference measurements result in two hyperbolae with a certain margin of error (dotted lines). By intersecting the resulting lines the confidence area can be found. It must be noted that the base stations involved into the time difference measurements are not necessarily the neighbour base stations of the handset, but any base stations visible and thus available for the time measurements. The more base stations are involved into the location estimation the better is the resulting positioning accuracy. Information about mathematical issues concerning TDOA can be found in section 3.3.5.1 of this paper.

One advantage of this method compared to those based on cell information is its improved accuracy. As a matter of fact, TDOA requires significant changes in the GSM infrastructure (LMUs required at the BSs) having the consequence that its roaming support is very poor in a world-wide application scenario. Furthermore, it shows performance problems in rural areas, where visibility of at least three base station is not guaranteed. Moreover, the positioning

accuracy depends strongly on the geometric arrangement of the base stations. This problem of Geometric Dilution of Precision (GDOP) is already known from GPS and means that measurements of base stations arranged in a straight line (as for example along highways) can lead to ambiguous results. An optimal arrangement in this context consists of base stations evenly distributed around a mobile handset. Furthermore, TDOA suffers from performance problems in urban areas, since its accuracy is significantly worsened by none-LOS conditions and multipath effects. As stated in [SILV96], the accuracy can be improved by detecting and correcting multipath signals.

Criterion	Specification	Résumé
Accuracy	Between 50m and 400m, depending on GDOP and environment	Good to moderate
Availability	At least three BTSs required, hence poor in rural areas, better in densely populated areas.	Moderate
Impact (Handset)	No changes required	Excellent
Impact (Network)	Additional infrastructure (LMUs) and signalling required	Poor
Needed Information	Measurements guaranteed by the additional infrastructure	Good
Operating Compatibility	Principle valid for GSM as well as UMTS, some infrastructure might be required as emerging to UMTS	Good
Roaming Support	An Uplink TDOA-enabled GSM network has to be available	Poor
Technology-specific	Required signalling uses additional bandwidth of the GSM infrastructure	Poor

Table 12: Evaluation Summary of Uplink TDOA.

As visible in Table 12, the main drawback of Uplink TDOA are its high implementation costs caused by significant infrastructure changes. This is even more critical in a world-wide application scenario where all GSM providers must be able to offer an Uplink TDOA-capable infrastructure. Nevertheless, Uplink TDOA might be an alternative in urban areas where the GPS signal is prone to be blocked. Such a scenario would have the restriction that TDOA could be realised only in cities of great economic interest due to the required high implementation efforts.

3.3.5 Downlink Time Difference of Arrival

Positioning methods following the principle of Downlink Time Difference of Arrival (Downlink TDOA) are the counterpart to Uplink TDOA with the difference that time measurements are performed by the mobile handset and not by several base stations. Its implementation in GSM is called Enhanced Observed Time Difference (E-OTD) while the UMTS variant is named Observed Time Difference of Arrival (OTDOA).

In general, a mobile handset measures the time differences among signals sent by several base stations. Due to the fact that these signals are usually sent via control channels, the corresponding measurements can be performed by a handset in dedicated as well as in idle mode. As Uplink TDOA, also its downlink version requires a known time reference if the employed network is unsynchronised. Concerning the performance characteristics, there are large similarities between Uplink and Downlink TDOA, too. This means that the accuracy of Downlink TDOA is also degraded significantly by missing LOS-conditions in urban areas. The mathematical principle of positioning based on time differences is explained in the next subsection, where the concrete implementation of TDOA in GSM, namely E-OTD is presented. Even if the time difference measurements are carried out by the handset, the positioning calculation can be performed either by a location server situated in the communication network (MS-assisted) or by the handset itself (MS-based).

3.3.5.1 Enhanced Observed Time Difference

E-OTD and OTDOA are hyperbolic location estimation techniques. The measurements of the time differences are based on the three parameters real time difference (RTD), observed time difference (OTD) and geometric time difference (GTD).

As stated in [SPIR00], RTD means the synchronisation difference between the TDMA frames of two GSM base stations. Thus, this difference depends on the employed network configuration and totally independent on the handset's position. If a base station sends a burst at time t_a and a second base station does the same at time t_b, the resulting RTD value between them will be t_b-t_a. Besides, RTD would be zero in the unreal case of a synchronised GSM network.

The time difference between the bursts of two base stations, which is observed at the handset, is called OTD. Consequently, OTD is dependent on the distance between the base stations and the handset. Assuming that the signal of base station one is received at time t_1 and the signal of base station two at time t_2, OTD is t_2-t_1.

The third parameter GTD finally means the absolute propagation delay between two different bursts sent by two different base stations. Hence, the value of RTD has to be subtracted from OTD in order to obtain this absolute delay:

$$GTD = OTD - RTD$$

The variable GTD can also be expressed by the formula below with d_1 and d_2 being the distance from the handset to two different base stations and c being the speed of light:

$$GTD = \frac{d_2 - d_1}{c}$$

The formula mentioned above clarifies the principle of employing a reference receiver in unsynchronised networks, since GTD can be determined by knowing the exact position of the handset and thus knowing the values of d_1 and d_2. At such a reference receiver, only the value of OTD has to be measured in order to obtain the current value for the real time difference. Knowing GTD and OTD the real time difference can easily be calculated:

$$RTD = OTD - GTD$$

This value of RTD can then be used for the location estimation of handsets at unknown positions. Employing a reference receiver according to the principle just mentioned is much more cost effective than implementing synchronised GSM base stations.

As already shown in Figure 14, the position estimation based on observed time differences is carried out by intersecting hyperbolae. Hyperbolae are obtained by constant values of GTD. The following illustration shows this intersection together with the employed variables and formulae.

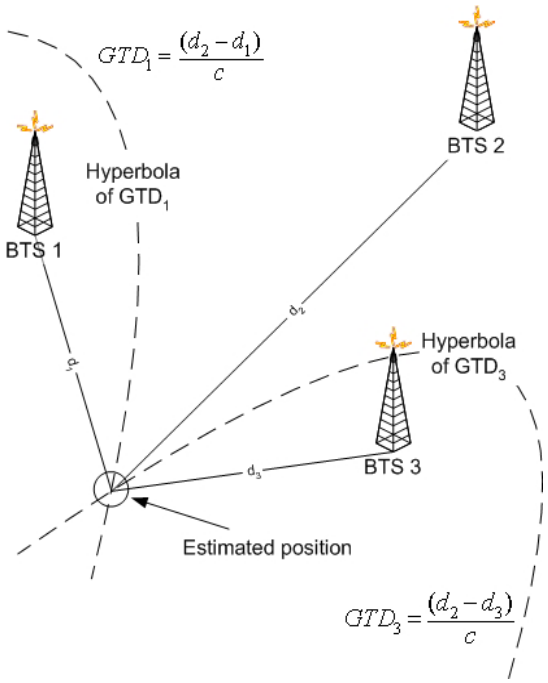

Figure 15: Intersection of Hyperbolae within E-OTD.

As shown in Figure 15, the two dotted hyperbolae established referring to the formulae for GTD_1 and GTD_3 just have to be intersected in order to perform location estimation. Another aspect clarified by the illustration above is the fact that at least three base stations are required for two-dimensional positioning. In case of having only two base stations, some additional information has to be involved into the location computation. An approach in this context is

presented by Spirito in [SPIR00], who suggests including TA values and CI in the positioning computation if only one TDOA-hyperbola is available. Furthermore, valuable information about the geometric definition of a home cell in consideration of antenna azimuth can be found in [SPIR00].

As already mentioned, the time differences are measured at the handset within Downlink TDOA. Referring to the bit period of GSM (T_{GSM} = 3,69 microseconds), this means that the positioning resolution P_R is about 554 meters. The formula introduced below shows the calculation of this resolution:

$$P_R = c \cdot \frac{T_{GSM}}{2} = 3 \cdot 10^8 m/s \cdot \frac{3.69 \cdot 10^{-6} m}{2} \simeq 554m$$

However, this resolution has to be enhanced (that is why the method is called Enhanced-OTD) in order to obtain proper accuracy. As stated in [CELL01], this can be done by oversampling of i.e. four times the chip rate. According to the formula above, this improves the positioning resolution to 277 meters, which shows that oversampling is obligatory for reaching a high positioning resolution. Spirito mentions in [SPIR00] that GTD values can be represented at a bit rate up to $T_{GSM}/256$ reaching a positioning resolution of four meters.

Referring to [LOPE99], a positioning request sent to a mobile handset capable of E-OTD may also contain relevant assistance data as i.e. frequencies to be scanned and offsets between several multiframes on the GSM broadcast control channel (BCCH). After that, the handset is able to scan frames sent by several base stations via the BCCH and estimate the time difference involving information about RTD delivered by several LMUs installed at known positions within the GSM infrastructure. The number of LMUs depends on network topology, redundancy aspects and striven installation costs. As mentioned in [LOPE99], the ratio of base stations to LMUs can approximately be between one and five in order to guarantee E-OTD positioning.

As Uplink TDOA, also E-OTD requires significant changes in the GSM infrastructure. Again LMUs and additional signalling must be realised to perform the time difference measurements and to transmit them via the GSM infrastructure, but in contrast to Uplink TDOA, also the mobile handset's software has to be modified.

Benefits of this positioning method are its improved accuracy compared to cell-based positioning, its high availability in densely populated areas and the fact that once a mobile handset is capable of E-OTD, it can perform the corresponding time difference measurements in dedicated as well as in idle mode. According to [MART02], E-OTD provides an accuracy

of 50 to 400 meters with an availability of 70% and 90% in rural and urban areas, respectively. Table 13 summarises the evaluation of E-OTD.

Criterion	Specification	Résumé
Accuracy	Between 50m and 400m, depending on GDOP and environment	Good to moderate
Availability	At least three BTSs required, hence poor in rural areas, better in densely populated areas.	Moderate
Impact (Handset)	Software-update required	Moderate
Impact (Network)	Additional infrastructure (LMUs) and signalling required	Poor
Needed Information	Measurements guaranteed by the additional infrastructure	Good
Operating Compatibility	Designed for GSM, analogue to OTDOA in UMTS	Good
Roaming Support	An E-OTD-enabled GSM network has to be available	Poor
Technology-specific	Required signalling uses additional bandwidth of the GSM infrastructure	Poor

Table 13: Evaluation Summary of E-OTD.

As visible in the fifth and ninth line of Table 13 the main drawback of E-OTD is the costly demand of additional infrastructure and signalling, so that it has to be stated that this positioning method is not feasible in a world-wide application because of its high implementation costs and its poor roaming support. Nevertheless, E-OTD could be used as a selective alternative to GPS in densely populated urban areas where many base stations are available. Even if the accuracy of E-OTD is prone to be degraded by multipath effects in such an environment the location estimation can be sufficiently accurate due to the fact that involving a high number of base stations in the time difference measurements improves the positioning precision.

3.3.5.2 Observed Time Difference of Arrival

As already mentioned in subsection 3.3.5.1, OTDOA is the implementation of Downlink TDOA in UMTS. Like E-OTD, it is based on measuring the arrival differences of downlink signals originating from several base stations. There are two different modes of OTDOA, the first is the UE-based mode and means that the location estimation is calculated directly at the handset. In the UE-assisted mode, the UE only measures the arrival time differences and forwards them to the Radio Network Controller (RNC) where the location estimation is computed. The latter mode including the RNC is part of the UMTS specification and thus available at all UMTS handsets.

A significant feature of UMTS is that it offers two different multiplexing modes. The first one is called UMTS Terrestrial Radio Access Time Division Duplex (UTRA TDD) and

guarantees synchronisation among the employed base stations providing the essential benefit that RTD need not to be measured in this synchronised mode. In contrast to that, the second UMTS-mode UTRA Frequency Division Duplex (UTRA FDD) is operated asynchronously. In that case, OTDOA requires precise determination of RTD values, which is carried out by several LMUs. According to [PORC01], UTRA FDD is the UMTS mode operated all over Europe. Hence, the assumption that only synchronised base stations can be used for OTDOA measurements within a world-wide tracking application does not hold. In contrast, LMUs will become necessary also for the UMTS-version of Downlink TDOA.

Due to its high chip rate of 3,84Mcps per second, UMTS provides a better positioning resolution than GSM. Without oversampling, a resolution of 78 meters is possible. As stated in [CELL01], this resolution can even be improved to about 19,5 meters by sampling at a rate of 4·3,84Mcps.

In order to compensate for the near-far problem, a UE near to its serving base station does not listen to neighbouring base stations in order not to jam signals from other handsets booked in neighbour cells. The near-far problem arises when a base station communicating with a near and a far mobile station simultaneously may encounter problems when listening to the distant handset because its signal is jammed by the strong signal of the near mobile. This causes the hearability problem and is critical since OTDOA requires signal measurements from at least three different base stations in order to perform two-dimensional positioning. A solution to this problem is the Idle Period on the Downlink (IPDL), which guarantees that the serving base station provides certain inactive periods. Within these periods, mobile handsets are requested to perform time difference measurements involving also the neighbour stations. Idle periods are typically short and organised in pseudorandom way. Even if idle periods in the downlink are standardised, their support at the UE is optional.

An enhancement of IPDL is its time-aligned version. This means that a common idle period among several base stations is created. Within this common idle period, every base station will either be inactive (70% of the period) or transmit a common signal (30% of the period). As a result, the base station interference is decreased and the positioning accuracy is improved since the mobile handsets can involve a higher number of base stations in their TDOA measurements.

A second problem of OTDOA is fast fading, which means that multipath effects cause abrupt variation of the received signal levels (reflected signal arrives more than one time with different signal strengths). Hence, measuring the time of arrival is sophisticated particularly in

urban environments. As a matter of fact, suitable multipath rejection algorithms have to be applied in order to compensate for this effect.

The major disadvantages of OTDOA are quite similar to those of E-OTD. Also OTDOA requires additional infrastructure like LMUs and extra signalling. Furthermore, requiring at least three base stations for two-dimensional positioning is critical in rural areas. Due to the hearability problem further complexity is added to the OTDOA method.

One major benefit of OTDOA is the fact that its UE-assisted mode is supported by all mobile stations without any further modification. Moreover, the accuracy is better compared to other GSM localisation methods. According to [PORC01], its accuracy is about 70 meters for 67% of the location estimations in urban areas with three visible base stations. In suburban and rural areas, the accuracy is even better, namely 20 meters for 67% of the positioning estimations. Table 14 shows the performance characteristics of OTDOA.

Criterion	Specification	Résumé
Accuracy	Between 20m and 400m, depending on GDOP and environment	Good to Moderate
Availability	At least three BTSs required, hence poor in rural areas better in densely populated areas. Hearability problem has to be solved.	Moderate
Impact (Handset)	UE-assisted mode supported by the handsets, modification necessary for UE-based mode	Moderate
Impact (Network)	Additional infrastructure (LMUs) and signalling required	Poor
Needed Information	Measurements guaranteed by the additional infrastructure	Good
Operating Compatibility	Implementation in up-to-date communication network	Excellent
Roaming Support	Additional infrastructure and signalling must be available in the roamed-to-network	Poor

Table 14: Evaluation Summary of OTDOA.

Looking at Table 14, it is observable that the performance characteristics of OTDOA can be compared to those of E-OTD. Thus, also OTDOA can be used as a selective alternative to GPS in densely populated areas but yielding a higher accuracy than the E-OTD method. Nevertheless, it has to be stated that E-OTD cannot be used as the only positioning technology in a world-wide tracking application, because every base station involved in the time difference measurements must be observed by at least one LMU due to the fact that GSM networks are not synchronised. Hence, the installation of LMUs all over the world would introduce too high implementation costs.

3.4 Combining GSM and GPS

Kan et al. [KAN03] recently presented a localisation method based on GPS and GSM. This method was developed to compensate for the loss of the GPS signal in urban canyons. In case of blocked GPS signals, the system is able to switch automatically to GSM localisation and choose the GSM positioning method, which is currently most accurate. The three positioning methods presented, namely weighted centre of gravity, circular trilateration and maximum likelihood methods, are all based on measurements of the GSM signal strength. Using signal attenuation helps to avoid the time synchronisation overhead within the involved base stations and handsets. The key functionality of the system presented is a calibration of the base stations. This means that the three positioning methods just mentioned are evaluated in periods where the GPS signal is available. For the maximum likelihood method that is done by measuring the distance and the signal strength of reachable base stations. Working a sufficient amount of time, regression lines for each base station can be built by the suggested algorithm.

As stated by Kan et al. [KAN03], choosing the right GSM positioning algorithm is not trivial. Within their approach, GPS is used as long as its signal is available. Moreover, a database containing the information, which GSM localisation method currently is the most accurate, is permanently updated. If the GPS signal is lost, the database is queried and the recently most accurate GSM positioning method is used. Kan et al. also presented an experiment performed with the use of a mobile phone, a personal digital assistant and a GPS receiver. They found out that the maximum likelihood method tends to perform better than the weighted centre of gravity and circular trilateration method. During their experiments in the urban centre of Hong Kong, the GPS signal was not available for more than 40% of the time. Nevertheless, the route driven could be estimated by the use of their dual channel system. This estimation became more accurate after averaging the obtained results (see Figure 16 and Figure 17).

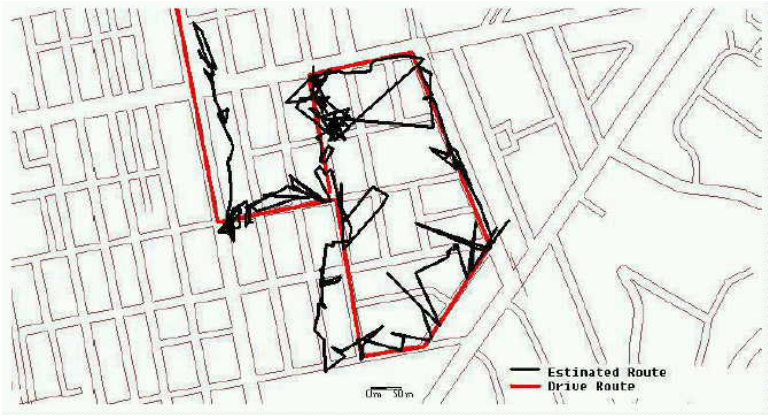

Figure 16: Dual Channel Route Estimation without Averaging, [KAN03] © 2003 IEEE.

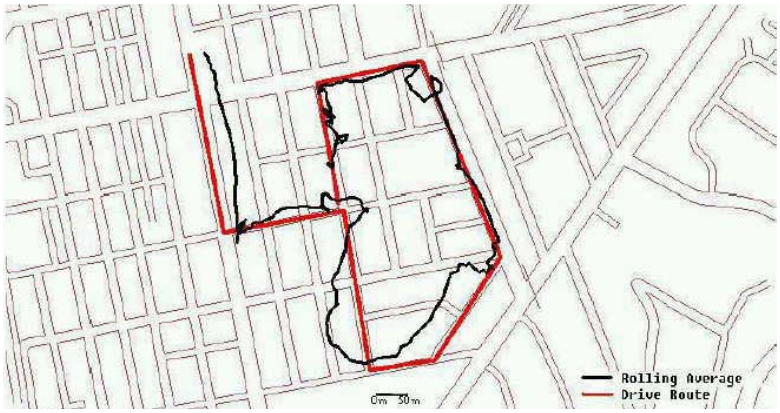

Figure 17: Dual Channel Route Estimation with Averaging, [KAN03] © 2003 IEEE.

Figure 16 and Figure 17show the results of the real world experiment presented in [KAN03], where the red (bright) line symbolises the real route driven, while the black route was obtained via using the dual-channel system introduced within [KAN03]. As visible from the figures, the resulting route is more accurate after having post-processed the obtained results. Nevertheless, an average accuracy between 40 and 57 meters was achieved. This relatively high precision results from the fact that there are usually many base stations in highly populated areas.

3.5 UMTS Localisation

Recent research in the field of positioning technologies is of course not only focused on GSM, but also on the third generation of mobile communication called Universal Mobile Telecommunications System (UMTS). Generally speaking, the localisation principles described in subchapter 3.3 are also valid for UMTS. In [PAGÉ02], Pagés-Zamora and Vidal presented an approach of combining the methods TOA, TDOA and AOA for UMTS localisation. The benefit of this concept is that the positioning accuracy increases without increasing the number of base stations.

Another research on UMTS and GPS was carried out by Heinrichs and presented in [HEIN02a]. Heinrichs sought initial answers to the question whether GPS and UMTS can be combined cost-effectively in one receiver, which seems to be feasible since there are similarities between the GPS and UMTS signal structures. The most important feature in this context is that both systems use the direct sequence - code division multiple access (DS-CDMA) spread-spectrum technology, which indicates that some receiver components can be shared for the reception of the UMTS as well as the GPS signal. Heinrichs presented his idea referring to the example of the RAKE receiver architecture and described a modification of this RAKE receiver in order to minimise multipath errors.

3.6 Database Comparison

In [LAIT01b], Laitinen et al. present a pattern matching location method is, which was motivated by the practically unrealistic LOS prerequisite in many location techniques such as AOA, TOA or TDOA, as already described above. The technology described in this subchapter is based on a database of signal information parameters, which are measured by a mobile station and compared with current measurements of these parameters. Figure 18 illustrates the system architecture applied on a GSM network although it can also be used in UMTS or GPRS networks.

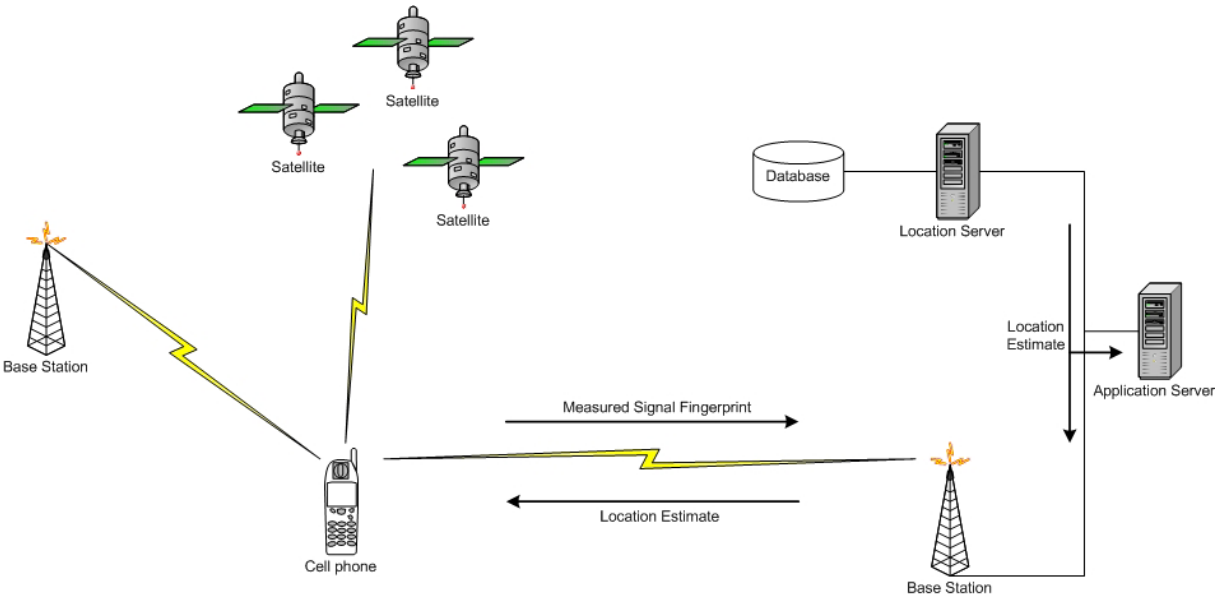

Figure 18: Main Architecture of the Database Comparison System Applied on a GSM Network.

According to [NYPA02a], the fingerprints of a certain position within a cell can contain signal strength, time delay, the cell identity, timing advance or the channel impulse response. The database can either be filled with measurements performed by the mobile station and the network or with parameters computed by a network planning tool. The first method is not surprisingly the more accurate one, but it requires a very big amount of time to set up the database. The calculation technique is less time-consuming, but it necessitates an exact model of the environment, which is often problematical to realise for urban areas.

The fingerprint measurements can either be performed by the network or by the mobile station. In an SMS message (when using GSM), the received fingerprint is sent to the location server, which computes the location estimate that is sent back to the mobile station or to an application server.

Obviously, the calculation of the position is very resource-consuming what requires distributed processing in large-scale implementations. In order to make the system work

reliably and to smooth out fast fading effects, the median of measurement values of a sufficiently long period of time, typically five seconds, is taken.

Laitinen et al. state that the database correlation method is more reliable in urban environments than in suburban areas because of the denser cellular network and building shadowing. The latter fact results in the noteworthy facilitation that the location error is typically directed along the street. Hence, the system's availability is perfectly suitable for urban areas, as the LOS requirement can seldom be met in such environments. Nevertheless, it has to be stated that the set up of the database is very time- and resource-consuming.

The authors have tested the database correlation system in both, an urban and a suburban environment, for which the measurements were carried out with a standard GSM phone gathering two fingerprints per second. The general outcome showed that a slower motion of the mobile station yields better accuracy and that reliability can be increased by taking several marker points into the position calculation. A detailed explanation of the whole location trial can be found in [LAIT01b].

Table 15 shows the summarised evaluation of the database correlation method.

Criterion	Specification	Résumé
Accuracy	44m (67%), 90m (90%)	Good
Availability	Increased accuracy in urban areas, where higher availability is given	Excellent
Impact (Handset)	No modifications necessary	Excellent
Impact (Network)	No modifications required	Excellent
Needed Information	No cooperation necessary	Excellent
Operating Compatibility	Operates on GSM, GPRS and UMTS networks	Excellent
Roaming Support	LS support (given in cellular networks)	Good
Technology-specific	Fingerprint database and a location server are necessary	Moderate

Table 15: Evaluation Summary of the Database Correlation Method.

3.7 Kytoons

In [AROR96], a low cost solution to the problem of blocked GPS signals in urban centres is presented. Kytoons are balloons normally used for performing weather studies or as repeaters in the field of long range telecommunication systems. Arora suggested supplying the Kytoons flying at a height of one to two kilometers with the suitable equipment to send GPS-like signals at the frequency of L1. This emulated GPS signal is unaffected by ionospheric and tropospheric errors. Furthermore, Arora also presented a differential version of his Kytoon

GPS, which can serve as a low cost underlay technique in areas where GPS signals are blocked.

3.8 Hybrid Approaches

There are numerous approaches, which combine several of the above positioning techniques; especially, GNSS systems are often used in combination with GSM localisation.

In [HACH03], Hachani et al. present the technical specification of the EMILY project, which is carried out by the European companies ERTICO, Dai Telecom LTD, Bouygues Telecom, UPC, Cap Gemini and uBlox AG supported by the European Commission. The main project goal is to create an optimised positioning method as a solid base technology for a multitude of location-based services. The technical implementation of the system will contain a combination of A-GPS, OTDOA, E-OTD and network-based information such as CI and TA.

The EMILY project seems very promising concerning its availability and accuracy, but there are no proven practical results yet since the project will only end within the next months. Further information on the approach can be found at the EMILY homepage [EMIL04]. For the project this thesis is based on, the combination of the technologies mentioned above will not be possible, firstly because a big amount of provider cooperation will be necessary and secondly because the realisation and installation costs are unreasonably high for a world-wide deployment.

Son et al. present a combination of GPS and TDOA, which is implemented by using a hybrid location algorithm in connection with Kalman filtering. More detailed information about this filtering method can be found in [COOP94]. In order to increase availability, TDOA signals are used in addition to GPS in areas where not enough satellites are visible for GPS positioning. Furthermore, Kalman filters are employed to estimate the error caused by Non-LOS signal propagation in the wireless cellular network. In [SON03], the authors state that the filtering process increases accuracy from 195 meters to 24 meters, which shows the drastic impact of non-LOS signal propagation on location estimation.

For the solution proposed in this project, the lastly mentioned approach cannot be taken into account because of the need for a mapping of the geographical positions to the cell identity of the employed base stations. This information cannot be obtained from providers of cellular network services and therefore it is not employable in a globally working solution.

A combination of A-GPS and Cell-ID, which considerably increases the availability versus pure A-GPS in areas with a high cell density, is described in [SNAP03]. Obviously, this method has many advantages like extensive roaming support, good accuracy and the ability to

use legacy handsets, but like the approach mentioned before, this system also requires the mapping of the Cell-ID to the BTSs' geographical position, which makes it inapplicable in a world-wide approach.

To sum up, it has to be stated that hybrid positioning solutions may be an excellent choice for spot-wise deployment of a location service because of the above mentioned advantages, but the requirement for different types of provider cooperation eliminates the possibility for such methods to be employed in a global system.

3.9 Statistical Modeling

A further possibility to estimate the location of mobile handsets within cellular networks is by using statistical modelling as presented by Roos et al. in [ROOS02]. The main difference compared to database correlation described in subsection 3.6 of this document is that the signal strength measurements are not matched to patterns contained in a pre-established database but their probability is calculated and thus, the handset's location is estimated using a pre-defined propagation model. The performance of statistical modelling strongly depends on the quality of the employed propagation model implying that big efforts have to be made during the process of building such a model. A main component in this context are cell planning tools, which are founded on radio wave propagation models and used by network operators in order to optimise their per-cell network access. By employing cell planning tools, it becomes possible to combine information about the environment in question with common knowledge about signal attenuation, reflection, diffraction and interference and to use the resulting parameters for an optimised dimensioning of GSM cells. As a matter of fact, the information available via such cell planning tools is also essential when creating a statistical model for location estimation. Once a suitable statistical model is established, the positioning can be done by estimating the location on base of the signal levels received at a mobile handset. Hence, the location estimation turns from a geometric problem, as described in subchapter 3.3, to a statistical estimation problem. Instead of relying on distance and angle measurements, which show performance problems in harsh environments, the positioning is derived by creating a statistical dependency between the transmitter's and receiver's locations and the signal properties present between these locations.

The first step of statistical modelling is to estimate propagation parameters and to set up a propagation model out of them. In a second step, this model can be used to estimate position variables. For the sake of simplicity, the creation of the propagation model, the mathematical coherences behind this positioning method and the corresponding formulae are not explained

in this thesis, but readers interested in this subject can find detailed and valuable information about these aspects in [ROOS02].

Moreover, Roos et al. presented a performance evaluation on base of a simulation and a real-world trial. It was shown that the proposed location method yields a positioning error, which is about 70 to 75 percent lower than that provided by pure Cell-ID (see also subsection 3.3.1.1). Table 16 shows a performance summary of positioning based on statistical modelling.

Criterion	Specification	Résumé
Accuracy	Mean location error of 279m, 95% of the location errors are below 620m	Moderate
Availability	Available in all GSM networks	Excellent
Impact (Handset)	Signal power levels available at the handset	Excellent
Impact (Network)	No modification required	Excellent
Needed Information	Access to providers' cell planning tools is essential for well-performing propagation model	Poor
Operating Compatibility	Same principle also applicable in 3G networks	Good
Roaming Support	Cell planning tools must be available world-wide	Poor

Table 16: Evaluation Summary of Statistical Modelling.

As visible in Table 16, this positioning method has several drawbacks. First of all, its accuracy is only moderate. Even if statistical modelling tends to perform much better than pure Cell-ID, its accuracy of 620m for 95% of all location estimates can easily be surpassed by other positioning methods presented in this paper.

The second main drawback is the fact that propagation models are established based on the providers' cell planning tools. Particularly concerning a world-wide application, creating adequate propagation models would necessitate access to the cell planning tools of GSM providers all over the world. The feasibility of such tight and international provider cooperation is very doubtful. Even if this tremendous amount of cooperation could be established, enormous and thus hardly practicable efforts had to be invested in the creation of many different propagation models. Due to the drawbacks just mentioned, the location estimation based on statistical modelling is not taken into account in this project.

3.10 Summary

The next step in the evaluation of possible alternatives of location estimation by the usage of pure GPS is providing a summarising revision of all these alternatives and a decision whether

these alternatives are suitable for the particular case of a world-wide operating goods-tracking solution. Table 17 contains all evaluation results presented in this thesis.

Positioning Method	Accuracy	Availability	Impact (Handset)	Impact (Network)	Needed Information	Operating Compatibility	Roaming Support	Technology Specific
A-GPS	Excellent	Excellent	Good	Good	Excellent	Excellent	Good	Excellent
IndoorGPS	Excellent	Excellent	Moderate	Excellent	Excellent	Excellent	Good	---
CI	Poor	Excellent	Excellent	Excellent	Moderate	Excellent	Excellent	---
CI + TA	Poor	Excellent	Good	Good	Moderate	Good	Excellent	---
CI + TA + RXLEV	Moderate	Excellent	Good	Moderate	Moderate	Good	Excellent	Moderate
AOA	Moderate	Poor	Excellent	Poor	Moderate	Moderate	Poor	---
Uplink TDOA	Good to Moderate	Moderate	Excellent	Poor	Good	Good	Poor	Poor
E-OTD	Good to Moderate	Moderate	Moderate	Poor	Good	Good	Poor	Poor
OTDOA	Good to Moderate	Moderate	Moderate	Poor	Good	Excellent	Poor	---
Database Comparison	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Good	Moderate
Statistical Modelling	Moderate	Excellent	Excellent	Excellent	Poor	Good	Poor	---

Table 17: Summary of Evaluation Results.

Table 17 shows that the GPS enhancements called A-GPS and indoor-capable GPS result in an excellent accuracy and availability. Furthermore, improving GPS by the method of massive correlation is a promising method and its realisation is currently about to be brought onto the market. Consequently, the thesis goal of making global positioning also available in harsh environments might be reached by developing sophisticated high sensitivity receivers. Nevertheless, the principle behind this method is not further taken into account for the creation of an innovative approach presented in this thesis because there are no representative and objective assessments about the performance of indoor-capable GPS available at this time. Another reason is that the investigations about GPS signal acquisition and the correlation methods involved in it are a large research area, which cannot be covered sufficiently within the range of this thesis.

Thus, it was decided to focus on positioning within cellular networks. As already stated, this kind of positioning may require provider cooperation with the big exception of location estimation based on database comparison. Nevertheless, the intensity of such cooperation varies; for instance, all methods except database correlation require knowledge about the

geographical coordinates of the involved base stations. The positioning principles based on time difference measurements require even stronger provider cooperation like additional signalling and infrastructure. Furthermore, statistical modelling can only be realised via access to the providers' cell planning tools. Thinking of a world-wide operable tracking application, the need of provider cooperation should be avoided because it affects the very important criterion roaming support if such cooperation has to be established world-wide. In order to be able to assess the providers' willingness to provide information like the coordinates of their base stations, the authors of this thesis sent numerous enquiries to GSM providers all over the world. Due to the fact that the corresponding answers were exclusively negative, the establishment of the necessary provider cooperation is very doubtful. Consequently, the fact that the database correlation method does not require any provider cooperation becomes a crucial advantage for achieving the goals of this thesis. The benefits of database correlation are even larger thinking of the fact that GSM signals are often available in environments where GPS tends to show performance problems like in urban areas. As already mentioned in subsection 3.6, the main drawback of database comparison is the big effort required for setting-up a suitable database. An infrastructure able to decrease this effort by automatic fingerprint collection is presented in chapter 4, which covers the way how to enhance the database correlation method by involving signal measurements of base stations of more than one GSM provider as well.

4 Innovative Approach

As already mentioned in subsection 3.10, the GSM localisation method database comparison is the best possibility to meet the goals of this thesis, namely a freight-tracking solution, which works even in circumstances where GPS suffers from performance problems. The following subsections contain a well-reasoned motivation for an approach based on database comparison and a detailed technical description of its initial implementation.

4.1 Motivation

As explained in subchapter 3.10, the measuring of GSM information like received signal levels, cell identities and base station identity codes as well as its mapping to a reference position obtained employing GPS is the first and the most essential step when realising the database comparison method. Since positioning based on correlation of pre-recorded cell fingerprints and currently measured signal properties does not necessitate any provider cooperation, the key barrier of making database correlation usable for a world-wide tracking solution is to simplify the process of fingerprint collection. Hence, an infrastructure allowing the automatic and global collection of cell fingerprints is suggested in this thesis. Once such an infrastructure is realised, it can be used to measure relevant GSM information on routes and areas of great interest as for instance the marts of Shanghai. The proposed principle represents an effective way of establishing the databases necessary for GSM positioning by measuring necessary information on routes and areas where goods will be transported later on. Due to its efficiency, the presented method is even usable in a world-wide application scenario. Moreover, the proposed method could be implemented as an embedded device within future research projects. Such a device could be mounted on different means of transport, allowing the automatic and effective collection of an enormous amount of fingerprint data while the means of transport are moving.

Considering the fact that former research was usually carried out in cooperation with only one GSM provider seeking answers to the question how GSM positioning can be realised for the provider's customers within the provider's network, a second main feature of the method presented in this thesis is involving base stations of more than one GSM provider into the process of fingerprint collection. By involving for example three different GSM providers, one cell fingerprint contains measurements of the signals coming from up to 21 different base stations considering three serving cells and up to 18 strongest neighbour cells. Relying on just one GSM provider, only up to seven different base stations, namely one serving cell and six

strongest neighbour cells, could be taken into account. The authors of this thesis expect a significant increase of the accuracy and the availability of the database comparison method by respecting GSM signals of more than one GSM provider. Nevertheless, a quantification of this increase will be subject to further research. The unique advantages of the presented automatic fingerprint collection are:

- Automatic retrieval of fingerprint data in order to make database establishment globally practicable
- A global solution which is not restricted to the network of a particular GSM provider
- Increased availability and accuracy by involving base stations of more than one GSM provider

In order to prove the technical feasibility of the suggested approach, the following key functionalities have to be provided by the initial implementation presented in this thesis:

- Performance of signal measurements taking into account more than one GSM provider
- Information retrieval in an automatic manner
- Integration of a GPS receiver used for recording reference positions

Concluding, it could be stated that the presented approach is the initial step to a proprietary positioning method based on database correlation operated by and located at the company initiating this thesis. Thus, the automatically established database should also be well-suited for future research carried out in further master theses.

4.2 Technical Description

Figure 19 shows the basic system set up of the innovative approach created within this project.

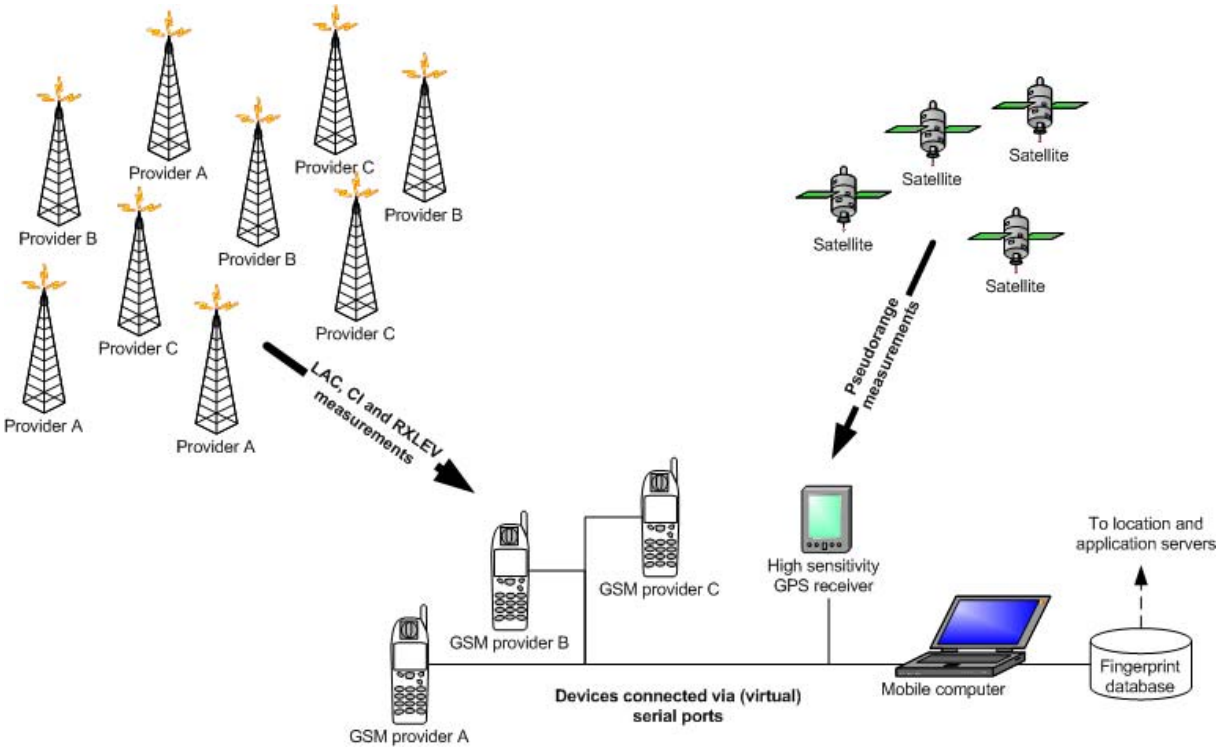

Figure 19: System Structure of the Innovative Approach.

Principally, the system comprises three GSM handsets of different providers, a high sensitivity GPS receiver, a mobile computer, where the measurement programme is running on, and a database, in which the cell fingerprints are stored.

The measurement process for obtaining the GSM parameters mentioned above functions as follows: the computer requests three different parameters from the handsets, namely the location area code, the cell identification and the signal level. These values, which form the cell fingerprint, are obtained for the serving cell and of as many neighbour cells as possible and are stored in the database together with the reference position calculated by the GPS receiver.

The database update is done automatically in a predefined interval, which makes the creation of the fingerprint database exceptionally easy and enormously time-saving. The communication of the central computer with the handsets is carried out via AT commands, which are described in the next subsection.

In a practical scenario, an application server could use the stored fingerprints to calculate the location estimate for a handset. This process is indicated by the dotted arrow at the right-bottom corner of Figure 19. The communication of the application server with the location server (LS), which directly accesses the database, is effected via the Mobile Location Protocol (MLP). Furthermore, the LCS (Location Service) client, which asks the handset to transmit

the measured signal fingerprint, communicates with the LS via the Mobile Positioning Protocol (MPP).

Because of the major significance of MLP and MPP for the general principle of location estimation but their lacking importance for the elucidation of the innovative approach at this place, these two mobile protocols are described in Appendix A: Mobile Protocols.

4.2.1 Attention Commands

AT (ATtention) commands, which were firstly introduced by the modem manufacturer Hayes, enable the communication of a computer with a modem via the serial interface. Different hardware- and connection-specific parameters such as the model number, call control functions and many more can be accessed. Originally designed for modem access, AT commands have been extended also for usage with GSM handsets.

The command structure is shown in Figure 20.

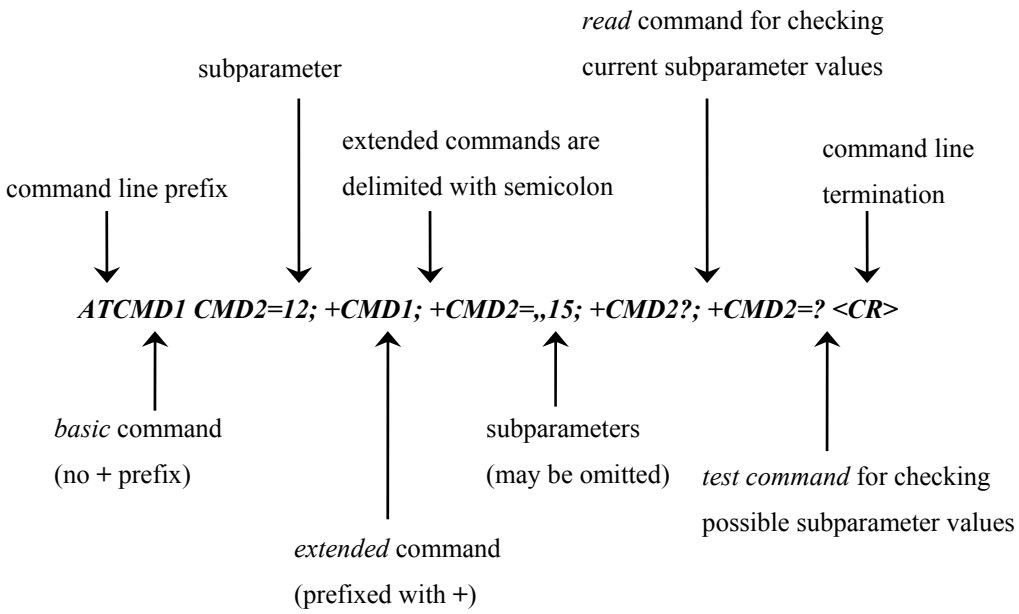

Figure 20: AT Command Syntax.

The standardised basic commands can be found in the V.25ter standard [ITUT99], whereas GSM-specific operations are achieved by the use of extended commands specified by the manufacturer of the handset.

The AT commands, which are necessary for the creation of the fingerprint database used in this project, are listed in Table 18.

AT Command	Description
AT+GMI	Returns the manufacturer of the device
AT +CSQ	Returns the signal quality of the serving cell
AT+CREG=2	Enables network registration and location information. Unsolicited result code: *+CREG: <stat>[,<location area code>,<cell-ID>]*
AT+CREG?	Returns network registration information
AT^SSTK=?	Returns profile of mobile equipment if this at-command is supported, otherwise the output is ERROR, more information about the use of this command can be found in subsection 4.3.2

Table 18: Employed AT Commands.

A detailed description of all GSM-specific AT commands can be found in [ETSI96] and [ETSI98a].

4.2.2 Subscriber Identity Module Application Toolkit

The SIM Application Toolkit (SIM AT) is a GSM Technical Specification (GTS) introduced by the Special Mobile Group (SMG) of the European Telecommunications Standards Institute (ETSI). This specification is published as the version GSM 11.14 [ETSI98b]. If a handset, the employed Subscriber Identity Module (SIM) card and the GSM network are SIM AT-capable, the mobile handset is programmable via the air interface. Furthermore, the "SIM Application Toolkit provides mechanisms which allow applications, existing in the SIM, to interact and operate with any ME which supports the specific mechanism(s) required by the application", [ETSI98b, p.12]. This means that applications can be sent to a user's SIM card, where they are stored and executable. Moreover, menus available in the handset can be changed and added by this procedure. Due to its proactive role, a SIM AT-capable SIM card is able to initiate pre-defined commands independently of the network and the handset. The following list taken from [ETSI98b, p.12], shows the features, which are provided by a proactive SIM:

- display text from the SIM to the ME;
- send a short message;
- set up a voice call to a number held by the SIM;
- set up a data call to a number and bearer capabilities held by the SIM;
- send a SS control or USSD string;
- play tone in earpiece;

- initiate a dialogue with the user;
- SIM initialisation request and notification of changes to EF(s);
- provide local information from the ME to the SIM.

As visible from the listing above, local information is also available by the use of a SIM AT-capable SIM card. According to [ETSI01], the following GSM parameters are among other information obtainable by the specified command *provide local information*:

- Location information: MCC, MNC, LAC and CI of the serving cell
- Network measurement results: RXLEV of serving cell, BSICs and RXLEVs of neighbour cells

Hence, the SIM AT can be employed for the retrieval of network information concerning the serving as well as the neighbour cells.

4.3 Practical Implementation

The programme used to obtain the parameters for the cell fingerprint and the insertion of the values into the database is implemented in Java. Detailed information about this object-oriented programming language can be found in [SUN04].

4.3.1 Main Programme

The main file of the application comprises two classes, which build the basic structure of the whole programme. The classes and their functions are described in this subsection.

The first step when the programme is executed is that all serial ports, to which a mobile device is attached, are read out from a pre-created configuration file. The first element, named *usedCOM1*, contains the port, which the GPS receiver is connected to. The element structure of the XML file containing all used ports looks like as follows:

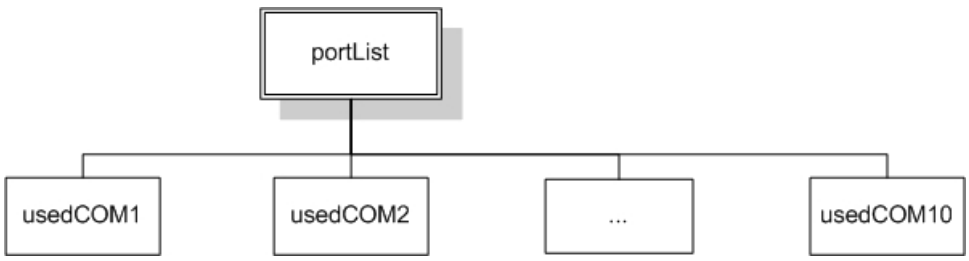

Figure 21: Element Structure of the XML Configuration File.

The retrieval of the ports from the XML file is done with the following lines of code:

```
Document conf = builder.parse("ports.xml");

NodeList portNodeList = conf.getChildNodes().item(1). getChildNodes();

for(int x=0; x<10; x++)

 usedPorts[x] =
 portNodeList.item(2*x+1).getChildNodes().item(0).getNodeValue();
```

After the ports to query have been retrieved, a detection of all serial ports available at the computing station is performed in order to verify the physical existence of the ports. This is done by the following Java statement:

```
portList = CommPortIdentifier.getPortIdentifiers();
```

Thereafter, measurements are performed for all ports contained in the configuration file. At first, the GPS reference position is retrieved by calling the constructor of the class `GPSReceiver`, which is described separately in subsection 4.3.3 of this document.

```
GPSReceiver myGPSReceiver = new GPSReceiver();
```

For the retrieval of the GSM cell fingerprints, the constructor of the class `CollectFingerprints` is called, in which a connection is opened to the selected serial port. As input parameters, the `open()` function takes the owner as a string and the time in milliseconds, for which the port is opened, as an integer:

```
serialPort = (SerialPort) outPortId.open("GPS", 10000);
```

After that, the parameters data rate, data bits, stop bits and parity are set for the opened port and an output stream and an input stream are created for the port:

```
serialPort.setSerialPortParams(9600, SerialPort.DATABITS_8,
    SerialPort.STOPBITS_1, SerialPort.PARITY_NONE);

outputStream = new PrintStream(serialPort.getOutputStream());

inputStream = new BufferedReader(new
    InputStreamReader(serialPort.getInputStream()));
```

In the next step, an event listener is added, which automatically notifies the function `serialEvent()` on specified events like that there are data available at the input stream.

```
serialPort.addEventListener(this);

serialPort.notifyOnDataAvailable(true);
```

Next, the manufacturer of the handset is requested by sending the command *"AT+GMI"* to the mobile equipment, which is done by the statement shown below. It has to be mentioned that the character sequence *"\r\n"* has to be added to the command itself in order to be

properly executed in the handset. Furthermore, an instance of the class `Interpreter()` is created, which serves for response interpretation when employing Siemens phones.

```
outputStream.write("AT+GMI\r\n".getBytes());

myinterpreter = new Interpreter();
```

Thereafter, the message array containing the AT commands to be sent is filled by invoking the method `fillMessageArray()`, which takes the vendor and the instance of the class `Interpreter`, created in the last step, as parameters in order to be able to decide, which vendor-specific messages should be sent to the mobile. The class, which decodes the answer given by a Siemens mobile, will be described separately in chapter 4.3.2 because of its complexity.

After having checked that the message array has been filled correctly, the messages are written to the serial port as a byte stream by using the following command in a while-loop until all messages have been sent:

```
outputStream.write(messages[writtenMessages].getBytes());
```

Then, the manufacturer of the equipment is retrieved by examining the response to the first sent AT command, which is done after the handset has returned the response to the received commands. This answer from the mobile handset is obtained via the automatic launch of the case `SerialPortEvent.DATA_AVAILABLE` in the `serialEvent()` function. This method firstly reads the answer into a character array:

```
inputStream.read(response, 0, 200);
```

If a Siemens handset is employed, firstly the interpreter method `read_neighbours()` is called in order to retrieve the cell identification, the local area code and the signal quality of the neighbour cells. These values are then read from different arrays iteratively in a while-loop to obtain the values for the different neighbour cells. As unfortunately no local area code is available for neighbour cells, the value for this parameter is set to -1. Furthermore, the cell-ID of the serving cell corresponds to the base station identifier code of the neighbour cells.

```
cid = Integer.toString(myinterpreter.getEntriesfromchl().get_bts_id
    (treatedCells));

lac = Integer.toString(-1);

iCSQ = myinterpreter.getEntriesfromchl().get_RXLEV(treatedCells);
```

To get out the corresponding values of the serving cell, the function `read_locinfo()` is called, which proceeds the response from the headset as mentioned above. With the following

commands, the cell identification, the local area code and the signal quality of the serving cell are retrieved:

```
cid = myinterpreter.getEntriesfromli().get_CI();

lac = myinterpreter.getEntriesfromli().get_LAC();

iCSQ = myinterpreter.getEntriesfromchl().get_RXLEV(0);
```

After the single parameters have been filtered out, they can be written to the fingerprint database. Therefore, a seperate class is defined, which is instantiated in the next step and its `insert()` method is called with the reported values:

```
writeParamsToDB writeParams = new writeParamsToDB();

writeParams.insert(lac, cid, csq, ref_pos_array);
```

If a Nokia handset is used, the parameters mentioned above can only be obtained for the serving cell in this implementation, which partly results from the lacking time for the creation of SIM AT interfaces supporting other vendors and partly from the minimal cooperation of many mobile phone vendors for the retrieval of such parameters. If another manufacturer is employed, an error message is printed out indicating that this vendor is not supported. The implementation of the support for several other vendors will be subject to future work, as mentioned in section 5.

In the remaining paragraphs of this subsection, an exemplary connection set up to an Oracle database is described. For other database types, the establishment of the connection in JDBC is principally the same, but some parameters such as the connect string differ.
Before the retrieved data can be inserted, a connection to the database has to be established. Therefore, firstly the driver has to be instantiated and then, the connection itself can be set up.

```
Class.forName("oracle.jdbc.driver.OracleDriver").newInstance();

Connection conn = DriverManager.getConnection(connectString, userName,
    password);
```

The sample query, which inserts the parameter values representing the cell fingerprint for one cell, is conveyed using the following command:

```
stmt.executeQuery("INSERT INTO fingerprint_DB (location_area_code,
    cell_id, signal_quality, ref_pos_x, n_ind, ref_pos y, w_ind)
    VALUES (" + _lac + ", " + _cid + ", "  + _iCSQ + ", " +
    _ref_pos_array[1] + ", " + _ref_pos_array[2] + ", " +
    _ref_pos_array[3] + ", " + _ref_pos_array[4] + ")";
```

As it can be seen from the above lines of code, the database comprises the three columns *location_area_code*, *identification* and *signal_quality* for the cell fingerprint representing the location area and the cell identification or the BTS identification code of the cell and the signal quality. Furthermore, the database contains four columns for the reference position measured by the GPS receiver comprising values for the latitude, the longitude as well as for the north and west indicators.

4.3.2 Subscriber Identity Module Application Toolkit Interpreter

According to the technical specification of the SIM AT, the adequate commands to retrieve location information have the structure shown in Table 19. These commands are written in hexadecimal format as for example *D009810301260082028182* representing a bit sequence sent from the SIM to the ME.

Octet Number	Hexadecimal Value	Interpretation
1	D0	Proactive command tag
2	09	Length
3	81	Command details tag
4	03	Length
5	01	Command number
6	26	Type of command: provide local information
7	00, 02	00: Get location information 02: Get network measurement results
8	82	Device identity tag
9	02	Length
10	81	Source: SIM
11	82	Destination: ME

Table 19: Structure of Proactive SIM Command.

As visible from Table 19, at octet number 7, the command, which has to be sent to the ME to get local information like LAC and CI is *D009810301260082028182*, while *D009810301260282028182* is the command to get the signal levels of the serving and the neighbour cells.

One problem still to be solved is how to send these commands via a serial connection to a mobile handset. The SIM AT is usually designed only to be accessible over the air interface of GSM, however, the well-known manufacturer Siemens has implemented a very useful interface to access the SIM AT via the proprietary AT command called *AT^SSTK*. According to [SIEM02], the syntax of using this SIM AT interface command is as follows:

AT^SSTK=<length>, <mode> <CR> PDU according to [ETSI98b] <ctrl-Z/ESC>

The field <*length*> means the length of the data protocol unit (PDU) in bytes; the supported modes (represented by the field <*mode*>) are *0* (single command is sent) and *1* (a sequence of SIM AT commands is sent). The PDU finally may contain commands as for example listed in Table 19. For simplification, Table 20 demonstrates the AT command sequence for sending a location information request to the SIM AT of a Siemens mobile phone.

Entered Commands	Remarks
AT^SSTK=11,0 <CR>	Send a single, 11 bytes long command to the SIM AT
D009810301260082028182 <ctrl+Z>	Request location information from the SIM AT
810301260082028281830100930742F08000193F55 OK	Received answer from SIM AT containing location information

Table 20: Sample AT Command Sequence for Interfacing SIM AT.

As shown in Table 20, the SIM AT answers with a bit sequence in hexadecimal format after the corresponding requests have been sent to it. The interpretation of these sequences and its technical implementation in Java are explained in the following two subsections. Even if the presented SIM AT interface via AT commands is Siemens-specific, the interpretation of the received answer sequences is vendor independent due to the standardisation of the ETSI.

4.3.2.1 Interpretation of Location Information

The first seven octets of the response sequence are identical to the request sequence shown in Table 19 with the exception that the proactive command tag and the first length field have to be left out. Table 21 represents the detailed structure of the sequence containing sample local information.

Octet Number	Hexadecimal Value	Interpretation
1	81	Command details tag
2	03	Length
3	01	Command number
4	26	Type of command: provide local information
5	00	00: Get location information
6	82	Device identity tag
7	02	Length
8	82	Source: ME
9	81	Destination: SIM
10	83	Result tag
11	01	Length
12	00	Command successfully performed
13	93	Location information result tag
14	07	Length of Results: 7 Bytes
15-16	42F0	Mobile Country Code: 240 (Sweden)
17	80	Mobile Network Code: 08 (Vodafone)
18-19	00 19	Local Area Code: 0019
20-21	3F55	CI of serving cell: 3F55

Table 21: Sample Response to Location Information Request.

Table 21 shows that the results of the location information request are contained in the octets 15 to 21. The representation of MCC and MNC (Octets 15 to 17) has to be reformatted; however, the values of LAC and CI can be used without further decoding.

In order to be able to retrieve information like MCC, MNC, LAC and CI automatically, a Java class providing the corresponding capabilities called `Interpreter` was designed. The local information is interpreted by its method `public void read_locinfo(String s)`, where the variable *s* contains the answer received from the SIM AT. The first step of interpreting the sequence *8103012600820282818301009307 42F08000193F55* is to identify the part of this sequence that contains the wanted information. This is done by taking into account only the bits, which follow the location information result tag at octet 13 by the Java line:

```
String help = s.substring(28,s.length());
```

The result is the bit sequence *42F08000193F55*, which consists of MCC, MNC, LAC and cell-ID of the serving cell. After some converting, 42F0 becomes an MCC of 240 (in this case

Sweden) and 80 becomes an MNC of 08 (in this case Vodafone), while LAC and CI do not have to be converted. The following lines perform the interpretation just explained:

```
String mcc = help.charAt(1) +""+ help.charAt(0) +""+ help.charAt(3) +
"";

String mnc = help.charAt(5) +""+ help.charAt(4) + "";

String lac = help.substring(6,10);

String ci = help.substring(10,14);
```

4.3.2.2 Interpretation of Network Measurement Results

The interpretation of the answer to a request of network measurement results is more sophisticated than the interpretation of the location information. Nevertheless, the first step is again to skip the message header. The network measurement result tag, again located at octet 13, indicates the beginning of measurement data. This means that the response sequence *8103012602820282818301009610 9B1B01985AC91123C499C85CA9A044509D101024B8E790C80000000000000000000* can be reduced to a sequence starting at octet 14. The channel list tag 9D at octet 31 shows the beginning of the channel list. Hence, according to the standard GSM 11.14, the octets 14 to 30 have to be taken into account in order to obtain information about the received signal level of all hearable cells and the BISCs of the neighbour cells. To fulfil this purpose, the following Java line of the method `public void read_neighbours (String s)` yields the bit sequence relevant for further interpretation:

```
String help = s.substring(26,60);
```

The result of this instruction is the hexadecimal sequence *109B1B01985AC91123C499C85CA9A04450*. This 17 octets long sequence represents the network measurement result (NMR) information as it is defined in [ETSI00, p. 347 ff.]. In order to be able to interpret the information contained in these 17 octets, the sequence has to be converted into binary format. This is done within a loop by the following Java line:

```
bits += hex_to_bits(help.charAt(i));
```

Table 22 contains the resulting bit sequence that has to be taken into account for appropriate interpretation.

	Octets 1 to 17			
Hexadecimal	10	97	17	01
Binary	0001 0000	1001 0111	0001 0111	0000 0001
Hexadecimal	96	5A	C7	09
Binary	1001 0110	0101 1010	1100 0111	0000 1001
Hexadecimal	33	C8	90	F3
Binary	0011 0011	1100 1000	1001 0000	1111 0011
Hexadecimal	41	12	A8	6B
Binary	0100 0001	0001 0010	1010 1000	0110 1011
Hexadecimal	F4	Legend: **Number of measured neighbours, 3 bit** RXLEV of serving & neighbour cells, 6 bit BSICs of neighbour cells, 6 bit Position in BCCH channel list, 5 bit		
Binary	1111 0100			

Table 22: Sample Network Measurement Result.

As explained by the legend of Table 22, the bit sequence contains the following information:

- Received signal level of serving cell
- Number of hearable neighbour cells N
- Received signal level of N neighbour cells
- BSIC of N neighbour cells
- Position of neighbour cell-entry in the channel list, which is transmitted via the BCCH

If the number of hearable neighbour cells is smaller than six, the corresponding bits in the NMR are set to zero. For the sake of simplicity, only the bits highlighted in Table 22 containing the information mentioned in the above listing are explained. An interpretation of the bits left out in this description can be found in [ETSI00, p. 347 ff.].

It has to be noted that the Interpreter presented in this subsection of the thesis is able to extract the information indicated in the listing above with the exception of the entry-position in the channel list where the channel numbers of the neighbour cells can be found. Since the neighbour base stations can also be identified with the GSM parameter BSIC, the utilisation of the information available at the BCCH is left for future enhancements.

As indicated in Table 22, the information about how many neighbour cells are audible by a GSM handset is packed into the fourth and fifth octet by a 3 bit value starting at bit 31. The extraction of this value is done by the following code:

```
String neighbours = bits.substring(31,34);

int hearableneighbours = bit_to_int(neighbours);
```

After taking the bits 31 to 33 by the method `substring()`, the 3 bit value can easily be converted into integer format, which results in a amount of six audible neighbour cells in the example presented in Table 22.

The extraction of the received signal levels follows exactly the same principle as the extraction of the number of neighbour cells. The only differences are that the corresponding bits are at other positions of the bit sequence and that the structure of this sequence allows a neighbour cell extraction by a for-loop. The received signal level is encoded into the bits 10 to 15, where the bit value has again to be converted into a decimal value:

```
String level = bits.substring(10, 16);

int rxl0 = bit_to_int(level);
```

The measurement example of Table 22 leads to a received signal level of 23. According to [ETSI95], this value has to be converted as per the principle shown in Table 23.

Parameter Contained in Bit Sequence	Parameter After Appropriate Converting
0	RXLEV less than -110 dBm
1	RXLEV between -110 and -109 dBm
2	RXLEV between -109 and -108 dBm
⋮	⋮
62	RXLEV between -49 and -48 dBm
63	RXLEV higher than -48 dBm

Table 23: Converting of Parameter RXLEV.

Following the specification in Table 23, the RXLEV of the serving cell is converted as follows:

```
chl.set_RXLEV(110 - rxl0 + 1,0);
```

By the formula *110 – rxl0 +1*, the lower limit of the intervals introduced in Table 23 is taken into consideration, but it has to be stated that the values of RXLEV still have to be converted into negative values, which is done within the class `CollectFingerprints`. The second parameter *0* means that the signal level of the serving cell is written into the first position of a signal level array containing the signal levels of the serving and all audible neighbour cells.

The extraction of the six bits containing the BSIC information of all neighbour cells follows exactly the same principle; once the six bits of one BSIC are extracted, they have to be properly converted. As defined in the GSM standard, the BSIC is composed as follows.

6 bits Base Station Identity Code (BSIC)	
010	110
Network Colour Code (NCC): 2	Base Station Colour Code (BCC): 6

Table 24: Format of BSIC.

In order to obtain the BSIC properly, the 6 bits contained in the measurement results have to be split up and converted into decimal format separately. After that, the BSICs can be written into an adequate integer array. The consequent Java loop is:

```
String val1 = bits.substring(45+17*i,48+17*i);

int bstid1 = bit_to_int(val1);

String val2 = bits.substring(48+17*i,51+17*i);

int bstid2 = bit_to_int(val2);

bstid[i] = bstid1*10+bstid2;

chl.set_bts_id(bstid[i],i+1);
```

Following the example of Table 24, this code results in a BSIC value of 26 for the first neighbour cell, which is written into the first position of the corresponding array.

4.3.3 Measurement of Reference Position

As already mentioned in this thesis, each GSM cell fingerprint also contains a reference position, which is accomplished within the presented implementation by involving the GPS 12 receiver manufactured by the Garmin Corporation for the retrieval of the necessary position information. The GPS 12 receiver supports two different message formats, namely the standard introduced by the National Marine Electronics Association (NMEA) and a Garmin-proprietary format. The differentiation between those formats is made by tuning the bit rate of the connection to the receiver. While a bit rate of 4800 bits/s results in the usage of the NMEA standard, a rate of 9600 bits/s has to be chosen for connecting the GPS receiver via the Garmin-proprietary protocol. For the presented implementation, the NMEA standard was employed to guarantee manufacturer-independency. Once a connection to the GPS 12 receiver is established via the serial port at a rate of 4800 bits/s, the receiver provides the NMEA-coded positioning information permanently without the need of requesting it in advance. The following screenshot shows sample GPS data in NMEA format, which was recorded in Halmstad, Sweden by connecting the GPS receiver via a terminal programme.

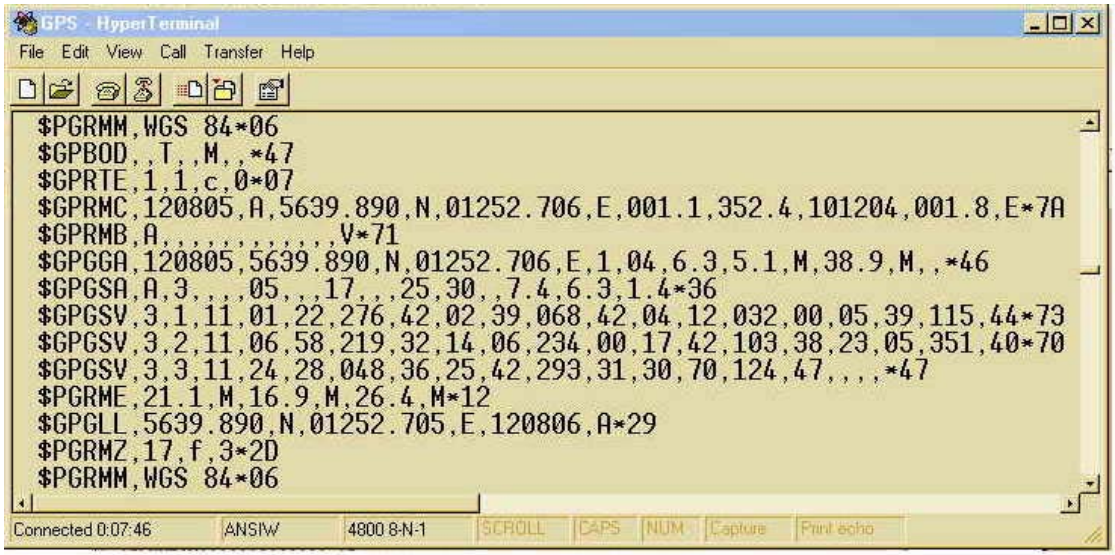

Figure 22: Screenshot About Output of GPS 12 Receiver.

The NMEA sentence starting with *$GPGGA*, which is found at line six of the above screenshot, contains all the information necessary for the recording of a reference position. Thus, retrieving the needed GPS information via the Java class `GPSReceiver`, which was implemented within this project, becomes straight forward. The two required steps are listening to the data stream sent by the GPS receiver to the serial port and then searching this stream for the keyword *$GPGGA*. The corresponding Java code is:

```
respString=inputStream.readLine();

NMEAsentence = respString.substring(1,6);

if (NMEAsentence.equals("GPGGA"))

{GPGGAentry=respString;}
```

Once the right GPS information is identified, it must be decoded by the programme according to the NMEA standard, whose properly interpretation is explained in [GARM02][1]. Table 25 shows how this interpretation is done correctly following the example shown in Figure 22.

1 Used with courtesy of Garmin Ltd. or its subsidiaries © Copyright Garmin Ltd. or its subsidiaries

Sentence Content	Interpretation
$GPGGA	Sentence ID
120805	UTC time in format hhmmss[2]
5639.890	Latitude in format ddmm.mmm
N	North/south-indicator
01252.706	Longitude in format dddmm.mmm
E	East/west-indicator
1	Measurement invalid (=0), valid (=1) or properly obtained via DGPS (=2)
04	Number of satellites used for positioning
6.3	Horizontal Dilution of Precision
5.1	Altitude
M	Unit of attitude measurement (M = meters)
38.9	Geodic separation
M	Unit of geodic separation measurement (M = meters)
	DGPS related information, blank in this example
*46	Checksum and end of line

Table 25: Structure of $GPGGA Sentence.

After having interpreted the GPGGA sentence according to Table 25, the obtained information is stored into an array provided by the class `PosInformation`.

[2] Units are listed as: h … hours, d… degrees, m … minutes, s … seconds

4.4 Testing Results

The new method of location estimation presented in this document measures fingerprints of GSM cells including signal levels of the serving cell as well as of up to six neighbour cells and retrieves a GPS reference position automatically. The tests performed within this project were done by employing the following hardware:

Model Identification	Description
Garmin GPS12	Standard 12-channel GPS receiver, connected via serial port
Siemens S35	Mobile phone connected via IrDA port
Siemens S55	Mobile phone connected via Bluetooth port
Nokia 6310i	Mobile phone connected via Bluetooth port

Table 26: Hardware Used for Testing.

The communication between the mobile computer and the handsets occurs via AT commands while the GPS receiver sends its current position without being queried.

The implementation created in this project allows to measure fingerprints involving neighbour cells when employing Siemens mobile phones, whereas for other handsets, only GSM parameters of the serving cell can be retrieved resulting from several reasons, which were mentioned in subsection 4.3.1. Due to this fact, the database entries presented in this part of the thesis contain signal measurements involving two different GSM providers, measured with the two Siemens handsets. Nevertheless, the designed programme also worked perfectly employing three handsets and thus, it could be proven that the implementation is scalable to more GSM providers. As stated in subchapter 4.1, the authors expect a better performance, meaning higher availability as well as a better accuracy of the database correlation method by involving a high number of GSM providers.

Within this project, a sample database containing measurements taken on the campus of Halmstad University was recorded. Figure 23 shows the map of the campus and several sequence numbers representing the positions and the order of the cell fingerprint measurements.

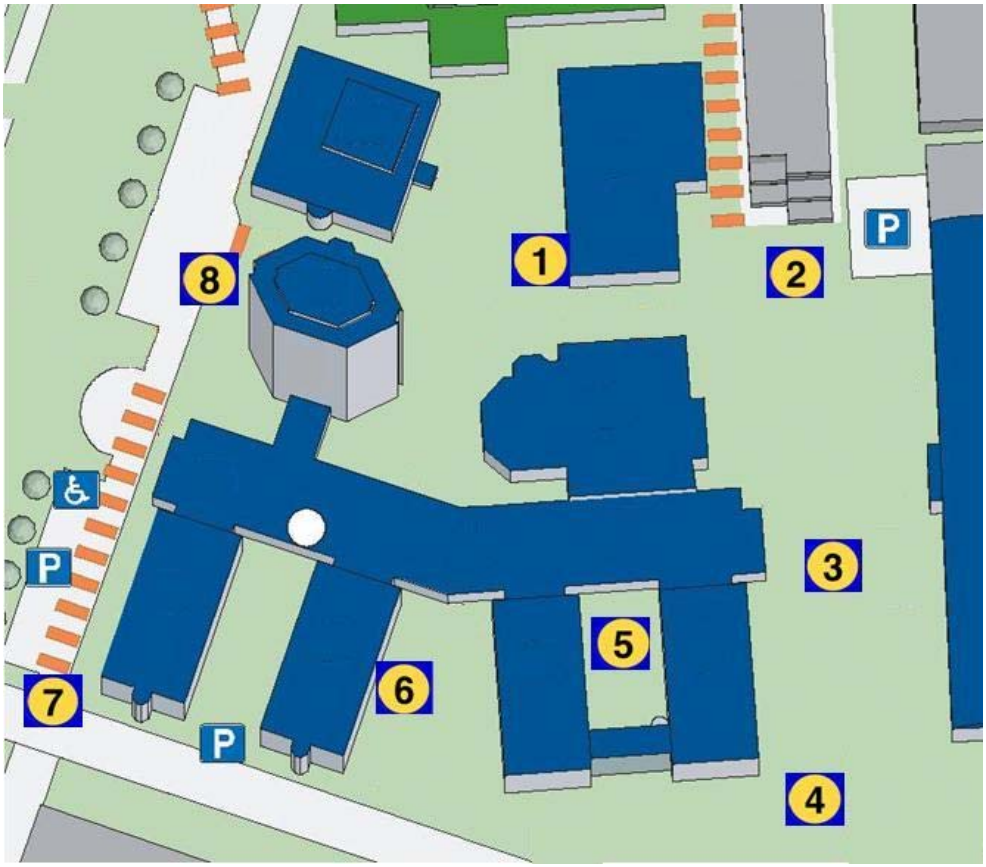

Figure 23: Measurement Route on the Campus of Halmstad University, [HOEG05] modified and reprinted with permission of Hans Halling.

A screenshot of the sample database resulting from the taken measurements is illustrated in Figure 24 by reusing the sequence numbers introduced above.

```
1  5639.870 N 01252.718 E -1 66 -88 -1 20 -92 -1 61 -95 -1 63 -86 -1 61 -83 -1 60 -80 03F7 2B71 -80
   5639.870 N 01252.718 E -1 24 -81 -1 22 -80 -1 22 -84 -1 27 -85 -1 64 -93 -1 20 -90 0019 179B -78

2  5639.849 N 01252.778 E -1 24 -62 -1 21 -70 -1 66 -74 -1 60 -74 -1 63 -75 -1 22 -76 03F7 A3A2 -58
   5639.849 N 01252.778 E -1 22 -80 -1 22 -79 -1 24 -86 -1 26 -91 -1 20 -94 -1 27 -93 0019 3A4A -75

3  5639.813 N 01252.750 E -1 60 -66 -1 21 -68 -1 63 -67 -1 66 -67 -1 20 -70 -1 65 -73 03F7 A3A3 -63
   5639.813 N 01252.750 E -1 22 -71 -1 64 -80 -1 22 -81 -1 24 -85 -1 20 -86 -1 27 -87 0019 179B -74

4  5639.818 N 01252.707 E -1 24 -60 -1 20 -64 -1 65 -69 -1 60 -77 -1 63 -66 -1 25 -94 03F7 2B71 -53
   5639.818 N 01252.707 E -1 22 -73 -1 26 -79 -1 20 -80 -1 23 -84 -1 22 -83 -1 24 -88 0019 3A4A -66

5  5639.845 N 01252.717 E -1 63 -73 -1 65 -89 -1 20 -73 -1 62 -80 -1 60 -68 -1 21 -74 03F7 A3A3 -75
   5639.845 N 01252.717 E -1 22 -70 -1 26 -81 -1 64 -77 -1 23 -84 -1 20 -80 -1 0 0 0019 3F55 -67

6  5639.838 N 01252.659 E -1 60 -77 -1 65 -78 -1 21 -81 -1 20 -83 -1 63 -83 -1 66 -87 03F7 A3A3 -77
   5639.838 N 01252.659 E -1 23 -80 -1 64 -81 -1 22 -84 -1 22 -86 -1 27 -93 -1 20 -100 0019 179B -75

7  5639.872 N 01252.636 E -1 20 -77 -1 21 -78 -1 24 -64 -1 60 -67 -1 65 -60 -1 66 -63 03F7 2C57 -71
   5639.872 N 01252.636 E -1 22 -70 -1 22 -78 -1 26 -77 -1 24 -85 -1 23 -87 -1 67 -87 0019 3A4A -71

8  5639.891 N 01252.704 E -1 60 -70 -1 24 -70 -1 22 -71 -1 20 -85 -1 20 -71 -1 21 -76 03F7 A3A2 -67
   5639.891 N 01252.704 E -1 24 -84 -1 22 -77 -1 64 -83 -1 26 -89 -1 20 -97 -1 0 0 0019 3F55 -72
```

Figure 24: Fingerprint Parameters Saved in a Text File.

Figure 24 shows eight cell fingerprints, which were automatically recorded by the implementation presented in this thesis involving two Siemens handsets and a Garmin GPS

receiver. The first column contains the sequence numbers of the measurements and the columns two to five represent the reference positions obtained via GPS. The remaining 21 columns contain GSM information of the serving cells as well as their neighbour cells as explained in Table 27. The fact that one cell fingerprint contains two identical GPS reference positions shows that the two mobile phones, which were subscribed to the Swedish GSM providers Vodafone and Telia, respectively, were used for retrieving the required GSM data at the same reference position. An explanation of the cell fingerprint obtained by the first measurement, which is shown in the first two lines of Figure 24, is presented in Table 27.

Description		**Fingerprint of GSM Provider Telia**	**Fingerprint of GSM Provider Vodafone**
Sequence number of cell fingerprint		1	
GPS reference position in ° and ‘		56° 39.870’ North 012° 52.718’ East	
First neighbour cell	LAC	-1	-1
	BSIC	66	24
	Signal level in dBm	-88	-81
Second neighbour cell	LAC	-1	-1
	BSIC	20	22
	Signal level in dBm	-92	-80
Third neighbour cell	LAC	-1	-1
	BSIC	61	22
	Signal level in dBm	-95	-84
Fourth neighbour cell	LAC	-1	-1
	BSIC	63	27
	Signal level in dBm	-86	-85
Fifth neighbour cell	LAC	-1	-1
	BSIC	61	64
	Signal level in dBm	-83	-93
Sixth neighbour cell	LAC	-1	-1
	BSIC	60	20
	Signal level in dBm	-80	-90
Serving cell	LAC	03F7	0019
	CI	2B71	179B
	Signal level in dBm	-80	-78

Table 27: Sample Database Entry.

The third line of Table 27 represents the reference position of the cell fingerprint, whereby the values for the x-coordinate and the y-coordinate are split up into degrees and minutes according to the description provided in Table 25. However, this separation is not done in the

database for reasons of easier processing. The following lines contain GSM information like signal levels in dBm, BSICs for all neighbour cells as well as LAC, CI and received signal level for the serving cell. Due to the fact that the parameter LAC is only available for the serving cell, this value is set to *-1* for all neighbour cells within the presented implementation.
As explained in Table 24, the first digit of the GSM parameter BSIC is the provider-dependent Network Colour Code (NCC). According to Table 27, the Swedish GSM provider Telia can be identified by an NCC of *6* and Vodafone employs the NCC value *2*. Furthermore, it has to be stated that the second neighbour cell of the Telia record is established by using a Vodafone base station and that Vodafone also uses a base station of the provider Telia, which can be seen from the entry representing its fifth neighbour cell. This can be explained by the common practice of GSM providers to share their base stations within inter-provider cooperation. As a matter of fact, this decreases the number of base stations available for fingerprint measurements and increases the importance of the presented approach to involve a high number of GSM providers into the process of establishing a fingerprint database.
Finally, it has to be stated that the recorded values were verified by comparing them to the values displayed at the GPS receiver and the values returned and displayed by the Siemens network monitor installed at the mobile phones.

5 Future Work

After having decided for database correlation as a complement to GPS within a global tracking solution, the main aim of the implementation presented in chapter 4 was to prove its technical feasibility. The information required for GSM cell fingerprints including base stations of more than one GSM provider is obtainable without any provider cooperation. Furthermore, the process of collecting fingerprint data could be done in an automated way. However, the described implementation can only be a starting point for the realisation of an embedded device that is capable to collect cell fingerprints along routes of great interests automatically. For instance, enhancing the availability of GPS during the process of fingerprint collection is one of the problems still to be solved. As a matter of fact, the cell fingerprints have to contain a reference position even in harsh environments. The benefit of the solution presented in this thesis is that enhancing the availability of GPS by involving for example an indoor-capable GPS receiver, map information or speed measurements is less cost-critical, since these enhancements must only be done for the embedded device collecting the cell fingerprints. The devices used for the tracking of goods later on just have to be able to measure GSM and GPS signals employing standard GSM and GPS receivers without the need of highly developed and costly GPS equipment.

Another critical aspect requiring future research is the timing behaviour of the implementation during cell-fingerprint collection. If the presented solution should be able to record GSM cell information while moving at a certain speed, the timing and thus the amount of motion have to be taken into account in order to obtain unsophisticated position data.

Finally, further investigations about the switching between GSM and GPS positioning, the benefits of measuring signals from more than one GSM provider, the implementation of an interpreter for other GSM handsets than those produced by Siemens and an adequate database correlation algorithm are necessary.

6 Conclusion

This thesis presents an evaluation of several location estimation technologies as well as a new positioning approach, which should provide the basis for a world-wide freight-tracking system.

Several existing positioning methods were assessed concerning the eight criteria positioning accuracy, world-wide availability, impact on the handset, impact on the existing network, needed provider cooperation, operating compatibility with underlying technologies, roaming support in other networks and technology-specific aspects. Further, these methods were examined regarding their suitability for a globally operable goods-tracking application.

By providing an extensive assessment, it was shown that three approaches, namely indoor GPS, assisted GPS and the database correlation technique are suitable bases for the realisation of a global goods-tracking system. Most other technologies could not be taken into consideration for the new method developed in this project because of knock-out criteria such as a too big amount of necessary provider cooperation, too complex implementation for a world-wide deployment or too high adaptation costs for the handsets as well as for the underlying network. A detailed evaluation summary can be found in subchapter 3.10 of this thesis.

The decision for the innovative approach yielded a combination of GPS and the database comparison method, with which cell fingerprint measurements can be performed automatically involving several GSM providers. A comprehensive description of this newly developed approach is provided in subsection 4. Finally, a verification of the measured values has been achieved by comparing them to the values returned by the Siemens network monitor running at the mobile phones and the reference positions directly displayed by the employed GPS receiver, respectively. Having provided a valuable basis for the implementation of a global freight-tracking application by this thesis, problems as the timing behaviour of the presented approach, the development of an adequate database correlation algorithm, the enhancement of GPS during fingerprint collections and, finally, the construction of the proposed embedded device still have to be solved within future research.

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Appendix A: Mobile Protocols

For the implementation of the innovative approach described in chapter 4, two mobile protocols have to be investigated because of their importance for the location estimation system as a whole. The first one is the Mobile Positioning Protocol (MPP), which is used to interface a Mobile Positioning System (MPS), and secondly that is the Mobile Location Protocol (MLP), which enables location applications to query position information from a GMPC entity in a wireless network. The practical application scenario of the two protocols is depicted in Figure 25.

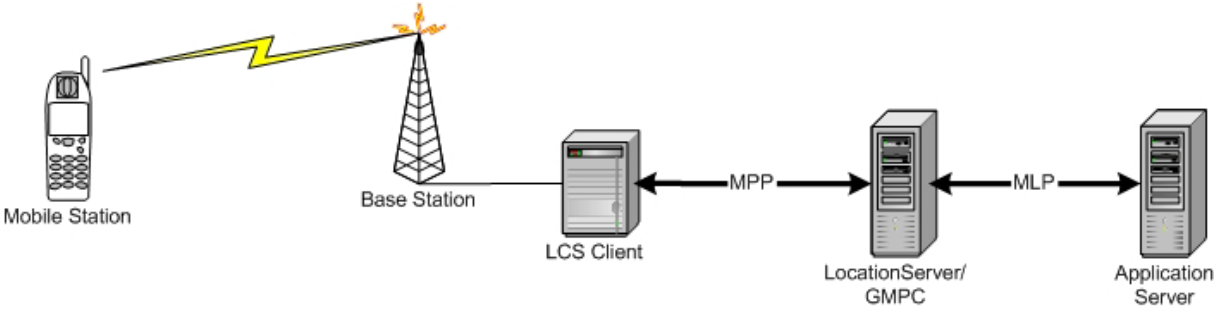

Figure 25: Practical Application Scenario of MPP and MLP.

Mobile Positioning Protocol

As mentioned in the protocol version 5.0 specification [ERIC03], MPP is employed to interface a Mobile Positioning System, meaning that this application-level protocol makes it possible to request the position of a mobile station.

MPP operates on top of HTTP 1.0 and HTTP 1.1, respectively, which are request-response type protocols. This model implies a communication between a server and a client, which are called GMPC (Gateway Mobile Positioning Centre) and LCS (Location Service) client, respectively. The communication itself can be performed over two ports, one serving for insecure messaging and one for Secure Socket Layer (SSL) encrypted communication.

The request sent by the LCS client must contain the entity-headers *Content-Type* and *Content-Length*, while the message body should comprise the position request itself in XML format. After this request has been sent by the LCS client, the GMPC answers with a successful response or with an error message, which can either concern HTTP or MPP what presumes the client to be prepared for both protocol error messages.

Within the request, two QoS parameters for the response time and the horizontal accuracy can be specified, which directly affect the overall accuracy of the positioning process. Furthermore, the way, in which the response shall be presented, can be submitted within the

request, which determines the coordinate system, the geodetic datum and the format of the response.

A successful answer means that it has correct syntax and it has passed all authority checks. A response is considered unsuccessful, if the request is rejected by the GMPC what happens as soon as at least one of the criteria mentioned above is not fulfilled.

A further and more detailed description of the elements of the request and the response messages, position areas, error codes as well as request and response examples of MPP can be found in [ERIC03].

Mobile Location Protocol

As stated in the version 3.0.0 protocol specification [LIF02], MLP enables location applications to query position information from a wireless network independently of the underlying positioning and wireless technologies. MLP can be seen as the interface between a location-based application and a location server. The application-layer protocol, which operates on HTTP and SSL, is syntactically based on XML. Figure 26 depicts the protocol stack of MLP.

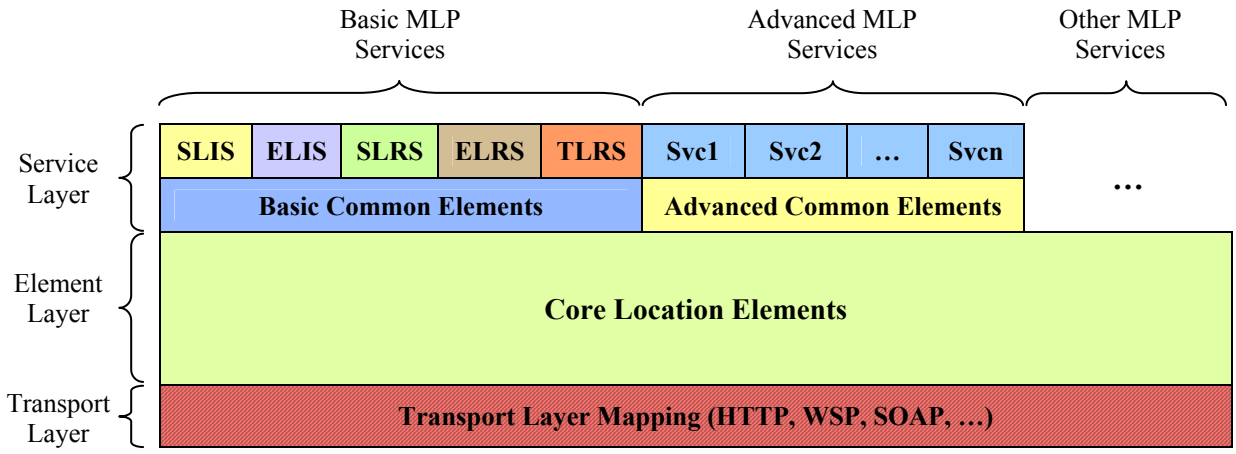

Figure 26: MLP Protocol Stack.

The *Transport Layer* of the protocol stack determines, over which protocol the XML content is transmitted. The *Element Layer* defines all common elements, which are used by the services of the uppermost layer. Such elements are e.g. Location Element Definitions, Quality of Position Element Definitions and several more. The *Service Layer* comprises the actual services provided by the MLP framework, which can divided in Basic MLP Services and Advanced MLP Services. The uppermost layer again comprises two sublayers. Firstly, these are the common elements used by all services and secondly, the actual services are defined in

the topmost layer. Using such a service presumes that a message contains two main parts, a context or a header part and a body part. The header consists of *subclient* elements, which identify the ASPs, resellers and portals in the sequence of service providers as well as the *sessionid* element representing the current session between the location server and the LCS client.

The body part of the message comprises the request and the answer, respectively and can use several services, which have already been illustrated in the protocol stack. In the following subsections, these services are particularly described.

SLIS

The Standard Location Immediate Service (SLIS) is a standard location service for simply querying the location of a mobile station. This service is used if a response to a location request is needed immediately, meaning within a certain period of time. The extended service offers several formats for the location response as well as parameters for QoS, location type and priority issues.

ELIS

The Emergency Location Immediate Service (ELIS) is used to obtain a mobile user's position in the special case that this user has initiated an emergency call what implies the necessity for an immediate answer.

SLRS

The Standard Location Report Service (SLRS) is employed when a mobile subscriber wants to convey the MS location to the LCS client what is done by the location server. The address of the application to be contacted should be defined by the MS or within the location server.

ELRS

The Emergency Location Reporting Service is used if the network automatically initiates an emergency call when a user originates an emergency call. The application, to which the report should be sent, as well as the required geographical format are defined in the location server.

TLRS

The Triggered Location Report Service (TLRS) is used when a mobile station's position should be reported at occurrences of certain events or in a periodic time interval and therefore serves for tracking a user's positions. Following [3GPP04], such events can be *UE available* and *Change of Area*. The first one occurs if the MSC/SGSN (Mobile Switching Centre/ Serving GPRS Support Node) has established a connection to the mobile station. The second

event means that the user has entered or left a pre-defined geographical area. In future specifications of the protocols, several other events like the FriendFinder application are planned to be included.

Additionally to these services, a General Error Message (GEM) is defined, which is returned if an LCS client has tried to invoke a service that is not defined in the specification.
An essential aspect to mention in connection with MLP is the protocol's extension mechanism, which is the result of a very thought ahead development. This mechanism implies separate Document Type Definitions (DTDs) that are used by all messages have been defined in order to facilitate their re-use. Furthermore, new messages can easily be added to the protocol by defining a "*%extension.message*"-parameter and finally, new parameters can easily be inserted into existing messages by the "*%extension.param*"-parameter, which should contain a vendor-specific prefix in order to ensure unambiguity. [LIF02]
A more detailed description of the elements, the structure, error mappings and the layer definitions can be found in [LIF02].